FINAL REPORT

Enhanced Amendment Delivery to Low Permeability Zones for Chlorinated Solvent Source Area Bioremediation

ESTCP Project ER-200913

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14. ABSTRACT

This project demonstrated the use of shear-thinning fluid based technology to improve treatment within low-permeability (low-k) zones of heterogeneous subsurface environments. These low-k zones can serve as a long-term secondary source of contamination because transport may be diffusion controlled, yet they are difficult to target using standard injection-based treatment approaches. A shear-thinning fluid can be used to distribute a bioremediation amendment (e.g., lactate) around an injection well such that the solution was able to better penetrate and deliver the amendments to both high and low-permeability zones. When injected at a relatively high velocity compared to natural groundwater flow velocities, the shear-thinning nature of the solution allows it to flow more readily and cross-flow from high to low-permeability zones is promoted. During the demonstration at Joint Base Lewis-McChord, the shear-thinning fluid improved amendment distribution by approximately 41% with enhanced persistence and treatment effectiveness within the lower-k zones of the heterogeneous aquifer. It is anticipated that permeability contrasts of 1-2 orders of magnitude are amenable to this technology (e.g., improving distribution to silt layers within a sand matrix, but not clay layers).

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Remediation, shear-thinning, amendment, bioremediation, low-permeability zones, cost-effectiveness

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACRONYMS

AFB	Air Force Base
CMT	Continuous Multichannel Tubing
CPT	Cone Penetration Testing
CVOC	Chlorinated Volatile Organic Compound
cDCE	cis-1,2-dichloroethene
DG	Downgradient
DNAPL	Dense Non-Aqueous Phase Liquid
DoD	Department of Defense
EBF	Electronic Borehole Flowmeter
ERT	Electrical Resistivity Tomography
EPA	Environmental Protection Agency
ESTCP	Environmental Security Technology Certification Program
ft bgs	Feet below ground surface
GSI	GSI Environmental Inc.
GW	Groundwater
HPT	Hydraulic Profiling Tool
ITRC	Interstate Technology & Regulatory Council
JBLM	Joint Base Lewis-McChord
Low-k	Low-permeability
m bgs	Meters below ground surface
MIP	Membrane Interface Probe
MNA	Monitored Natural Attenuation
MW	Monitoring Well
OD	Outer diameter
ORP	Oxidation-reduction potential
PI	Principal Investigator
PNNL	Pacific Northwest National Laboratory
PV	Pore volume
PVC	Polyvinyl chloride
SEAR	Surfactant enhanced aquifer remediation
SERDP	Strategic Environmental Research and Development Program
SLA	Sea Level Aquifer
STF	Shear-thinning fluid
TCE	Trichloroethene
TOC	Total organic carbon
TW	Tap water
VC	Vinyl Chloride
VOC	Volatile Organic Compound
WAC	Washington Administrative Code

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This report presents the results and conclusion from a collaborative project between researchers at GSI Environmental, Inc. (GSI) and the Pacific Northwest National Laboratory (PNNL) This demonstration project was funded by the Environmental Security Technology Certification Program (ESTCP), with the main goal of testing a method for potentially enhancing the delivery of remedial amendments in low-permeability (low-k) zones.

Investigators for this project included Dr. Charles Newell (Principal Investigator, GSI), Dr. David Adamson (GSI), Michael Truex (PNNL), and Dr. Lirong Zhong (PNNL). Other GSI personnel who provided technical support included Michal Rysz, Claire Krebs, Poonam Kulkarni, Isabella Mezzari Landazuri, Roberto Landazuri, and Mir Ahmad Seyedabbasi. PNNL personnel who provided technical support included Vince Vermeul, Mart Oostrom, Rob Mackley, Bradley Fritz, Jake Horner, Timothy Johnson, Jonathan Thomle, Darrel Newcomer, Christian Johnson, and Thomas Wietsma.

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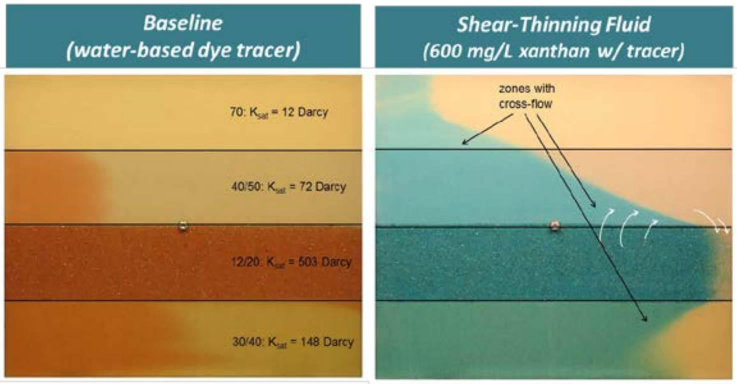
EXECUTIVE SUMMARY

Overview

The technology is focused on improved treatment within low-k zones of heterogeneous subsurface environments. These low-k zones can serve as a long-term secondary source of contamination because transport may be diffusion controlled, yet they are difficult to target using standard injection-based treatment approaches. A shear-thinning fluid can be used to distribute a bioremediation amendment (e.g., lactate) around an injection well such that the solution is able to better penetrate and deliver the amendments to both high and low-permeability zones. When injected at a relatively high velocity compared to natural groundwater flow velocities, the shear-thinning nature of the solution allows it to flow more readily and cross-flow from high to low-permeability zones is promoted. It is anticipated that permeability contrasts of 1-2 orders of magnitude are amenable to this technology (e.g., improving distribution to silt layers within a sand matrix, but not clay layers).



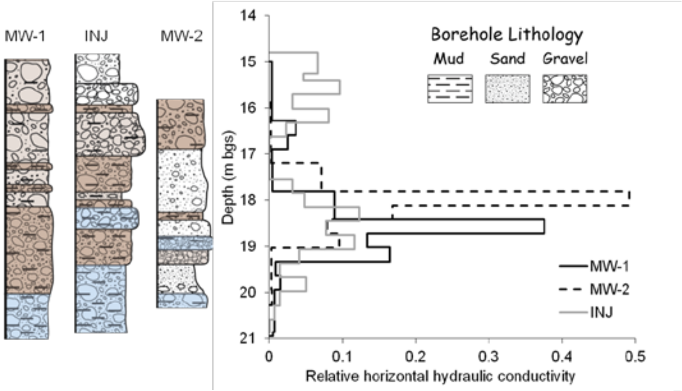
Flow cell showing improved distribution of tracer amended with a shear-thinning fluid in lower-k zones of a heterogeneous formation due to cross-flow

Background and Technology Description

The term “shear-thinning” is applied to fluids to describe their dynamic viscosity-reducing behavior when shear rates are increased. Shear-thinning fluids are non-Newtonian, meaning that their viscosities exhibit a temporary drop when the applied shear rate is increased. For amendment delivery to the subsurface, the viscosity-modifying shear force is applied by injecting the fluid through a well screen and into porous media. Shear-thinning fluids are typically water-soluble organic polymers, such as xanthan gum. Due to their solubility, they are ideally suited for subsurface remediation applications where injections of water-based amendment solutions are frequently used.

For the enhanced amendment delivery process, the shear-thinning behavior causes a more significant viscosity reduction to the fluid flowing through the lower-k zones relative to the viscosity reduction of the fluid flowing in higher permeable zones. Therefore, the preferential flow through the more permeable zones is significantly reduced while the flow into the lower-k zone is increased. In addition, mobility reduction behind the viscous injection fluid front in a higher-k layer creates a transverse pressure gradient that drives cross-flow of viscous fluids into adjacent less permeable layers. These mechanisms result in an improvement in the sweep efficiency within a heterogeneous system and lessen by-passing of low-k zones. Once injection stops, the injected fluid viscosity increases and creates a more stable zone for biodegradation reactions because the amendment-laden fluid with high viscosity is not as easily displaced by flow from upgradient groundwater.

Project Results and Performance Objectives



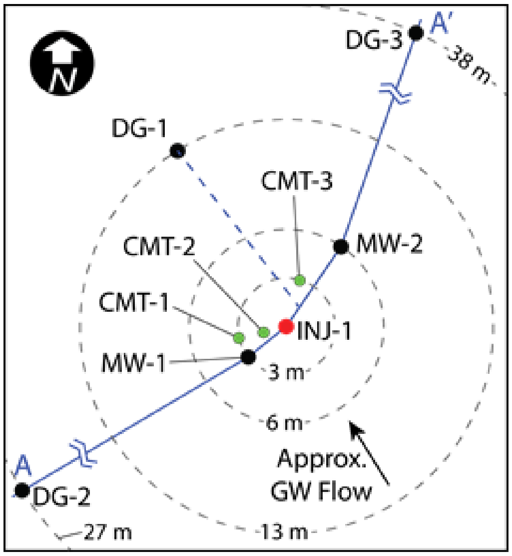
Results of Electronic Borehole Flowmeter (EBF) testing to establish permeability contrasts in mixed glacial outwash and till present at demonstration site

The field demonstration included installation and operation of a test cell in a chlorinated solvent plume at the Area D TCE plume at Joint Base Lewis McChord (JBLM). Site geology is characterized by glacial outwash and till features with varying silt content and consolidation are present at the site with a wide range of permeability values. Based on pre-test characterization data, low-level residual contamination is present within till or higher silt zones of the aquifer. These data support the conceptual model of a continuing source of TCE to the downgradient plume caused by TCE migration from muddy gravel zones with potential contributions from the consolidated till zones.

Following the characterization activities, the demonstration was conducted in 3 distinct stages:

1) ***Baseline Stage:*** After injection and pressure testing, a bromide tracer solution was injected to evaluate distribution of soluble amendments through the heterogeneous aquifer under typical injection conditions (i.e., using a Newtonian fluid). Breakthrough patterns were also used to classify monitoring intervals as low-k or high-k zones.

2) ***Shear-Thinning Fluid Injection (STF) Stage:*** About 3 weeks after the baseline stage, an amendment solution injection containing substrate (ethyl lactate) and tracer (chloride) in STF (xanthan gum) was injected to evaluate the impact of STF on distribution patterns.



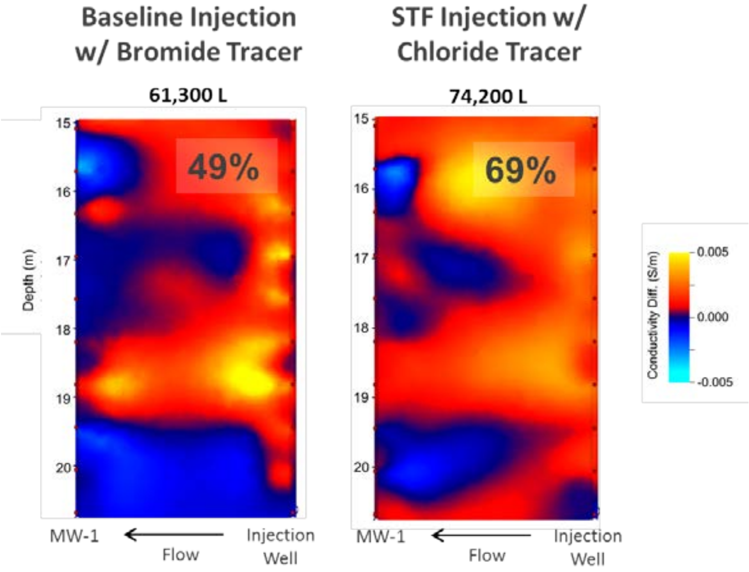
Plan-view layout of test cell used for both baseline and STF injections. Similar injection rates achieved for both tests (30 gpm).

3) ***Performance Monitoring (Treatment stage):*** After the STF stage, performance monitoring was conducted over a period of approximately 8 months to assess the impact of the shear-thinning amendment on contaminant removal, followed by post-test characterization.

The well network consisted of an injection well for amendment distribution and monitoring wells that included multi-port CMT wells for vertically discrete groundwater monitoring. Amendment, contaminant and competing electron acceptor flux for the treatment cell was evaluated by comparing concentrations at the various monitoring locations. In addition, electrical resistivity tomography (ERT) was applied for a 2-D cross section between the injection well and monitoring well MW-1 and used to map distribution for both the baseline and STF injections.

Collectively, the injection test and post-test monitoring demonstrated the presence of preferential pathways within the heterogeneous formation that would contribute to inefficient amendment delivery and treatment in the absence of the STF. When the STF was injected, it resulted in measurable TOC levels in all layers, including the lower-k zones. A number of different metrics were used to demonstrate the improvement in distribution using the STF, including:

- Improvement in the relative percent difference in the breakthrough volume between the STF and baseline tests (10 of 12 monitoring locations);
- Improvement in the relative percent difference in the percentage of the injected tracer concentration at the end of each test (11 of 12 locations);
- Improvement in the overall sweep efficiency from 49% in the baseline case to 69% in the STF case (estimated from ERT data; see figure at right).



Baseline Injection w/ Bromide Tracer

STF Injection w/ Chloride Tracer

Comparison of amendment distribution using ERT images. Each panel shows the distribution of the higher electrical conductivity (red/yellow shades) solutions as a conductivity difference between the baseline injection (left panel) and STF injection (right panel) over the depth interval of the screen. Note that the injection volume for the STF injection was estimated based on the total injection volume of 106,400L and an estimated amount of this fluid that was lost to the subsurface above the injection interval target (see Section 5.7.3)

At the end of the 8-month performance monitoring period, the continued presence of elevated TOC confirmed the long-term persistence of the amendment once it was delivered to the treatment zone. In particular, there was evidence of enhanced persistence in low-k layers relative to higher-k layers. The parent compound (TCE) was completely removed from all locations via biological reductive dechlorination, and there was no rebound in the TCE concentration.

In general, the quantitative performance objectives that were established for this technology demonstration were met (see next page). The objectives focused on improved distribution into lower-k zone, as well as the treatment effectiveness and persistence of the STF.

Performance Objective	Success Criteria	Success Criteria Achieved?
1. *Quantify Improved Distribution of Amendment to Lower k Zones*	Improvement (> 50%) in volume of amendment delivered to lower-k zones within cell during STF vs. baseline phases	**YES** • STF injection distribution was more similar uniform within the target injection zone, which included low-k zones, based on the volume injected compared to the radial distance of tracer breakthrough. ERT data show an improvement of about 41% for STF distribution compared to the baseline within the monitored 2-D cross section. • The ratio of tracer arrival in high and low-k zones decreased by 50% in CMT-2 and by 28% in CMT-1. Thus, this criterion was met in CMT-2 and partially met in CMT-1. • Tracer concentrations in 4 of 5 monitored low-k zones were >10% of the injected concentration and were improved with STF versus baseline and worse at one. • Amendment concentration (as TOC) in 4 of 5 monitored low-k zones were >10% of the injected concentration.
	Improvement (> 50% decrease) in ratio of tracer arrival between high and low-k zones during the STF stage relative to the baseline stage	
	Measurable tracer concentrations (> 10% of concentration in injection solution) in CMT ports within low-k zones for the STF stage	
	Measurable amendment penetration in low-k zones (> 10% of concentration in injection solution) in CMT ports within low-k zones for the STF stage	
2. *Determine Effectiveness in Enhancing Concentration Reduction in Low-k Zones*	Improved parent compound concentration reduction (> 50%) in low-k zone	**YES** • Pre-treatment parent compound concentrations were reduced by >70% in all low-k zones following treatment, including 100% reduction in 4 of 5 monitoring locations • Sum of daughter product concentration following treatment was > 25% of initial (pre-treatment) parent compound in all 5 monitored low-k zones • Criteria were also met in fully-screened wells in the treatment zone and all high-k monitoring locations
	Measurable concentration of one or more dechlorination daughter products (Sum > 25% of initial parent compound concentration) in low-k zone	
3. *Determine Effectiveness in Enhancing Persistence of Amendment and Effects*	6-month duration for lactate, by-products, and depleted competing electron acceptors within treatment zone	**YES** • Elevated TOC was still present in low-k zone locations after 8 months, with little change between 5 and 8 months • Sulfate was depleted by average of > 99% after 8 months • Daughter product production maintained through 8 months • Persistence not dependent on distance from injection well

Implementation Issues and Design Recommendations

Implementation of this technology is straightforward given its similarity to in situ bioremediation. There are no extraneous permitting, procurement, or regulatory requirements. It is expected to be applicable at a wide variety of sites with low-k soils where in situ bioremediation is being considered.

Key design considerations for use of this technology include the following:

- It will not be effective to directly inject STF solutions into low-k materials (e.g., clays) due to the reliance on cross-flow from high-k zones into low-k zones (except near the injection well). A rule of thumb would be to target aquifers with permeability contrasts < 2 orders of magnitude and/or for low-k layers thinner than about 0.5 m if distribution to the center of the layer is necessary. This permeability contrast would be equivalent to silt layers present within a sand matrix, but not clay layers.
- STF fluids are injected at a relatively high velocity compared to natural groundwater flow velocities to promote shear-thinning behavior and flow. The injection pressure for the STF can be estimated by multiplying the baseline injection pressure (water-only solution) by the viscosity of the STF under the injection conditions.
- If injection pressure becomes a limiting factor, then the rheological properties (i.e., viscosity) of the STF can be modified. While viscosity is needed to induce cross-flow and distribution of amendment into low-k layers, there are diminishing returns at higher viscosities. A rule of thumb is to use a static viscosity of near 100 cP for the STF when applying the technology.

Implementation Costs

To provide a basis for estimating costs of a full-scale implementation of the technology, a cost model was developed using project-specific data and several scenarios were evaluated.

The first scenario estimated that the cost of implementing a small-scale injection of the shear-thinning technology was approximately $40,000, and that 51% of this cost was associated with conventional enhanced bioremediation. Therefore, the inclusion of STF increased the cost by approximately a factor of 2 relative to the baseline. However, this incremental cost is scale-dependent and does not consider potential long-term benefits associated with the technology.

The second scenario evaluated project life-cycle costs and assumed that the better distribution of substrate achieved through the use of STFs results in fewer injection events over the project lifetime and leads to site closure within 5 years vs. the baseline case where 25 additional years of MNA are required. For the case where the shear-thinning technology was used, the total life-cycle cost was $96,000, while the cost associated with the alterative was estimated to be $194,000, with 79% of the cost was associated with long-term monitoring obligations. As a result, the total life-cycle cost for the shear-thinning case was 51% less than the baseline case.

The key cost driver is the scale of the remediation being performed, with the STF technology representing a progressively larger cost savings as the size of the site increases.

1.0 INTRODUCTION

This document serves as the final report for ESTCP Project Number ER-200913, "Enhanced Amendment Delivery to Low-Permeability Zones for Chlorinated Solvent Source Area Bioremediation". It was prepared by the Principal Investigators (PIs) for this project, GSI Environmental Inc. (GSI) and Pacific Northwest National Laboratory (PNNL), and is being submitted in accordance with ESTCP program guidance.

1.1 Background

Heterogeneity of hydraulic properties in aquifers may lead to dissolved and sorbed contaminants residing in lower-permeability (lower-k) zones, primarily due to diffusive mass flux from nonaqueous phase liquid (NAPL) source zones into low-k zones (Chapman and Parker, 2005; Sale et al., 2013). Contaminants residing in low-k zones have the potential to cause persistence of plumes and increase the remediation timeframe (i.e., the time required to reach regulatory concentration goals) because of diffusion-controlled release of contaminants back into transmissive zones (i.e., matrix or back diffusion). Reviews of chlorinated ethene source remediation (Stroo and Ward, 2010; Kueper et al., 2014) and other studies have highlighted the potential impact of this process (Ball et al., 1997; Liu and Ball 2002; Parker et al., 2004; Chapman and Parker, 2005; Parker et al., 2008; West and Kueper, 2010; Seyedabbasi et al., 2012). For instance, Parker et al. (2008) collected high resolution data from a trichloroethylene (TCE) site in Florida and concluded that matrix diffusion from one or a few thin clayey beds in a sand aquifer could result in persistent plume concentrations above drinking water standards long after isolation or removal of the original NAPL source zone. In another case study at an industrial site in a sand aquifer overlying a clayey silt aquitard in Connecticut, Chapman and Parker (2005) used field observations and modeling to conclude that TCE concentrations will remain much above the drinking water standards for centuries. Rivett et al. (2006) noted that pump and treat data from numerous field sites demonstrated a tailing effect, and that supporting laboratory studies identified slow NAPL dissolution, diffusion from less permeable strata, and slow desorption from aquifer solids as key tailing-related processes.

For remediation processes such as in situ bioremediation, delivery of remediation amendments using traditional injection approaches distributes amendments primarily to higher-permeability zones. Back diffusion of contaminants from low-k zones has been reported to inhibit the success of site remediation as reported in pump-and-treat systems (Mackay and Cherry, 1989; Rivett et al., 2006), surfactant-enhanced aquifer remediation (Saenton et al., 2002), and injection of amendments for bioremediation (Damgaard et al., 2013). In particular, bioremediation is a promising source zone treatment technique, but like many technologies, it is most effective at treating the mass present in transmissive zones. In addition to limitations associated with delivery of amendments to stimulate bioremediation in low-k zones, bioremediation of chlorinated solvents is also limited by biological reactions that compete or interfere with the contaminant degradation process and by advective movement of amendments out of the target zone prior to utilization. Because competing electron acceptors such as oxygen, nitrate, and sulfate can interfere with dechlorination reactions, controlling the concentration of these compounds can enhance the effectiveness of remediation. These constituents, along with those amendments injected into the subsurface to stimulate dechlorination, are carried into and out of the treatment zone by advection. Thus, methods are needed to overcome certain inefficiencies that may be caused by advective processes during bioremediation once amendments have been delivered to the source zone.

Current bioremediation practice focuses on selection of different types of substrate to induce dechlorination and address site-specific issues such as inefficiencies due to advective processes. Soluble substrates (e.g., lactate, ethanol) provide a ready supply of the hydrogen needed for efficient dechlorination of high contaminant concentrations that are present in source zones. Other hydrogen-producing substrates that are sparingly soluble or slowly fermentable (e.g., vegetable oils) provide lower rates of dechlorination, but slowly release hydrogen within the source zone for longer-term treatment. A combination of substrates to provide efficient initial dechlorination and long-term polishing can also be applied for source zone bioremediation. However, these techniques deliver substrate only to permeable zones. Thus, there are limitations in these current bioremediation techniques with respect to treating mass that has diffused into low-k zones because substrate utilization tends to be rapid relative to the rate of contaminant diffusion.

Methods of providing more uniform distribution of injected fluids (i.e., enhancing sweep efficiency) through mobility control induced by use of viscous injection fluids that reduce the mobility of fluids in higher-permeability zones have been developed (e.g., polymer flooding) and widely implemented by the petroleum industry to solve the heterogeneity-induced bypassing problems encountered during oil recovery (e.g., Sorbie 1991; Jackson et al. 2003). Injection of a viscous fluid into a heterogeneous aquifer induces cross-flow, enhancing transverse movement between higher- and lower-permeability layers as described by Silva et al. (2012). Mobility reduction behind the viscous injection fluid front in a higher-permeability layer creates a transverse pressure gradient that drives cross-flow of viscous fluids into adjacent less permeable layers. The transverse pressure gradient and associated cross-flow of the injection solution to lower-permeability layers is enhanced by water movement from the lower- to higher-permeability layer ahead of the viscous injection fluid front in response to the upstream cross-flow process, further slowing the velocity of the viscous injection fluid front within the higher permeability layer and enhancing velocities in the less permeable layers (Silva et al. 2012).

Polymer solutions of non-Newtonian fluids exhibiting shear-thinning (pseudoplastic) behavior have been used to create viscous injection fluids. The viscosity of a shear-thinning fluid (STF) decreases as a function of the shear rate applied to the fluid. In porous media, shear rates of injected fluids varies with fluid velocity and the hydraulic characteristics of the porous media. Due to high velocities near the injection well, shear rates are relatively high and STFs help maintain lower injection pressures than would occur with injection of a non-STF of the same static viscosity (Silva et al. 2012; Truex et al. 2011a). STFs have been investigated in laboratory and field studies to facilitate remedial amendment delivery for subsurface remediation (Zhong et al., 2008, 2011; Smith et al., 2008; Vecchia et al., 2009), as a stabilizer to enhance delivery of particulate suspensions used in remediation (Truex et al., 2011a,b; Tiraferri et al., 2008, Tiraferri and Sethi, 2009; Comba et al., 2011; Comba and Sethi, 2009; Oostrom et al. 2007), to improve recovery of NAPLs (Martel et al., 1998a, 2004; Robert et al., 2006; Giese and Powers 2002), and to suspend manganese dioxide particles produced from oxidation of permanganate in aqueous phase (Crimi and Ko, 2009). Xanthan gum is a biopolymer that can be used to form a STF and has been evaluated for use in remedial amendment delivery. Xanthan solutions showed strong shear-thinning behavior over a range of polymer concentrations and salinities and when mixed with remedial amendments (Zhong et al., 2013). Xanthan solutions have been shown to enhance the delivery of remedial amendment into low-k zones in laboratory 2-D flow cell heterogeneous systems (Zhong et al., 2008; Chokejaroenrat et al., 2013; Silva et al. 2012). Additional laboratory two-dimensional (2-D) flow-cell experiments are presented herein to extend these results to consider a larger range of hydraulic conductivities for sediment layers in the flow cell and demonstrate the cross-flow and improved uniformity (swept area) that can be achieved using an injection solution containing xanthan.

The proposed use of shear-thinning fluids as a delivery technique in bioremediation applications represents a further advancement in promoting efficient treatment of low-k zones. The delivery technique addresses limitations due to diffusion process in low-k zones and advective processes within high-permeability (high-k) zones. The technology is expected to deliver bioremediation amendments to low-k zones for which treatment is typically limited by matrix diffusion effects when standard amendment delivery processes are utilized. In addition, the enhanced amendment delivery can reduce overall treatment cost by decreasing treatment time, promoting efficient bioremediation through the temporary exclusion of competing electron acceptors, and potentially serving as a long term carbon source.

1.2 Objective of the Demonstration

The overall goal of this project is to demonstrate and validate the use of shear-thinning delivery fluid for enhanced delivery of bioremediation amendments at a DoD site where chlorinated solvents are present. The specific objectives for the project are the following:

- Demonstrate that use of a shear-thinning fluid improves delivery of amendments into the lower permeability zones of a heterogeneous site compared to injection solutions without a shear-thinning modifier.
- Quantify the increased bioremediation efficiency due to shear-thinning fluid enhanced delivery in terms of rate and extent of bioremediation for the targeted treatment zone, in particular for the lower permeability zones and the duration over which the fluid helps maintain suitable dechlorination conditions through diversion of competing electron acceptors and biodegradation of the shear-thinning agent.
- Determine the cost factors for applying the shear-thinning fluid enhanced delivery technology and compare these costs to baseline bioremediation practices.

These objectives will be achieved through the completion of a pilot-scale demonstration at a single site, as outlined in the subsequent sections of this document.

1.3 Regulatory Drivers

Cleanup of chlorinated solvent source zones has proven to be difficult and expensive at DoD sites, in part because federal drinking water standards (0.005 mg/L or less) are often 2 to 5 orders of magnitude below pre-treatment concentrations at sites. A series of projects funded by SERDP/ESTCP (McGuire et al., 2006; McGuire et al., 2014) evaluated the actual performance of in-situ source zone treatment technologies and showed that the median reduction in source zone concentration was only about one order of magnitude (e.g., 90%). Therefore, improving the performance of treatment technologies is required to meet the most stringent cleanup objectives. The proposed technology aims to more efficiently deliver bioremediation amendments to aquifers with low-k zones for which treatment is typically limited when standard amendment delivery processes are utilized. As a result, the technology targets these zones which serve as long-term contributors to low-level groundwater impacts via back diffusion.

2.0 TECHNOLOGY

2.1 Technology Description

2.1.1 Theory and Approach

The proposed technology is focused on treatment within low-k zones of heterogeneous subsurface environments. A shear-thinning fluid is used to distribute a bioremediation amendment (e.g., lactate) around an injection well such that the solution is able to penetrate and deliver the amendments to both high and low-k zones. When injected at a relatively high velocity compared to natural groundwater flow velocities, the shear-thinning nature of the solution allows it to flow readily. Based on laboratory tests, it is anticipated that permeability contrasts of 1-2 orders of magnitude can be overcome to distribute the amendment (e.g., impacting silt layers within a sand matrix, but not clay layers).

The term "shear-thinning" is applied to fluids to describe their dynamic viscosity-reducing behavior when shear rates are increased. Shear-thinning fluids are non-Newtonian, meaning that their viscosities exhibit a temporary drop when the applied shear rate is increased. A viscosity-modifying shear force can be applied using methods as simple as mixing or shaking of the solution, or—in the context of subsurface delivery—by injecting the fluid through a well screen and into porous media. Shear-thinning fluids are typically water-soluble organic polymers, such as xanthan gum. Due to their solubility, they are ideally suited for subsurface remediation applications where injections of water-based amendment solutions are frequently used.

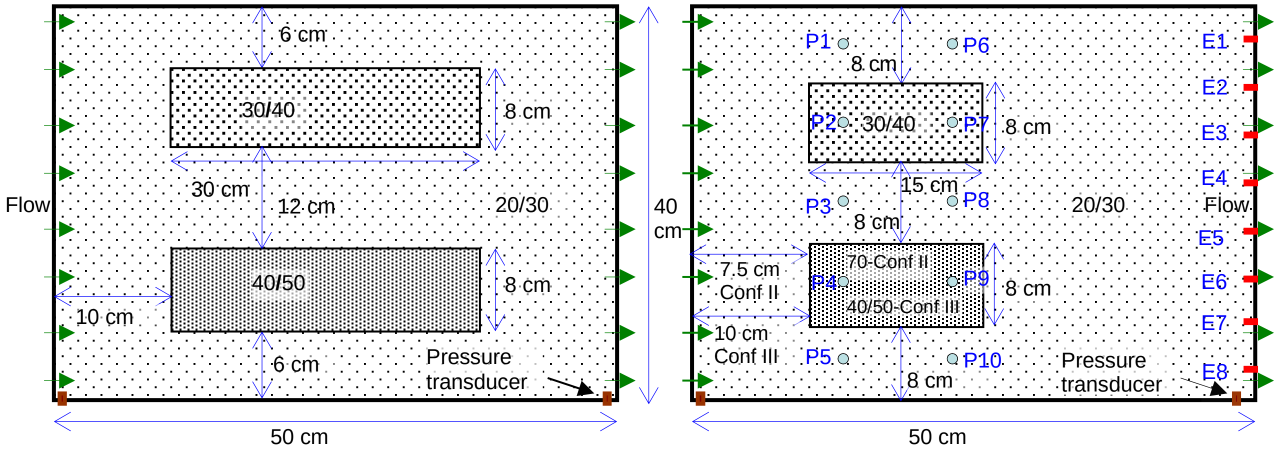
For the enhanced amendments delivery process, a non-toxic biodegradable polymer, such as xanthan gum, is added to the injection solution to form a non-Newtonian fluid with shear-thinning properties. The shear-thinning behavior causes a more significant viscosity reduction to the fluid flowing through the lower permeability zones relative to the viscosity reduction of the fluid flowing in higher permeable zones, i.e. the fluid mobility in the higher permeability zone is controlled. Therefore, the preferential flow through the more permeable zones is significantly reduced while the flow into the lower permeability zone is increased. In addition, Mobility reduction behind the viscous injection fluid front in a higher-permeability layer creates a transverse pressure gradient that drives cross-flow of viscous fluids into adjacent less permeable layers. These mechanisms result in an improvement in the sweep efficiency within a heterogeneous system. The remedial amendments added to the shear-thinning solution therefore can be delivered to low-k zones which otherwise would be bypassed.

Once injection stops, the injected fluid viscosity increases and creates a stable zone for biodegradation reactions because the amendment-laden fluid with high viscosity cannot be readily displaced by flow from upgradient groundwater. Thus, groundwater will be diverted around the injection zone until the xanthan gum biodegrades to the point when viscosity is considerably decreased. Because groundwater is diverted, there is no continuous source of competing electron acceptors (e.g., oxygen, sulfate) entering the treatment zone. Consequently, inefficiencies associated with supplying sufficient electron donor to reduce these competing electron acceptors are minimized, and the appropriate conditions for promoting growth and activity of dechlorinating populations can be maintained over a long period of time. Additionally, the amendments will not move downgradient and out of the targeted treatment zone. Over time, the xanthan gum will degrade and is anticipated to act as a long-term carbon source as the treatment zone returns to pre-treatment hydraulic conditions.

Multiple laboratory studies and intermediate-scale flow cell research on this enhanced delivery technology has been completed. The results of these studies demonstrated several advantages of the proposed treatment technology, including:

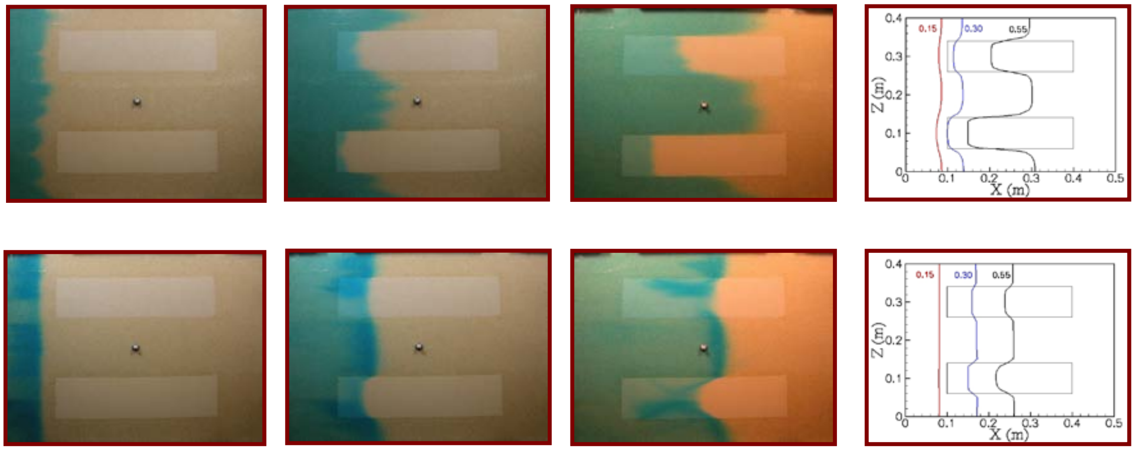
- ***Enhanced sweep efficiency:*** Flow cell studies (**Figure 2.1**)were applied to investigate the sweep efficiency comparison (**Figure 2.2**) between water flood (upper set of panels) and shear-thinning fluid flood (lower set of panels) in Configuration I (see **Figure 2.1**). In both cases, the fluids were dyed blue. For the water flood, flow bypassing is significant for the two low-k zones, especially for the zone formed with 40/50 Accusand (lowest hydraulic conductivity). In the shear-thinning fluid flood, the displacing front is straighter across the low-k zones. The simulated fluid displacing fronts at the respective pore volumes are also included in **Figure 2.2**.
- ***Enhanced amendment delivery.*** Improved sweeping of low-k zones and enhanced amendment delivery to those zones were demonstrated in the tests using sodium phosphate as the amendment for delivery (Oostrom et al. 2014). For example, test results are shown as phosphate concentrations observed in the sampling ports (**Figure 2.3**). Under the same shear-thinning fluid concentration and same flow rare, the delivery enhancement is more significant in the 70 grade sand than in the 30/40 sand, indicated by the shortened time needed for phosphate to reach the sampling port in the shear-thinning fluid flood compared to water flood. The permeability of the 70 grade sand is more than 1 order of magnitude lower than 20/30 grade matrix sand. As shown in **Figure 2.3**, the delivery enhancement is more significant in lower permeability zone.
- ***Enhanced persistence of amendment solution in low-k zones after injection.*** After an amendment solution is delivered to the low-k zones, the shear-thinning polymer solution containing the amendment will tend to remain in the low-k zones during the natural groundwater flow (**Figure 2.4**). The mobility ratio is unfavorable for the natural groundwater flow to displace the emplaced more viscous polymer solution. Water will bypass the zones occupied by polymer solution until the polymer is either significantly diluted or biodegraded. The xanthan gum polymer solution has been shown to preserve up to 60% of its initial viscosity 300 days after injection for enhanced oil recovery application (Han et al., 1999). Faster biodegradation of the xanthan gum is anticipated in a groundwater setting as reported by Cadmus et al. (1982). Zhong et al. (2013) observed significant xanthan degradation in 2 weeks when the polymer solutions were in contact with field sediments. Xanthan gum may serve as a long-term carbon source to support dechlorination of target constituents.
- ***Stabilized displacing front.*** Density differences as low as 0.8 kg/m^3 can induce unstable displacement (Schincariol and Schwartz, 1990), resulting in preferential and non-uniform

flow. The displacement stability can be improved by manipulating the viscosity of the displacing fluid based on theoretical studies (Lake 1989; Shook et al., 1998). The stabilized displacing front was demonstrated in experiments as shown in **Figure 2.2**. The unstable fluid displacement front is shown in the upper set of panels in **Figure 2.2**, and the stabilized displacing front observed when the shear-thinning solution was applied is shown in the lower set of panels. Note that these particular tests included a surfactant, with the shear-thinning fluid resulting in TCE (red fluid) displacement.



Configuration I **Configuration II and III**

Figure 2.1. Schematic of packing configurations and sampling ports locations for lab-scale testing. The labels 20/30, 30/40, 40/50, and 70 refer to the grade level of the Accusand. Ports P1 through P10 are sampling ports located in the porous medium and E1 through E8 are effluent sampling ports.



0.15 PV 0.30 PV 0.55 PV

Figure 2.2. Sweeping efficiency comparison during lab-scale testing. A heterogeneous porous media system is flushed with blue-dyed water (*top row of panels)* and with blue-dyed xanthan gum polymer solution with viscosity of 46 cP (*bottom row of panels*) at a shear rate of 0.5 sec^{-1}. The sweeping pattern of the injected fluid is shown at equal pore volumes (PV). The media system consists of high-k sand containing two embedded cells of lower permeability sand. Simulation results (using STOMP) at the same PVs are shown.

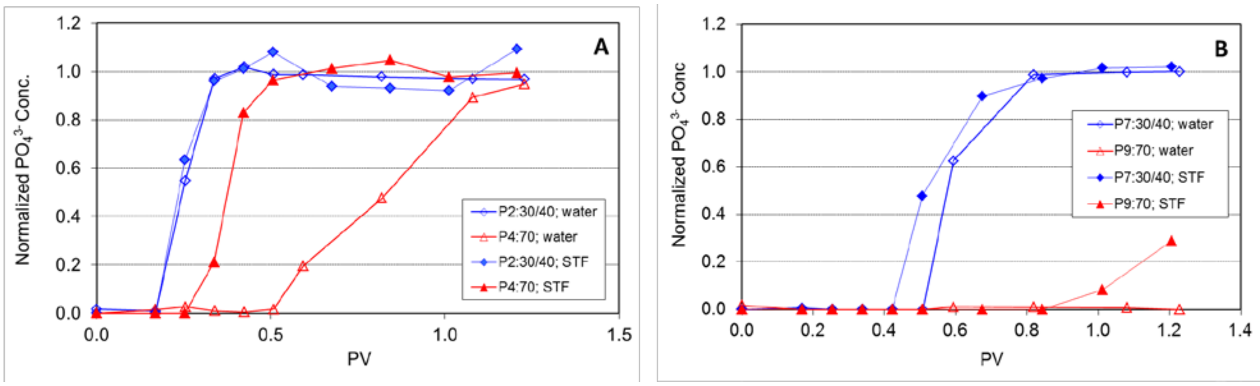


Figure 2.3. Comparison of normalized phosphate concentrations for enhanced delivery of phosphate to low-permeability zones by shear thinning fluid (STF) during lab-scale testing. These tests used Configuration II for the flow cell (see Figure 2.1). Port numbers (P*) refer to ports shown in Figure 2.1, Configuration II. A. Comparison of enhanced delivery between 30/40 sand and 70 sand in sampling ports P2 and P4; B. Comparison between 30/40 sand and 70 sand in sampling ports P7 and P9.

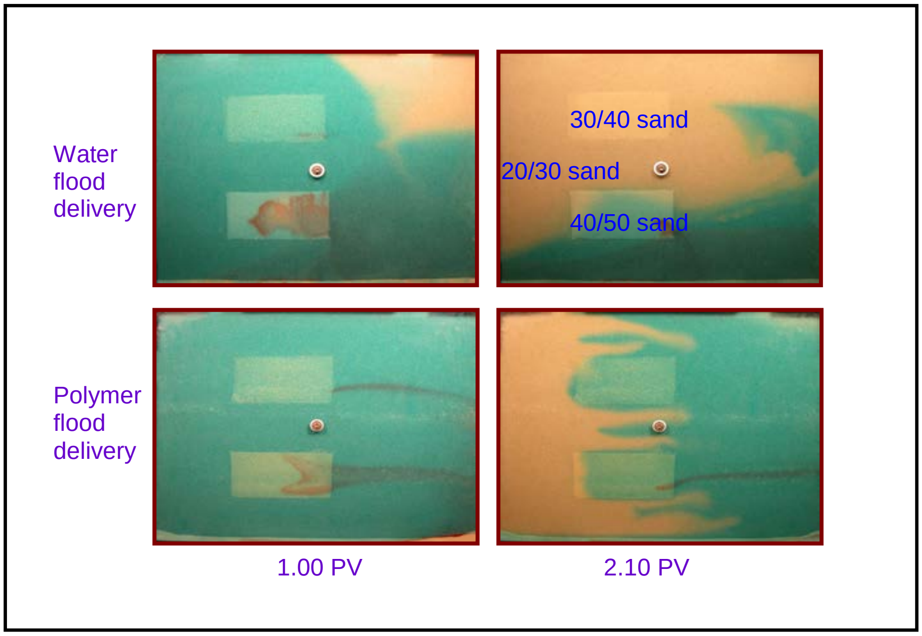


Figure 2.4. Long-term persistence of remedial amendment delivered to the low-permeability zones by polymer solution during lab-scale testing. The upper two pictures display the persistence of phosphate-containing fluids when injected solely via water flooding, and the lower pictures display the persistence of fluids when injected as a polymer solution. After 1 PV of phosphate solution (blue) was injected, water flow was used to displace the solution.

In layered heterogeneous systems, cross flow between layers is the primary mechanism leading to increased sweeping efficiency (Silva et al., 2012). As described in Truex et al. (2014), experiments were conducted in flow cells containing four layers of porous media with a larger range of hydraulic conductivities, and using a packing sequence consistent with a portion of the injection interval at the JBLM site. The flow cell experiments were conducted in the same 0.5-m-long, 0.4-m-high, and 0.05-cm wide flow cell described in detail by Zhong et al. (2008). The porous media used in the experiments were four grades of silica sands (12/20, 30/40, 40/50, and 70 mesh) obtained from the Unimin Corporation (Le Sueur, MN). The flow cell was packed with four, 10-cm high layers under saturated conditions to avoid air trapping.

The flow cell experiment demonstrates distinct differences in injected fluid movement with and without a STF additive. The dye tracer experiment (no STF, **Figure 2.5a**) shows independent horizontal transport in each of the layers with limited transverse fluid migration between layers. The dye in the 12/20-mesh sand reached the outflow boundary after 0.2 PV (35 min). A total of 9 PVs (27 hr.) was needed to sweep the whole flow cell. However, when a xanthan STF was injected, mobility reduction in the higher-permeability layers, due to an increased viscosity, resulted in considerable cross-flow of viscous fluids from the higher-permeability into lower-permeability layers. In addition, pore-water ahead of the advancing polymer solution cross-flows from the lower-permeability into the higher-permeability layers. The combination of both cross-flow phenomena, evident in **Figure 2.5b**, result in an improved sweep-efficiency. For instance, after injection of 0.67 PV (**Figure 2.5b**), the sweep efficiencies for the tracer and xanthan injections, expressed as a fraction of the total pore space, were approximately 0.4 and 0.65, respectively. Examples of the cross-flow zones during STF injection are indicated in Figure 2.5b. Cross-flow results from the development of a dynamic 2-D flow field, transporting the STF solution into lower permeability zones and STF-free water into the higher-permeability layer. In this experiment, only 2 PVs (6 hr.) were needed to completely occupy all the layers with the STF.

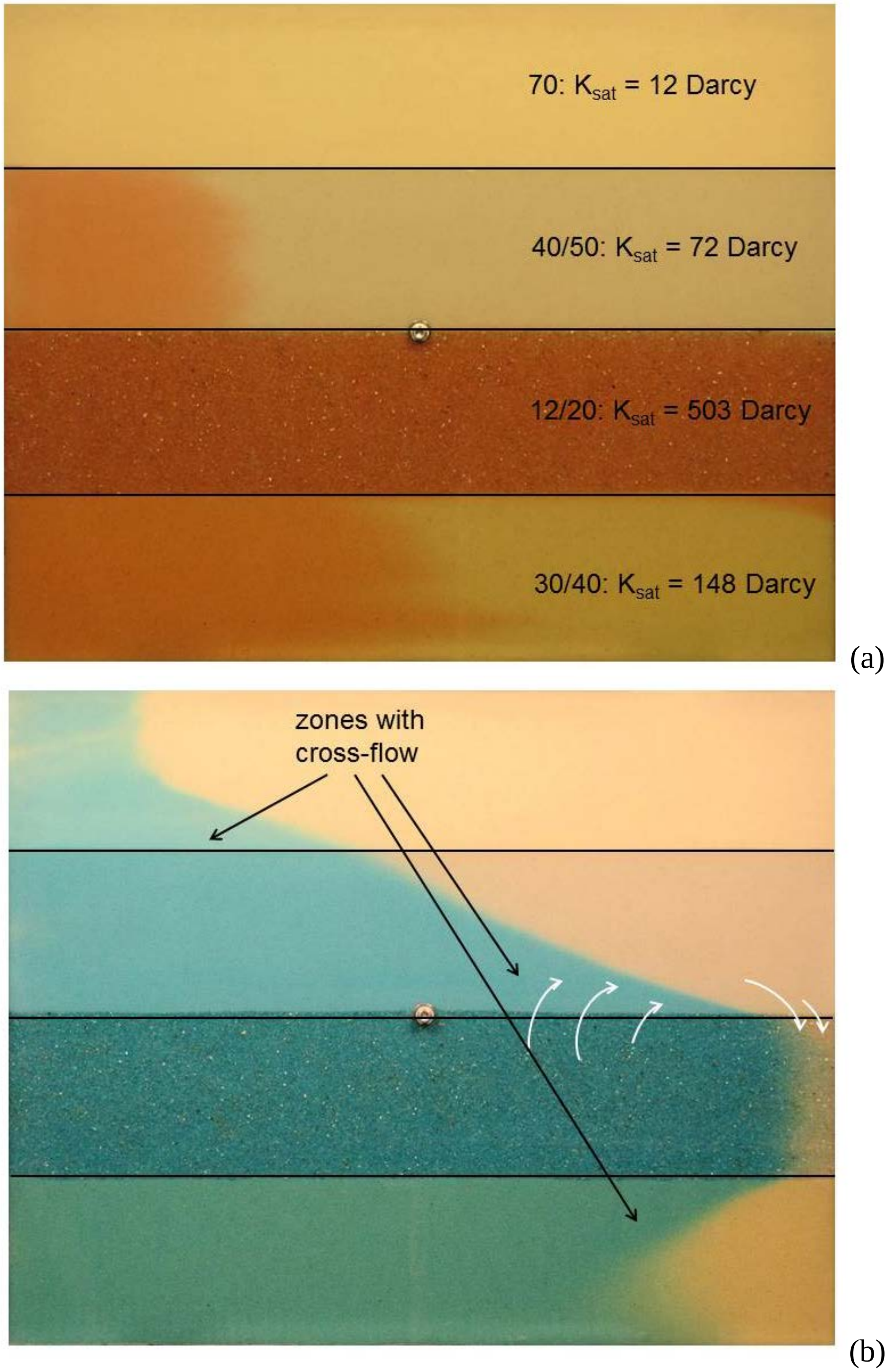


Figure 2.5. Fluid distribution in flow cell experiments after injection of 0.67 PV for (a) tracer transport in Experiment I, and (b) xanthan transport in Experiment II. The white arrows represent an example of a dynamic flow system associated with cross-flow mechanism.

2.1.2 Expected Technology Applications

The shear-thinning fluid technology is expected to be applicable at a wide variety of sites. It includes those sites where in situ bioremediation is being considered as a remedy (e.g., for either source or plume control), as well as those sites with a distinct low-k strata in contact with (or embedded in) the targeted groundwater bearing unit. Given the increasing understanding of the role of diffusion from low-k in contaminant flux and plume development (Guswa and Freyburg, 2000; Johnson et al., 2003; Parker et al., 2004; Sale et al., 2013), it is anticipated that many future remedial decisions will have to account for the presence of contaminant mass in these finer-grained units. The use of shear-thinning polymers is intended to improve distribution within heterogeneous aquifers. However, given the mechanisms involved, it should not be considered as a method to directly injected solutions into low-k materials (e.g., clays).

The applicability of the technology is aided by its inherent similarity to conventional in situ bioremediation. The primary difference is that the amendment formulation includes a polymer. Because most bioremediation applications already use a liquid, food-grade compounds, the addition of a polymer with similar characteristics (such as xantham gum) is not expected to pose any limitations to its use. Furthermore, injection well configurations for the proposed technology are essentially identical to those designed for existing bioremediation applications.

2.2 Technology Development

The proposed technology represents a combination of two technologies that have been used in subsurface remediation, specifically *bioremediation* and *shear-thinning fluid (STF)* for mobility control and enhanced delivery. Bioremediation of chlorinated solvent source zones is considered a mature technology (AFCEE/NAVFAC/ESTCP, 2004; ITRC, 2005; McGuire et al., 2006; ITRC, 2008; Stroo and Ward, 2010) with several hundred applications across the country. Detailed technology guidance documents have been published for field practitioners (AFCEE/NAVFAC/ESTCP, 2004; ITRC, 2008). A study sponsored by SERDP (McGuire, 2006) determined that the median percent reduction in parent compound concentration was 95% using data compiled from 26 sites where bioremediation was implemented. Due to the widespread acceptance and implementation of bioremediation, this section instead focuses on the use of shear-thinning polymers in subsurface remediation. A brief chronology of work related to the shear-thinning technology for injection of amendments for in situ remediation processes is presented in **Table 2.1**:

Shear-thinning fluids have long been recognized for their potential to modify fluid characteristics and to maximize recovery of fluids in the subsurface. Surfactants have long been used as part of subsurface remediation projects (Simpkin et al, 1999). Their widespread use in the petroleum industry to enhance crude oil recovery led to an interest in exploiting surfactant properties for treating NAPL contamination (Pennell and Abriola, 1997; Simpkin et al., 1999; ITRC, 2003). In the latter case, the process is generally referred to as surfactant-enhanced aquifer remediation (SEAR). Their use and potential benefits are cited in guidance documents for SEAR (AATDF, 1997; ITRC, 2003).

To-date, few applications of shear-thinning fluids in subsurface remediation have been reported, Those applications for which detailed information is available are small-scale projects where polymers were used for mobility control in combination with surfactants and/or co-solvents. However, there are no published reports of successful full-scale field applications of the surfactant/shear-thinning technology, including in recent ITRC guidance (ITRC, 2003). Typically, performance and/or other site issues eliminated their use in full-scale applications at those sites where pilot-scale studies were completed. This includes several cases where a polymer was included as part of larger soil washing demonstration projects (typically xanthan gum at > 1 g/L) (Simpkin et al., 1999). In these cases, the polymer addition was only one component of the treatment process and the use of the polymer was typically not optimized as part of the design, such that these tests were not true evaluations of the surfactant/shear-thinning technology. These include the use of xanthan gum as a mobility control for surfactant/co-solvent injections at the following three sites (1) Laramie, Wyoming (creosote-based DNAPL); (2) Hialeah County, Florida: hydraulic-oil based DNAPL; and (3) Fredricksburg, Virginia: (creosote-based DNAPL). During each of these projects (all of which were completed by 1990), recovery of NAPL was reportedly either poor or not judged to be cost-effective, and therefore was not retained as part of the final remedial design. Note that a similar technology, the use of polymers to create a surfactant foam, has also been tested in the field (Hirisaki et al., 2000).

Table 2.1. Chronological Summary of the Development of the Technology

Time Period	Description of Technology Development
1960s – 1970s	• Widespread adoption of shear-thinning polymer solutions in subsurface applications (enhanced oil recovery for petroleum reservoir management)
1980s	• First uses of shear-thinning polymers as part of field-scale surfactant enhanced aquifer remediation (SEAR) projects, with objective of NAPL recovery (summarized in Pennell and Abriola, 1997; Simpkin et al., 1999)
1990s	• Successful lab-scale studies demonstrating enhanced recovery of contaminant mass when surfactants and polymers used in combination (Martel et al. 1998a, 1998b, 1998c, 1998d; Dwarakanath et al. 1999) • Publishing of guidance documents for SEAR, including use of shear-thinning polymers to improve mobility control (e.g., AATDF, 1997)
2000s	• Additional guidance documents for SEAR, including use of shear-thinning polymers to improve mobility control (ITRC, 2003) • Additional successful lab-scale studies for combined surfactant/cosolvent/polymer systems (Dwarakanath et al. 2000; Giese and Powers, 2002; Darwish et al. 2003) • Successful lab-scale studies demonstrating enhanced delivery of other remedial amendments by using shear-thinning polymer solutions as part of the injection fluid (Zhong et al., 2008; Smith et al., 2008)
2010-present	• Additional laboratory and modeling studies to demonstrate mechanisms for enhanced sweep efficiency and distribution of injected fluids (Silva et al., 2012, Chokejaroenrat et al., 2013, 2014; Zhong et al., 2013) • Field studies to demonstrate performance of shear-thinning amendments for ISCO (Crimi et al., 2013) and in situ bioremediation (Smith et al., 2014)

While the use of shear-thinning polymers as a remedial aid should be considered developmental due to the lack of field applications, several lab-scale studies have established their potential utility, with a focus on the combination of surfactants and shear-thinning polymers. These include studies by Martel et al. (1998a, 1998b, 1998c, 1998d), Dwarakanath et al. (1999, 2000), Giese and Powers (2002), and Darwish et al. (2003).

These prior applications have focused on the use of shear-thinning fluids for enhancing recovery of DNAPL. Their potential in aiding the delivery of other remedial amendments (carbon-based substrates, oxidants) has only recently been recognized. One of the first demonstrations of the benefits was published by PIs in the current project. Specifically, Zhong et al. (2008) reported increased efficiency on delivery into lower permeability zones after conducting a series of tests designed to demonstrate the use of shear-thinning fluids for improved delivery of remedial amendments. Another study examined the use of a number of different shear-thinning polymers to enhance in situ chemical oxidation as opposed to SEAR (Smith et al., 2008). The authors made it clear that the objective of this research was to demonstrate the utility of shear-thinning fluids for improving treatment of low-k zones. This study established that combinations of xanthan gum and potassium permanganate were most successful at maintaining desired fluid viscosity while promoting significant contaminant oxidation. Of note is that both of these studies emphasized that a key advantage of shear-thinning polymers is the minimization of flow-bypassing of low-k zones that typically occurs during injection-based subsurface remediation.

More recently, Silva et al. (2012) reported a study on improved sweeping over layered heterogeneous systems using shear thinning fluid injection. Fluid cross flow among the layers was identified as the major mechanism of sweeping enhancement. In a series of flow cell experiments using xanthan gum solution to deliver permanganate, Chokejaroenrat et al. (2013, 2014) presented a set of data supporting that the use xanthan is a means of enhancing MnO_4^- delivery into low permeable zones for the treatment of dissolved TCE. In one case, they were able to demonstrate 90% improvement in sweep efficiency when including the shear-thinning polymer (Chokejaroenrat et al., 2014).

The viability of shear-thinning fluids containing vegetable oils has also begun to be investigated. As a substrate for bioremediation, vegetable oils have been shown to induce effective dechlorination, have limited geochemical impacts, and good longevity. Because vegetable oils are non-aqueous phase liquids, distribution in the subsurface can be difficult or expensive. STF has the ability to maintain a suspension of micron-size oil droplets. Due to shear-thinning properties and small oil droplet size, an oil-xanthan gum solution can be used to uniformly distribute vegetable oil in heterogeneous formations. Zhong et al. (2013) have studied the transport of vegetable oil and xanthan gum mixture through porous media and have reported promising results on the oil flow through and distribution in porous media column.

Shear-thinning fluids have also been recently applied to deliver vegetable oil substrates targeting a silt layer within a glacial outwash hydrogeology at the Time Oil Well 12A site (Smith et al. 2014). For one part of this application, high-concentration xanthan solutions were used to suspend waste vegetable oil as micron-scale droplets for injection. This approach was successful for a portion of the site where the bulk hydraulic conductivity at the screened interval was relatively high. However, logistics for mixing of the xanthan and waste vegetable oil were difficult. Subsequent applications at this site have used lower-concentration xanthan solutions mixed with a commercial emulsified oil product. This mixture has been successfully used to injection over 800,000 gallons of amendment solution into the subsurface. Post injection coring has indicated delivery of the vegetable oil to within the targeted silt layer.

In addition to the project described in this demonstration project (ER-0913), the DoD has funded several other projects through SERDP/ESTCP that are related to the use of polymers in enhancing subsurface amendment delivery. This includes ESTCP ER-0912, a field demonstration that focuses on the use of xanthan gum polymer to improve sweep efficiency of permanganate additions while also providing additional carbon for biostimulation. This ESTCP project was preceded by several SERDP projects (ER-1484 and ER-1686) by the same research group that provided fundamental information on the behavior of polymers as a part of remedial amendment delivery systems. In the field demonstration that was part of ESTCP ER-0913, the sweep efficiency improved from 37% when permanganate was used alone to 67% when permanganate was injected as a shear-thinning fluid in combination with xanthan gum and sodium hexametaphosphate (as a stabilizer).

Collectively, these projects have increased awareness and acceptability of polymer-based methods for delivering amendments to the subsurface, particularly in heterogeneous formations that limit the efficiency of conventional remedial efforts.

2.3 Advantages and Limitations of the Technology

The proposed technology is an in situ treatment method for chlorinated solvents and other subsurface contaminants with emphasis on treating zones with contaminants in low-k zones. Therefore, the advantages and limitations of this technology should be evaluated in relation to similar in situ approaches (conventional bioremediation, chemical oxidation, thermal treatment, surfactant-enhanced remediation). These are summarized in **Table 2.2**. Note that a number of the advantages of using shear-thinning as part of bioremediation have been discussed in detail in Section 2.1.

Table 2.2. Advantages and Potential Limitations of the Technology

Advantages	**Limitations**
Increased ability to treat low-k matrices w/ potential for increased substrate persistence	Unproven in field applications
Similar in design to in situ bioremediation (established technology)	Design must be tailored on a site-by-site basis (consistent with most bioremediation designs)
Appropriate for source zones	May not be suitable for use in DNAPL source zones.
Utilizes non-toxic chemicals with no special handling requirements	Difficult to track polymer degradation by-products using standard analytical methods
Can be implemented by experienced engineers with no special training	
Costs are known or easy to estimate	

Technology performance is a function of site properties, and it is envisioned that this approach should be implemented primarily at those sites with favorable site conditions. Well-delineated contaminant distribution and subsurface hydrogeology are key inputs to in situ remedy design, including use of shear-thinning fluids. Performance of shear-thinning fluids for enhancing delivery of amendments to low-k zones is most effective when permeability contrasts between high and low-k zones differences are about one or two orders-of-magnitude.

3.0 PERFORMANCE OBJECTIVES

For the purposes of evaluating the cost and performance of the field demonstration, the following performance objectives were envisioned (**Table 3.1**). A full description of the various components of the proposed approach listed in **Table 3.1** is provided in Section 5.0 (Test Design). Additional detail on the evaluation of these objectives is provided in Section 6.0

Table 3.1. Performance Objectives for the Field Demonstration

Performance Objective	Data Requirements	Success Criteria	Success Criteria Achieved?
Quantitative Performance Objectives			
Quantify Improved Distribution of Amendment to Lower Permeability Zones	Tracer/amendment arrival and concentration in all multi-level wells located in injection zone; in-test ERT data; amendment volume used during shear-thinning fluid (STF) stage vs. baseline stage	Improvement (> 50%) in volume of amendment delivered to lower permeability zones within cell during STF vs. baseline phases	YES, as quantified below and described in more detail in section 3.1. • STF injection distribution was more similar uniform within the target injection zone, which included low-k zones, based on the volume injected compared to the radial distance of tracer breakthrough. ERT data show an improvement of about 41% for STF distribution compared to the baseline within the monitored 2-D cross section. • The ratio of tracer arrival in high and low-k zones decreased by 50% in CMT-2 and by 28% in CMT-1. Thus, this criterion was met in CMT-2 and partially met in CMT-1. • Tracer concentrations in 4 of 5 monitored low-k zones were >10% of the injected concentration and were improved with STF versus baseline and worse at one. • Amendment concentration (as TOC) in 4 of 5 monitored low-k zones were >10% of the injected concentration.
		Improvement (> 50% decrease) in ratio of tracer arrival between high and low-k zones during the STF stage relative to the baseline stage	
		Measurable tracer concentrations (> 10% of concentration in injection solution) in CMT ports within low-k zones for the STF stage	
		Measurable amendment penetration in low-k zones (> 10% of concentration in injection solution) in CMT ports within low-k zones for the STF stage	

Quantitative Performance Objectives (continued)			
Determine Effectiveness in Enhancing Concentration Reduction in Low-k Zones	Pre- and post-treatment groundwater contaminant concentrations in all wells, with focus on wells screened in lower permeability zone	Improved parent compound concentration reduction (> 50%) in low-k zone Measurable concentration of one or more dechlorination daughter products (Sum > 25% of initial parent compound concentration) in low-k zone	**YES** • Pre-treatment parent compound concentrations were reduced by >70% in all low-k zones following treatment, including 100% reduction in 4 of 5 monitoring locations • Sum of daughter product concentration following treatment was > 25% of initial (pre-treatment) parent compound in all 5 monitored low-k zones • Criteria were also met in fully-screened wells in the treatment zone and all high-k monitoring locations
Determine Effectiveness in Enhancing Persistence of Amendment and Effects	Pre- and in-test contaminant and amendment concentrations in GW within treatment cell and upgradient of treatment cell	6-month duration for lactate, by-products, and depleted competing electron acceptors within treatment zone	**YES** • Elevated TOC was still present in low-k zone locations after 8 months, with little change between 5 and 8 months • Sulfate was depleted by average of > 99% after 8 months • Daughter product production maintained through 8 months • Persistence not dependent on distance from injection well
Qualitative Performance Objectives			
Ease of use	Feedback from field personnel on ease of handling and injecting polymer fluids	Single mobilization required for injection	**YES**, STF injection required a single mobilization using essentially standard injection equipment and protocol. However, the STF must be mixed the day before injection and allowed to hydrate.

3.1 Performance Objective: Quantify Improved Distribution of Amendment to Lower Permeability Zones

The highest-priority objective of this technology was to demonstrate that the injection of amendments as a shear-thinning fluid results in improved distribution to lower permeability zones relative to conventional approaches (e.g., lactate or other carbon source diluted in water). Several sub-objectives related to amendment sweep efficiency and amendment penetration into lower permeability zones were developed and tested.

3.1.1 Data Requirements

Distribution was monitored during the course of injection using a tracer solution that was measured at the multiple radial distances from the injection well. The tracer concentration was measured in the multi-level and fully-screened wells located within the treatment zone through regular sampling. In the case of this demonstration, bromide for the baseline stage and chloride for the STF stage were used as tracers and were monitored at all monitoring well clusters in the injection zone. During the STF stage, TOC, as a surrogate for the substrate amendment, and viscosity, as a surrogate for the shear-thinning polymer (xanthan), were also measured to evaluate distribution of the injection solution. ERT data was collected as part of both injection phases for a 2-D cross section between the injection well and monitoring well MW-1 located 10 ft from the injection well. The ERT monitored the screen depth interval (20 ft) within this cross section and provided an indication of the 2-D distribution of injected solution based on the increased electrical conductivity of the injection solution compared to the background.

3.1.2 Success Criteria

The objective was considered achieved if the shear-thinning fluid injection results in improved amendment delivery to the lower permeability zones. Specifically, there must be measurable evidence that the tracer has penetrated the low-k zones and at higher concentrations (>50% volumetric improvement in distribution) relative to the water-only injection. Another related criterion was to demonstrate an improvement (> 50% decrease) in the ratio of tracer arrival between high- and low-k zones during the STF stage relative to the baseline stage, an indicator of improved uniformity of distribution (sweep efficiency). Success was also evaluated based on whether the concentration of the tracer and amendment in monitored low-k zones reached 10% of the concentration of the tracer in the injection solution.

3.1.3 Results

- An ideal injection would fully distribute solution to MW-1, and no solution would reach MW-2. 100% distribution of STF was achieved at MW-1 compared to 89% distribution of tracer from the baseline injection. At MW-2, tracer arrival was not observed at MW-2 during the STF, but breakthrough during the baseline test was achieved at a volume that was equivalent to 13% of the idealized radial volume. Monitoring in a sandy zone above the targeted injection interval showed less STF distribution upward than was observed for the baseline injection. Thus, more of the injected volume was maintained within the targeted injection radius, including low-k zones, with use of STF. ERT data show that injection solution, as measured by increased bulk conductivity, was present in 69% of a 2-D cross section over the first 3-m from the injection well for STF versus 49% for the baseline injection. This is equivalent to a ~41% improvement in distribution for the STF stage.

- At CMT-2, a 50:1 ratio between the fastest and slowest breakthrough volumes was observed during the baseline injection, followed by a decrease to 25:1 during the STF injection, a 50% decrease. At CMT-1, the ratio during the baseline injection was 11:1 and decreased to 8:1 during the STF injection, a 28% decrease. Thus, this criteria was met in CMT-2 and partially met in CMT-1
- Tracer concentrations in 4 of 5 monitored low-k zones were >10% of the injected concentration and were improved with STF versus baseline and worse at one. Tracer concentrations in 4 monitored low-k zones as a % of injected tracer concentration were for the STF and baseline stage were (STF/baseline) 91%/81%, 100%/73%, 100%/69%, 65%/39% and 5%/40%.
- Amendment concentration (as TOC) in 4 of 5 monitored low-k zones were >10% of the injected concentration. Amendment concentration (as TOC) in monitored low-k zones were 84%, 91%, 41%, 33%, and 1% of the injected concentration.

3.2 Performance Objective: Determine Effectiveness in Enhancing Concentration Reduction

A primary objective of this type of treatment technology is to achieve a reduction in contaminant concentration because concentration is the typical metric used for regulatory compliance.

3.2.1 Data Requirements

The primary requirement for this objective was pre- and post-treatment contaminant concentrations from the full set of groundwater monitoring wells that were installed as part of the project, including both fully-screened and multi-level wells. Temporal groundwater monitoring data collected during the performance monitoring stage was used to support the concentration reduction evaluation.

3.2.2 Success Criteria

The objective was considered achieved with observation of dechlorination in the lowest permeability zones based on parent and daughter compound concentrations. In addition to these depth-discrete comparisons, concentration data from the fully-screened monitoring wells within the treatment zone (MW-1, MW-2) was evaluated to determine the bulk contaminant reduction percentage to provide a basis of comparison to the depth-specific contaminant reduction percentages. Success was achieved if: i) the parent compound concentration decreased by > 50% in the low-k zone at the conclusion of the performance monitoring period; and ii) the sum of dechlorination daughter products at the conclusion of the performance monitoring period was > 25% of the initial parent compound concentration,

3.2.3 Results

All success criteria were achieved. The parent compound concentration was decreased by > 50% in all wells screened in low-k zones following treatment, with 100% reduction occurring in 3 of the 5 locations. Following treatment, the sum of the dechlorination daughter products was also > 25% of the initial parent compound concentration in all wells screened in low-k zones. The daughter compound concentrations also represented between 75% and 100% of the total CVOC concentration measured in the low-k locations after the 8 month monitoring period.

These same criteria were met in all CMT monitoring locations screened in high permeability zones, as well as all fully-screened monitoring wells that were located within the treatment zone.

3.3 Performance Objective: Determine Effectiveness in Enhancing Persistence of Amendment and Effects

The technology is designed to improve the length of time that an injected amendment remains in the treatment zone relative to conventional technologies where substrate is not effectively delivered to low-k zones and post-injection flushing of the high-k zones limits substrate retention in the target zone.

3.3.1 Data Requirements

Temporal data from the performance monitoring events (groundwater well data) are the primary information used to support this objective, along with a spatial comparison between wells located closest to the injection well vs. those farther away. The aqueous concentration of substrate was be measured (as TOC) in all wells during all performance monitoring events to determine changes in substrate levels over time at various locations within the treatment area. Similarly, contaminant metabolites (cDCE, VC, ethene), competing electron acceptors (sulfate), and various geochemical parameters (oxygen and oxidation-reduction potential) were monitored during all events to determine if the inclusion of the shear-thinning polymer in the amendment solution was successful at maintaining reducing conditions within the treatment zone.

3.3.1 Success Criteria

The objective was considered achieved if the amendment and/or its direct effects persist for at least 6 months within the low-k zones of the treatment zone. This includes monitoring the duration that substrate, reducing conditions (measurable downward shift in ORP), and/or contaminant metabolites are detected in the treatment zone. This objective was evaluated primarily in the monitoring wells screened in the low-k zones since these are the depth intervals being targeted by the technology, but a quantitative evaluation of bulk conditions will also be performed.

3.3.2 Results

All success criteria were achieved. The final monitoring event was completed after 8 months instead of 6 months, and elevated levels of TOC were measured in all wells screened in low-k zones after 8 months. There was little change in TOC concentration in these wells between the 5 and 8 month monitoring events, providing further evidence for persistence with the low-k zones. In contrast, TOC also remained elevated in all CMT monitoring locations screened in high-k zones (as well as all fully-screened monitoring wells), but these wells exhibited moderate decreases in the period between 5 and 8 months. There was no evidence that TOC concentrations declined more rapidly in wells located in upgradient portion of the treatment area relative to those in the more downgradient areas of the treatment area.

Other data confirmed that proper reducing conditions were maintained. Daughter products (primarily cDCE) continued to increase in concentration throughout the performance monitoring period. Sulfate was used as the primary indicator for diversion of competing electron acceptors. Because the pre-treatment sulfate concentration (average of 107 mg/L in low-k locations) decreased significantly through 8 months (average of 1 mg/L in low-k locations), the results confirmed that the criterion for success was achieved.

3.4 Performance Objective: Ease of Use

A qualitative performance objective is proposed based on the ease of implementing the proposed core collection and sub-sampling and analysis procedures. These procedures are relatively straightforward and can be adopted by most field personnel with minimal additional training.

3.4.1 Data Requirements

This element was judged primarily on the feedback from field personnel regarding time and effort required for injection (relative to conventional techniques)

3.4.2 Success Criteria

Success was based on the amount of time required for completing the amendment injection with shear-thinning fluid, specifically that all work can be completed within a single mobilization.

3.4.3 Results

This qualitative objective was met for the demonstration at JBLM. The procedures were relatively easy to implement by field personnel with experience with standard injection-based remediation methods in a single mobilization. Personnel for the test were already experienced with the use of shear-thinning polymer as a co-amendment, but the procedures should be transferrable to others generally familiar with injection for bioremediation or other in situ technologies requiring amendment injection. Preparation and mixing of the amendment solution, which requires complete hydration of the shear-thinning polymer in an aqueous solution, was completed in one day (using an overnight hydration period). Pumping to the desired radius of influence also required less than one day and was achieved using a reasonable pumping rate (30 gpm). For this demonstration, the number of personnel on-site during the shear-thinning fluid injection (four) was larger than that for a conventional aqueous injection, but that was a function of the process monitoring requirements of this demonstration project.

4.0 SITE DESCRIPTION

4.1 Site Selection

Selection of an appropriate site for the demonstration was the first task to be completed. A preferred site was not identified at the proposal stage. Due to the widespread occurrence of heterogeneities within subsurface environments containing chlorinated solvents, it was anticipated that this technology would be applicable at many sites. Because of this, there were a number of candidate DoD sites to evaluate for technology demonstration.

A list of potential demonstration sites was generated based on recommendations from the program office and contacts with DoD site managers. Site selection criteria were developed, and sites from the preliminary list were screened against these criteria. Preferred sites included those with baseline source area characterization data identifying potential hot-spots, as well as a heterogeneous subsurface suitable for testing the concept of substrate delivery to low-k zones. The candidate list also focuses on facilities that have previously been involved in successful innovative technology demonstration projects or that were receptive to the proposed technology demonstration. The complete site selection criteria, as well as an evaluation of the characteristics of each site versus these criteria, are included in the Site Selection Memorandum that was submitted to ESTCP in October 2009.

Using these selection criteria, the site initially chosen for the field demonstration was **Offutt AFB** (specifically the LF4 portion of the site) in southeastern Nebraska. This set met the majority of the criteria, including all of those with the highest relevant importance. For the sites included in the Site Selection Memorandum that were not selected, the primary reasons were: 1) access limitations; 2) low-permeability units that were discontinuous or not sufficiently thick; or 3) poor native dechlorination ability. However, as described in Section 4.1.3, the demonstration site was later changed to **Joint-Base Lewis McChord** (JBLM).

4.1.1 Original Demonstration Site

The Landfill 4 (LF4) solid waste management unit at Offutt AFB was the area of interest for the demonstration project. LF4 covers approximately 10 acres on a grassy slope adjacent to the southern property boundary line of the base. It includes the MWR building, which was used as a liquid oxygen facility in the 1950s and 1960s and is the likely source of subsurface contamination in the area.

A complete description of the site was included in the Demonstration Plan submitted to ESTCP in June 2010. For the purposes of this report, the most relevant information for Offutt AFB LF4 is the site stratigraphy. Based on information collected during previous site investigations, soils underlying the LF4 site at Offutt AFB generally consist of artificial fill (mainly clay and sand, typically 1 to 15 ft thick), followed by lacustrine clay (3 to 5 ft thick) and Missouri River alluvium silts and sands (typically > 40 ft thick), and finally a bedrock unit (starting at 50 to 90 ft bgs). These investigations have determined that the unconsolidated soils act as a single aquifer unit with three hydrologically distinct units. These are referred to as the shallow, intermediate, and deep saturated zones. The intermediate zone was targeted for this demonstration, and available geologic information confirmed that there considerable heterogeneity represented in this zone. Based on a boring log from a location in the vicinity of the anticipated test location (LF4-MW18I), the soils within the intermediate zone from 25 ft to 45 ft bgs contain approximately 5 ft intervals of silty clay (25 to 30 ft bgs), silty sand (30 to 35 ft bgs), sand (35 to 40 ft bgs), and silty sand (40 to 45 ft bgs). This profile allows for a thorough interpretation of the influence of shear-thinning amendment on delivery efficiency within a reasonable permeability range.

In addition to the criteria outlined above, Offutt AFB was also chosen as the initial demonstration site because of the following factors:

- Available data confirmed that dechlorination to VC and some ethene occurs, such that there is a reasonable expectation for success in stimulating dechlorination;
- Large-scale biostimulation efforts have been performed at the site and have been successful at transforming parent compounds (primarily TCE) to lesser chlorinated metabolites (primarily cDCE and VC), but there are still relatively large areas with low levels of TCE; and
- The site is accessible and the project team has successfully worked with the site manager in previous technology demonstration projects.

4.1.2 Rationale for Changing Demonstration Sites

During the completion of baseline characterization and several rounds of detailed tracer injection and elution testing at Offutt AFB during the late-2010 to mid-2011 time periods, the project team identified several problems related to the site conditions and our original objectives. Specifically, permeability contrasts at the site are different than expected, resulting in a decreased capacity to measure improvements with the shear-thinning technology. Rather than four distinct permeability layers at the site (as indicated by initial characterization data), there are only two with a relatively high-k contrast. As a result, it was clear that proceeding at this site with the existing well network would prove difficult in terms of demonstrating improvements in amendment volume delivery. In addition, the extensive tracer test had not been successful, in part because of the presence of preferential pathways from the injection well away from the existing monitoring well network. Importantly, the current injection well was no longer functional and suffered from severe leakage, necessitating the installation of a new injection well. Full descriptions of the work completed and problems encountered were included in technical memorandums submitted to the program office in October 2010 and September 2011.

Subsequently, the project team submitted a series of options for proceeding to the program office, and the initial preference was to find another location at Offutt AFB for the demonstration project. In this option, a new injection well was to be installed either in a different portion of the LF4/LF12 area or in an entirely different plume in an attempt to minimize the problems encountered in the original test cell. This would also necessitate reinstalling monitoring wells and completing a baseline soil and groundwater characterization within the new test cell. The tracer test would then be repeated in the new test cell to demonstrate amendment distribution under baseline conditions (i.e., water delivery of amendment), followed by the completion of remaining tasks (shear-thinning fluid injection, performance monitoring, and post-test characterization).

Considerable time elapsed between the period when a formal proposal was developed (late 2011), finalized (July 2012), and approved (April 2013). During this period, conditions changed at both the original demonstration site (Offutt AFB) and an alternate site (Joint Base Lewis McChord) that was considered during the earlier discussions with ESTCP. These changes are summarized below:

1. The project team had difficulty identifying a location with suitable hydrogeology for the technology demonstration at any of the multiple plumes present at Offutt AFB. This problem was evident during the first phase of injection activities at the initial plume locations (LF4/LF12), and the challenges became even more apparent following review of other plumes at the site. Essentially, there was still doubt that a suitable site could be identified at Offutt AFB.
2. There was uncertainty about continuing at the original demonstration site (Offutt AFB) due to the start of remedial activities under new Performance-Based Remediation Contracts in March 2013. The base manager was receptive but remained unsure about what challenges the new arrangement might bring (e.g., scheduling issues, coordinating with new site personnel, etc.).
3. The presence of favorable hydrogeologic conditions was confirmed at the proposed JBLM site. Extensive characterization data has been recently collected for this site, which would minimize characterization data collection efforts as part of ESTCP ER-0913 and focus funds on conducting the demonstration.
4. There was an ability to leverage existing characterization data and equipment from PNNL's existing project at JBLM. For example, a suitable injection well and several monitoring wells that would be suitable for use had already been installed at the site, and only a few additional wells would need to be installed for the current project.

Collectively, these conditions led the project team to conclude that the demonstration project would be more successful if implemented at the JBLM site. The change to JBLM was approved by the program office in mid-June 2013.

4.2 Site Location and History

JBLM is located in northwest Washington within the Puget Sound region. It was established in 2010 following the merger of Fort Lewis (established in 1917) and McChord Air Force Base (established in 1947) (**Figure 4.1**). The area of interest for this demonstration is the American Lake Garden Tract, Area D site, which is located at the northwest edge of JBLM. A TCE plume has persisted at Area D for more than 15 years despite the imposed pump-and-treat remedy using

3 extraction wells placed at three locations along the axis of the plume downgradient of the source. Available information indicates that former waste disposal site 5/39 is the source of the TCE plume and apparent continuing source during pump-and-treat operations. Subsurface contamination at waste site 5/39 may be present over an areal extent of 2 to 3 acres. The area is currently being used as the golf course for the base.

Figure 4.1. Location of Joint Base Lewis-McChord.

The area of interest for this demonstration includes a portion of Area D that has been characterized extensively over the past five years to support an assessment of bioremediation as a long-term remedial approach. As such, the area includes several existing monitoring wells and injection wells, as shown in **Figure 4.2**. These characterization efforts form the basis for the geologic characteristics described below.

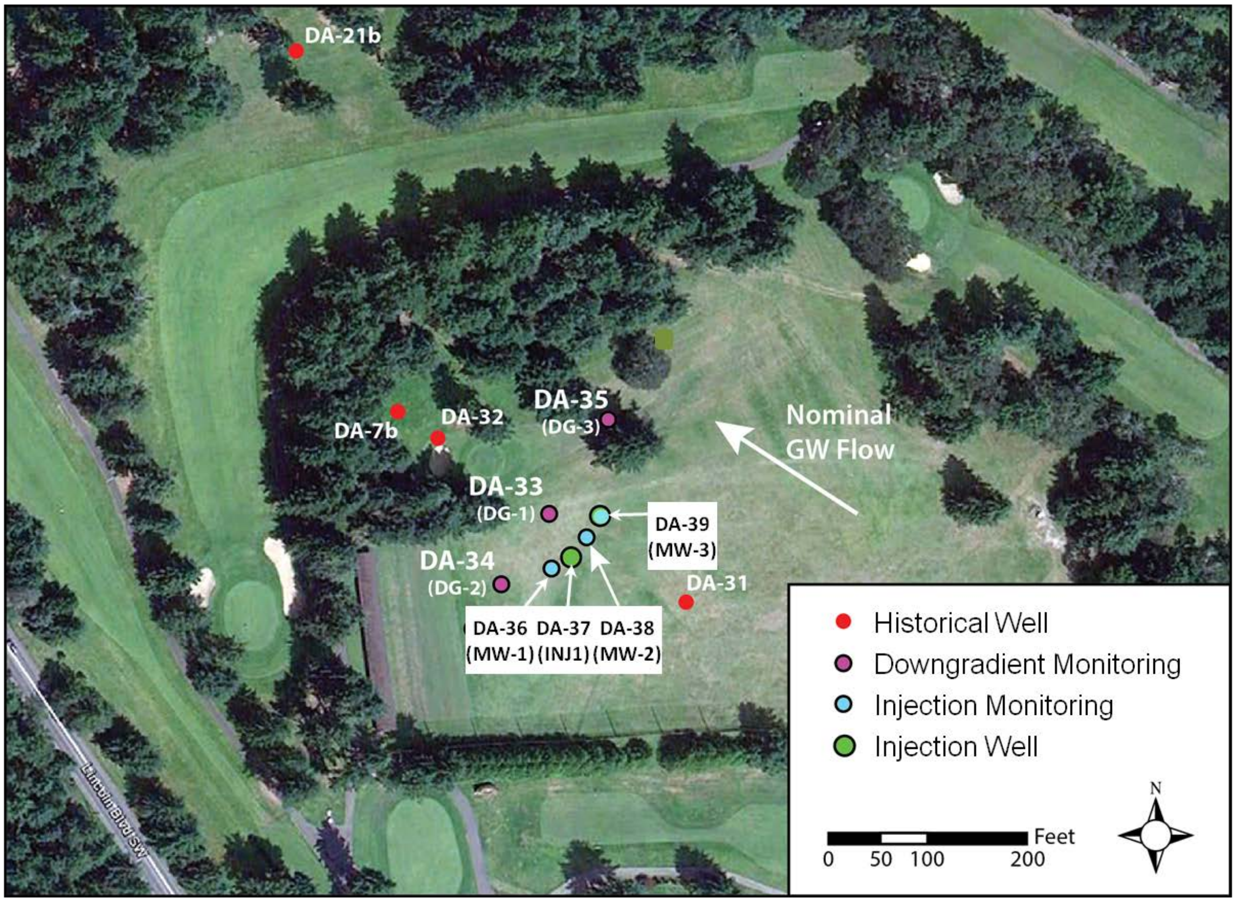


Figure 4.2. Site map showing existing wells at the test site (prior to the start of the current demonstration project). Well IDs in parentheses are those used for this demonstration.

4.3 Site Geology and Hydrogeology

Past field investigations, groundwater monitoring, and modeling activities have provided a conceptual hydrogeologic model in the vicinity of the Area D site where the field demonstration was conducted. Borden and Troost (2001) recently described the aquifer system beneath JBLM. This description defines the major geologic features related to groundwater flow. The upper unit in the subsurface, termed the Vashon Unconfined Aquifer (Vashon Aquifer), comprises a nominally 100-ft-thick zone. A generally continuous non-glacial unit having aquitard properties (termed the Qpon Aquitard) underlies the Vashon Aquifer. The Qpon Aquitard consists of mostly non-glacial, fine-grained deposits laid down during the Sangamon Interglacial period and generally believed to span the period 50,000 to 120,000 years ago; this unit was formerly referred to as the Kitsap Formation. The thickness of the Qpon Aquitard varies, but it is generally about 10 to 20 feet thick. Beneath the Qpon Aquitard is a confined aquifer termed the Sea Level Aquifer (SLA). The SLA is bounded at the bottom by another non-glacial deposit with aquitard properties. The SLA appears to consist of mostly permeable glacial outwash deposits from the next-to-last glacial cycle. The thickness of the SLA roughly varies between 50 to 150 feet. Following the A-A' transect shown in **Figure 4.3** (adapted from Borden and Troost, 2001), **Figure 4.4** (adapted from Borden and Troost, 2001) illustrates the interpreted geologic cross section and provides an approximation of the distribution of different sedimentary facies for Area D. The field demonstration at Area D was conducted within the Vashon Aquifer.

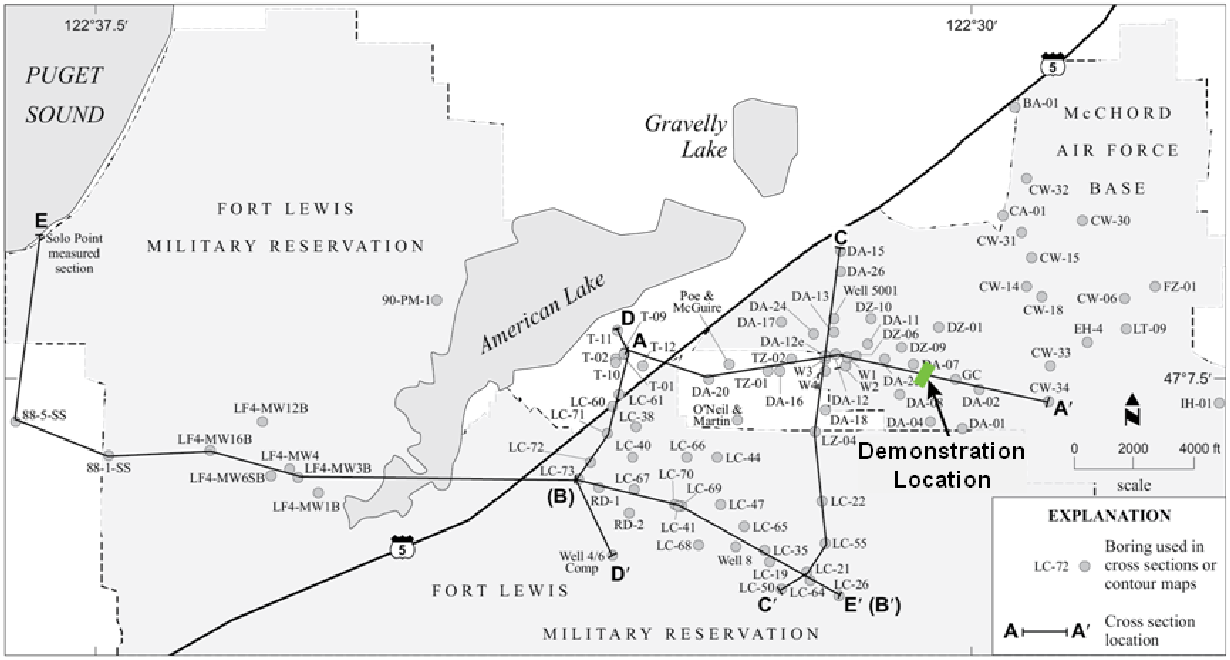


Figure 4.3. Regional borehole and cross-section location map (adapted from Borden and Troost, 2001). The Area D test location is shown with a green line.

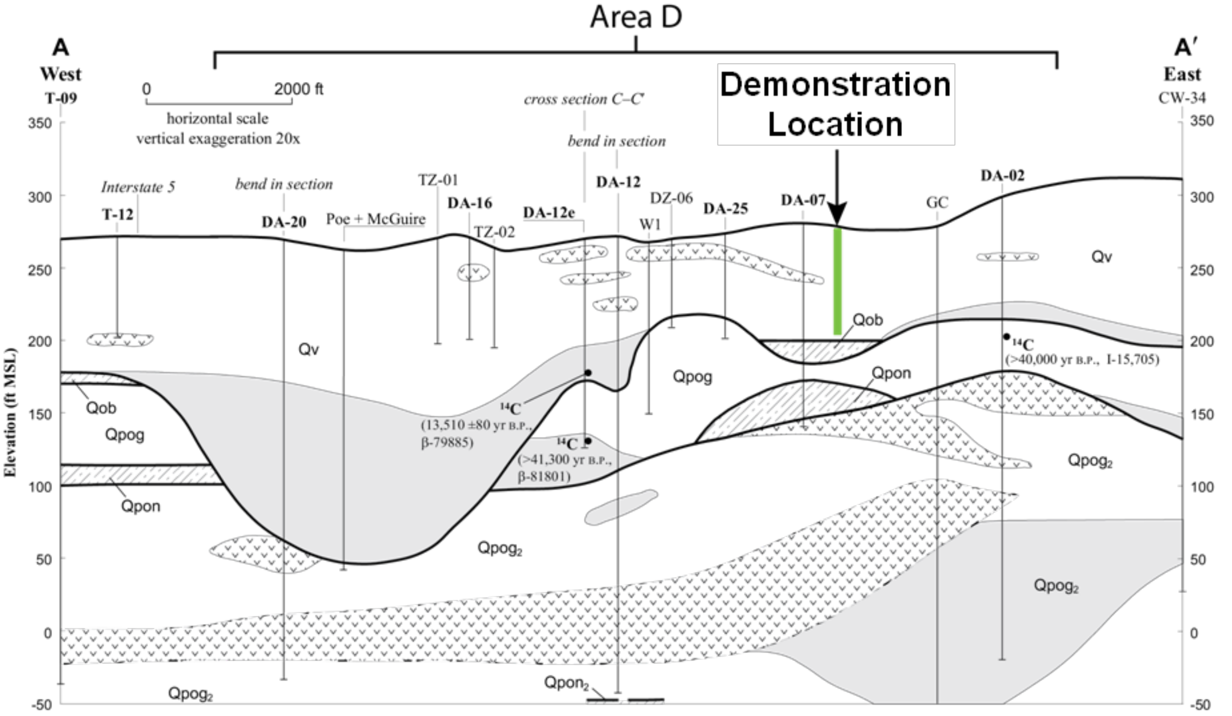


Figure 4.4. Conceptual geologic cross-section A-A' (see **Figure 4.3** for transect location). The cross section (adapted from Borden and Troost, 2001) is generally located along the centerline of the Area D plume in the Vashon Aquifer. For the cross section, white areas (Qv, Qpog, Qpog2) correspond to outwash gravels, the grey area is glaciolacustrine aquitard sediment, Qob is Olympia bed material, the hashed areas (Qpon and Qpon2) are non-glacial aquitard materials, and the areas with the "v" symbol pattern correspond to till material. The Vashon Aquifer lies above the uppermost Qpon aquitard.

The Vashon Aquifer is composed of inter-layered outwash and till that, in general, overlie older glacial outwash termed the Pre-Olympia drift. In some areas, non-glacial deposits referred to as the Olympia beds are present between the Vashon outwash/till and Pre-Olympia deposits. Distinct hydrologic layers in the Vashon Aquifer include the Steilacoom Gravel at the top followed by several alternating layers of laterally continuous to discontinuous glacial till and outwash. A mixture of Pre-Olympia drift, Olympia beds, and/or lacustrine beds is present toward the bottom of the aquifer. Within Area D, the bottom of the aquifer primarily consists of Olympia beds and/or lacustrine beds of variable thickness. About a quarter mile downgradient of the field demonstration site, sand-dominated outwash sediments of the Pre-Olympia drift form a local paleotopographic high that forms the bottom of the aquifer. Downgradient of the Pre-Olympia high, the bottom of the aquifer consists of a lacustrine-filled paleochannel that forms a thick hydraulic barrier above the underlying SLA.

A representative geologic cross section for the Vashon Aquifer in the area and depth intervals of interest is presented in **Figure 4.5**. Characterization efforts at the downgradient portion of the disposal zone confirm that TCE concentrations are highest in lower-permeability portions of the mixed till/outwash aquifer (**Figure 4.5**). Contaminants present in these lower permeability zones are suspected of acting as a continuing source to the downgradient plume within the more permeable zones such as the upper Steilacoom Gravel unit. The data shown in **Figure 4.5** were generated from depth-discrete groundwater samples collected during well installation and analyzed by EPA method SW846 8260B (TCE, cDCE, vinyl chloride).

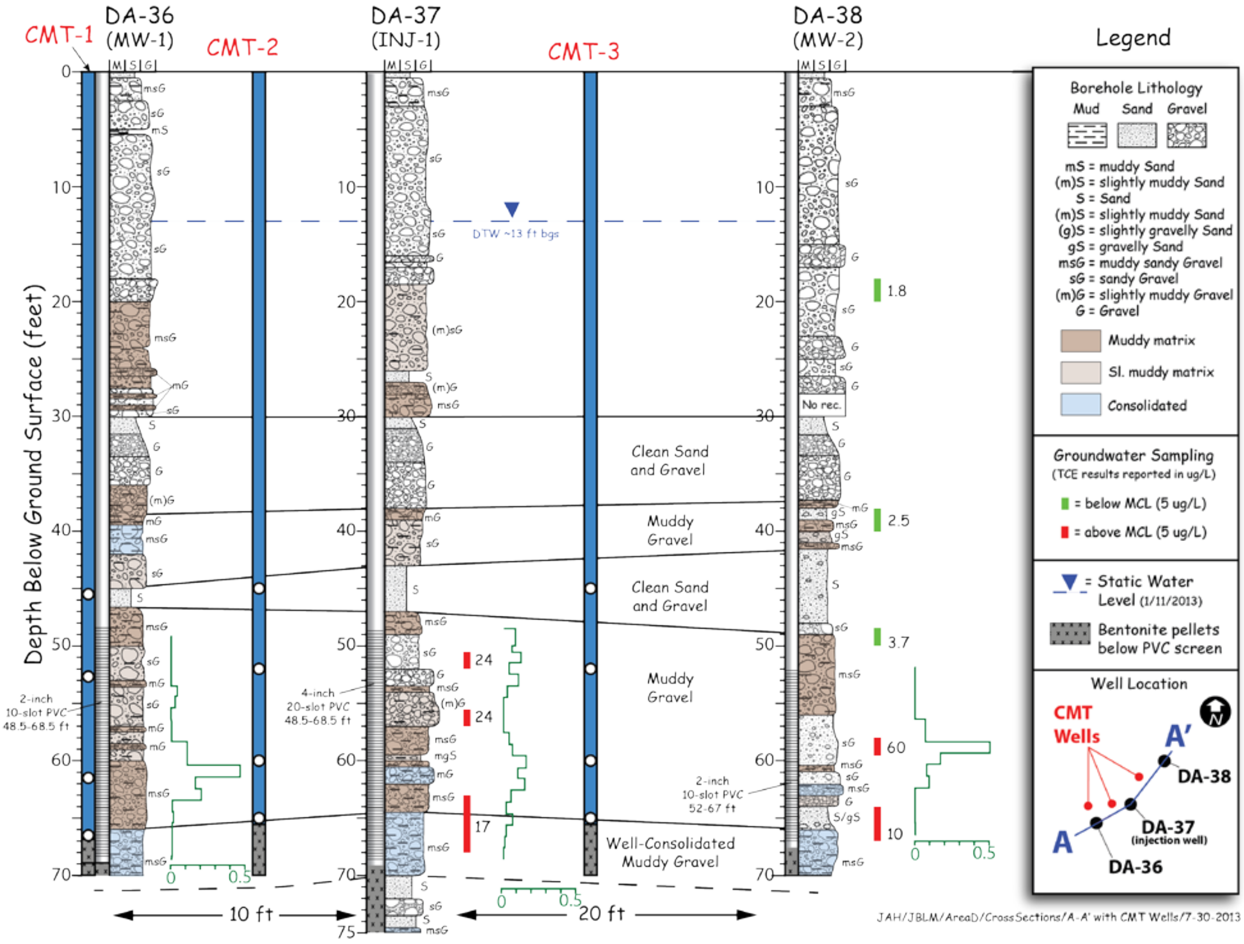


Figure 4.5. Cross section at the test site (see Figure 4.2 for transect location). Contaminant distribution from groundwater sampling and vertical distribution of relative hydraulic conductivity (see text below) are also shown.

Glacial outwash and till features with varying silt content and consolidation are present at the site with a wide range of permeability values. Reported outwash hydraulic conductivity values range from 10 to 50+ m/d while till values range from 0.5 to 6 m/d (Vermeul et al. 2000; Truex et al. 2006; USACE 2002; Ebasco Environmental 1991). A representative bulk hydraulic conductivity for test site wells with screens intersecting the upper Steilacoom Gravel unit is approximately 15 m/d (Ebasco Environmental 1991). The bulk hydraulic conductivity of the targeted injection interval, based on analysis of a constant-rate discharge test conducted in the injection well, was estimated at ~3 m/d. Pump testing was performed using a 3-inch diameter submersible pump installed near the bottom of the wellbore in well DA-37, with pressures were monitored in the stress well (INJ-1) and two observation wells (MW-1 and MW-2) using submersible pressure transducers, and well water levels were verified using manual depth-to-water measurements.

Groundwater in the aquifer generally flows in a west-northwest direction at the demonstration site. Groundwater is first encountered at about 4 m bgs, and hydraulic gradient is nominally 0.001. Given the range in hydraulic conductivity of 3 to 15 m/d, estimated groundwater velocity would range from 0.015 to 0.075 m/d.

4.4 Contaminant Distribution

A plan-view depiction of the evolution of the Area D TCE plume in the Vashon Aquifer is shown in **Figure 4.6**. As indicated, TCE primarily migrates in a west-northwesterly direction with a plume above the MCL about 800-m long. This figure also shows the approximate location of the field demonstration site.

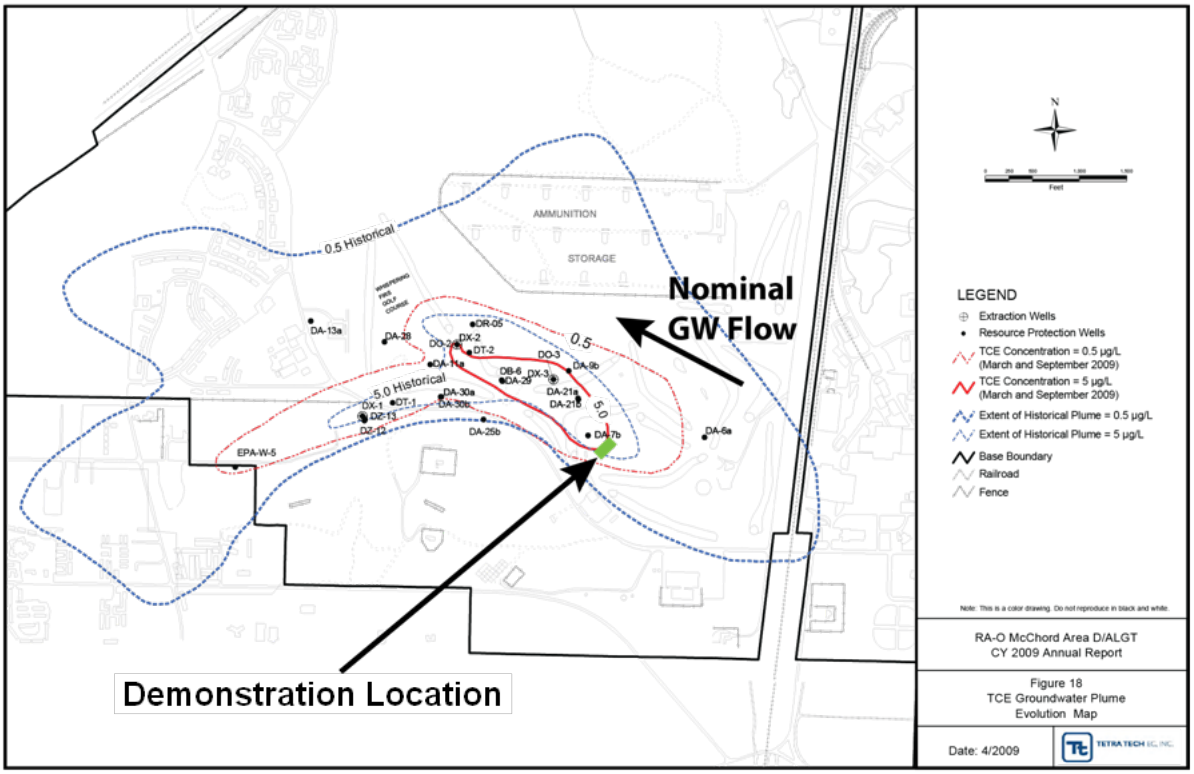


Figure 4.6. TCE groundwater plume evolution at Area D. The field demonstration site is at the downgradient edge of the suspected source zone (adapted from Tetra Tech EC, Inc. 2010).

Based on the characteristics of the persistent plume and recent characterization data, residual contamination is present within till or higher silt zones of the aquifer with highest remaining concentrations in the 50-70 ft bgs interval. **Figure 4.5** illustrates an example cross section of existing subsurface contaminant data at the location of the test site (groundwater flow is perpendicular to this cross section). These data confirm that current concentrations in the source zone are relatively low, with concentrations in the clean gravel and sand in the aquifer above the interbedded muddy gravel/till zone below the MCL for TCE. These characterization data support the conceptual model of a continuing source of TCE to the downgradient plume caused by TCE migration from muddy gravel zones with potential contributions from TCE in the consolidated till zones. The TCE contribution from the consolidated till is expected to be smaller than from the muddy gravel zones because of the low hydraulic conductivity of the till units. The chlorinated solvent analysis data from the depth discrete sampling are shown in Table 3. All quality assurance criteria for the analyses were met. In addition to their use in evaluating the distribution of TCE at the site, these data also indicate relatively high concentrations of TCE reductive dechlorination daughter products (cis-1,2-dichloroethene [cDCE] and vinyl chloride

[VC]) in a few of the samples. Thus, some dechlorination processes appear to be occurring in isolated portions of the source area.

Table 4.1. Results for Chlorinated Solvent Analysis of Depth-Discrete Groundwater Samples.

Well	Sample Depth (ft)	TCE	cDCE	VC	1,1-DCE
DG-1 (DA-33)	18.5 - 20.5	0.97	ND	ND	ND
DG-1 (DA-33)	28 - 30	2.1	ND	ND	ND
DG-1 (DA-33)	37 - 38.5	2.2	ND	ND	ND
DG-1 (DA-33)	47 - 48	43	0.59	ND	ND
DG-1 (DA-33)	58 - 60	35	41	ND	ND
DG-1 (DA-33)	65 - 68	4.8	4.6	ND	ND
DG-1 (DA-33)	39 - 69	6.8	1.3	ND	ND
DG-2 (DA-34)	38 - 30	0.69	ND	ND	ND
DG-2 (DA-34)	43 - 45	18	ND	ND	ND
DG-2 (DA-34)	50 - 53	31	ND	ND	ND
DG-2 (DA-34)	67 - 69	30	12	ND	ND
DG-3 (DA-35)	28 - 30	1.8	ND	ND	ND
DG-3 (DA-35)	49 - 50	14	23	1.3	ND
DG-3 (DA-35)	58 - 60	49	200	26	2.1
DG-3 (DA-35)	64 - 67	29	260	28	2.6
MW-2 (DA-38)	28 - 30	1.8	0.6	ND	ND
MW-2 (DA-38)	38 - 40	2.5	1.8	ND	ND
MW-2 (DA-38)	38.5 - 50	3.7	3.6	ND	ND
MW-2 (DA-38)	58 - 59.5	60	5.4	ND	ND
MW-2 (DA-38)	64 - 67	10	1.2	ND	ND

Notes: (1) Results are shown in units of µg/L; (2) Non-detect results are indicated by “ND”.

5.0 TEST DESIGN

The technical objectives of this project were met through a field demonstration of the shear-thinning technology, including pre-test and post-test site characterization to assess performance of the technology. The following section provides a summary of the system design, the sampling and analysis plan for the project, and the results of the field demonstration.

5.1 Conceptual Experimental Design

The field demonstration included installation and operation of a test cell in a chlorinated solvent plume at the JBLM site. Following the completion of characterization activities (Section 5.2), the demonstration was conducted in three distinct stages:

1) ***Baseline Stage:*** Step and constant-rate injection tests with water were completed to verify suitability of the selected injection parameters (e.g., rate, pressure) for the test. A bromide tracer solution was then injected to evaluate distribution of soluble amendments through the heterogeneous aquifer under typical injection conditions (i.e., using a Newtonian fluid that does not exhibit shear-thinning characteristics).
2) ***Shear-Thinning Fluid Injection (STF) Stage:*** About 3 weeks after the baseline stage, an amendment solution injection containing soluble amendment (ethyl lactate) and tracer (chloride) in STF (xanthan gum) was injected to evaluate the impact of STF on substrate distribution patterns within the heterogeneous aquifer.
3) ***Performance Monitoring (Treatment stage):*** After the STF stage, performance monitoring was conducted over a period of approximately 8 months to assess the impact of the shear-thinning amendment on contaminant removal, followed by post-test characterization.

The well network consisted of an injection well for amendment distribution, upgradient and downgradient monitoring wells, and several treatment zone monitoring wells, including multi-port wells for vertically discrete groundwater monitoring. Amendment, contaminant and competing electron acceptor flux for the treatment cell was evaluated by comparing concentrations at the various monitoring wells. In addition, electrical resistivity tomography (ERT) was applied for a 2-D cross section between the injection well and monitoring well MW-1 and used to map amendment distribution for both the baseline and STF injections.

The groundwater and soil sampling specifically targeted an interval with significant heterogeneity to evaluate the relative impact of STF in improving amendment distribution and promoting faster and more complete remediation.

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5.2 Characterization Activities

Preliminary characterization work was completed at the site as part of an existing PNNL project. The focus of the preliminary work was to understand hydrogeologic conditions and contaminant concentration and distribution within the targeted area as described in Section 4.3. These data were augmented by installation of CMT wells and an ERT system. The results of these activities are provided in this section, while a detailed description of the methods involved in collecting the data are provided in Section 5.4. The locations of the relevant monitoring and/or injection locations are shown in **Figure 5.1**.

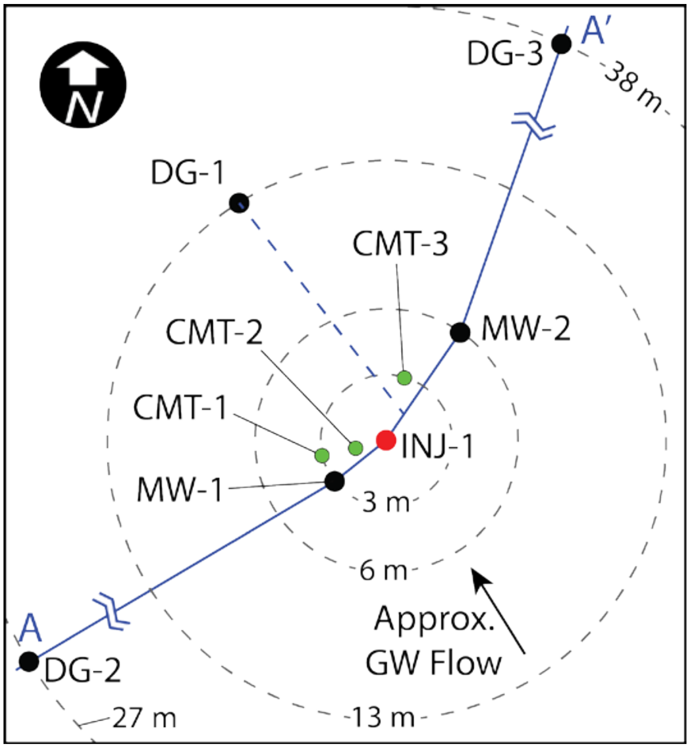


Figure 5.1. Site map showing all monitoring and injection wells used during demonstration. Note that the cross-section for transect A-A' is shown in **Figure 5.3**. Each of the continuous multichannel tubing (CMT) wells include screened intervals at multiple depths.

5.2.1 Electronic Borehole Flowmeter (EBF) Testing

To supplement existing data, EBF testing was completed at wells MW-1, MW-2, and INJ-1 in August 2013 to characterize the vertical distribution of relative horizontal hydraulic conductivity. As described in Section 5.4.2, the EBF is a downhole probe (Quantum Engineering Corporation, Loudon, Tennessee) that uses Faraday's Law of Induction to relate the voltage induced by a conductor moving through a magnetic field to the velocity of the conductor (in this case, groundwater). Data were collected at a spatial resolution of 0.3 m over the screened interval of each well (approximately 50 to 70 ft bgs) using standard EBF profiling protocols (Young et al. 1998; Flach et al. 2000). In each case, the peak hydraulic conductivity was noted within a relatively narrow interval around 60 ft bgs (**Figure 5.2**). Within INJ-1, a similarly high hydraulic conductivity was noted within the 50 to 55 ft bgs interval.

While this approach is not necessarily able to characterize the full magnitude of permeability contrast encountered across the profiled interval, it is able to demonstrate the relative degree of heterogeneity at the tested well locations and identify primary inflow zones. However, because of the heterogeneous nature of site outwash and till sequences (as illustrated in **Figure 5.2** by the markedly different boring logs and EBF profiles obtained from the individual wells), these data cannot be used to identify specific layers or infer connectivity of preferential pathways between wells, as may be possible at more uniformly layered sites.

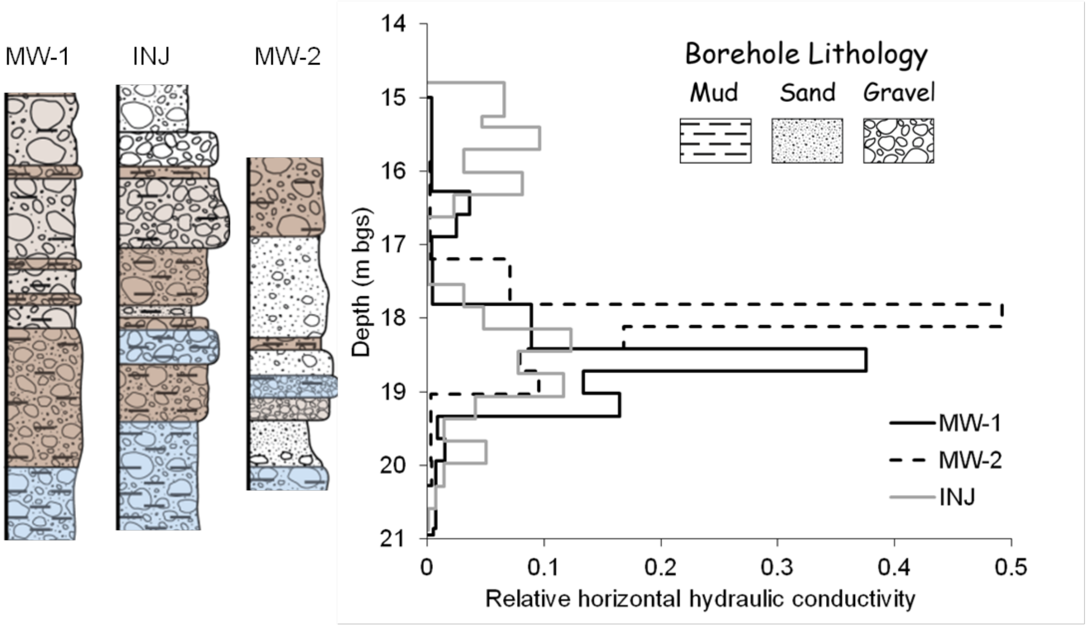


Figure 5.2. Borehole geologic log in well screen interval and Electromagnetic Borehole Flowmeter (EBF) data interpreted as the vertical distribution of relative horizontal hydraulic conductivity at each individual well. Borehole log brown shading indicates silt content with darker zones showing more silt. Borehole log blue shading indicates zones of more consolidated materials.

Note that a comparison of the EBF data shown in **Figure 5.2** with the contaminant data shown in **Figure 4.5** (collected during an earlier characterization phase) are consistent with the presence of elevated levels of contamination in the lower-k regions of the groundwater-bearing unit.

5.2.2 Continuous Multichannel Tubing (CMT) Well Installation and Sampling

CMT wells were installed at 3 locations (CMT-1, CMT-2, and CMT-3) within the test site in August 2013 (as described in Section 5.4). Each location contained sampling ports at 4 different depths, with approximately the same depths used at each location (e.g., the A channel was screened at approximately 14 m bgs at CMT-1, CMT-2, and CMT-3). The goal was to have channels at four distinct, evenly-spaced depths within a heterogeneous aquifer to provide more depth-discrete information than can be obtained with longer-screened monitoring wells.

During the baseline characterization, each of the multi-level wells and fully-screened wells was sampled and analyzed for various parameters (as described in Section 5.5) in August 2013. The results are shown in **Figure 5.3** and **Appendix B (Table B.1)**. Important findings include the following:

- Total CVOC concentrations were below 100 μg/L at all sampling points, despite the fact that the wells are located near the presumed source. These low levels are consistent with other recent investigations at the site and reflect significant attenuation over time.
- TCE generally present at higher concentrations than cDCE, particularly at the fully-screened wells (e.g., MW-1, MW-2). However, shallower wells typically saw higher concentrations of cDCE than TCE, while the reverse was observed at deeper wells. This suggests dechlorination activity are more favorable in the overlying sands than deeper in the outwash.
- While the presence of detectable levels of cDCE at most sampling points suggests that reductive dechlorination is an active pathway, there is little evidence for dechlorination beyond cDCE. VC was present at only one location (C3A, 2.3 μg/L). Similarly, only one location contained detectable levels of ethene (C2A, 18 μg/L).
- Geochemical conditions are consistent with the observed patterns in dechlorination products. In general, groundwater appears to be mildly reducing with evidence of more oxidizing conditions in the fully-screened wells, suggesting that there are zones where anaerobic activity is less favorable. pH values are near neutral to slightly basic. Methane is present but at relatively low levels (<0.1 mg/L). Sulfate concentrations range between 6.7 and 100 mg/L, meaning that there is only moderate competition between sulfate reduction and reductive dechlorination. Finally, little TOC is present throughout the treatment area, such that the injection of the STF amendment should: 1) result in discernible levels of organic carbon (i.e., high levels relative to background); and 2) stimulate pre-existing biological activity.

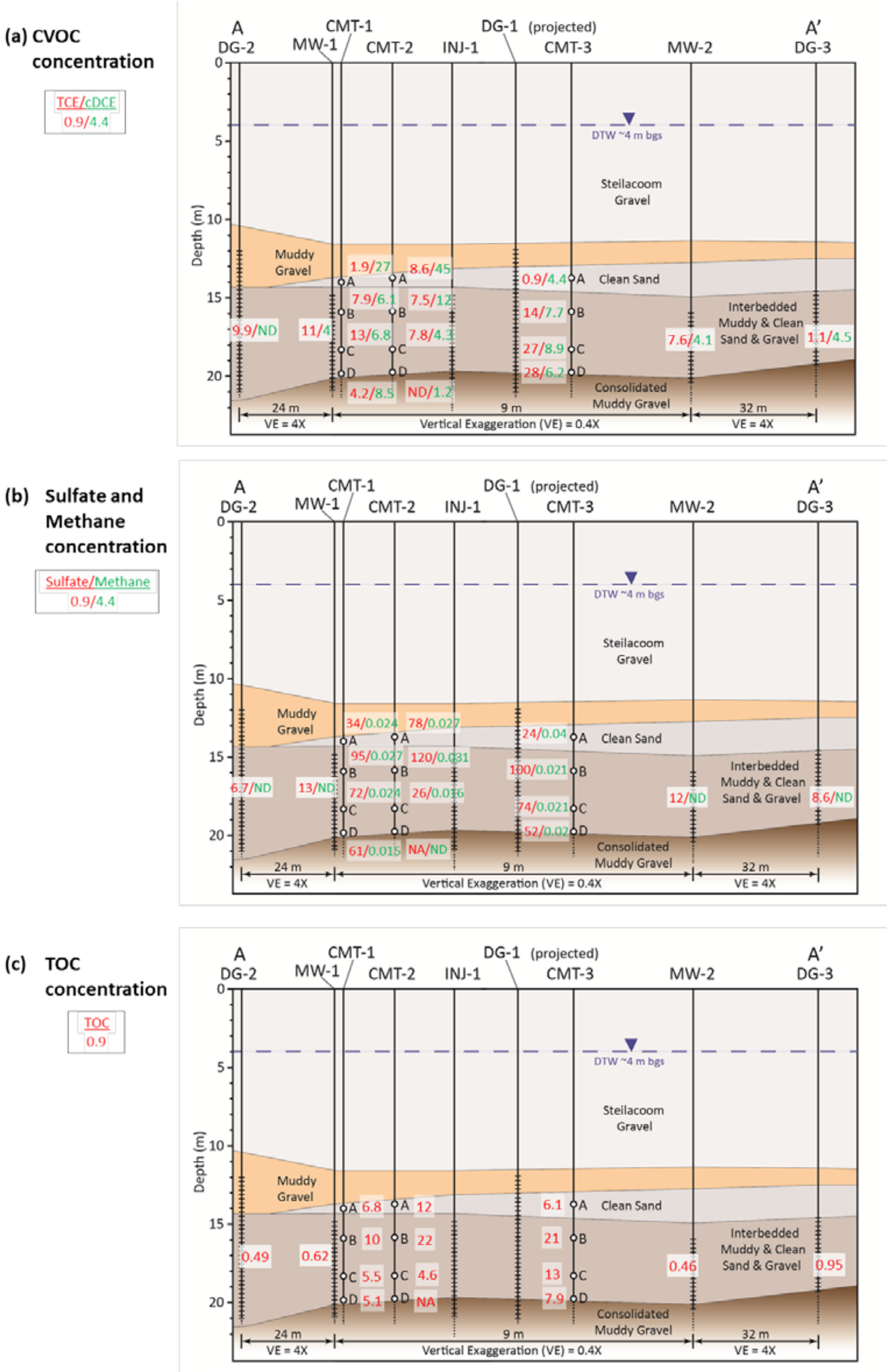


Figure 5.3. Groundwater sampling results from baseline characterization. The location of cross-section A-A' is shown in **Figure 5.2**.

5.2.3 Electrical Resistivity Tomography (ERT) Imaging

An ERT image of the subsurface was collected prior to the start of the baseline injection tests in September 2013. Electrodes were placed at 10 specific depths in wells MW-1 and INJ-1 to measure resistivity in the area between the two wells. This information serves as the background resistivity distribution which was used in conjunction with ERT surveys conducted during baseline injections to remove the variations inherent in the background so that the ERT images during injection only represent changes induced by the injection. A second background ERT image was collected just prior to the STF injection for use in establishing the starting conditions for the STF image.

5.3 Laboratory Study and Design Factors

5.3.1 Laboratory Studies

Laboratory studies were conducted during an early phase of the project to provide information on the rheological properties of potential shear-thinning polymer solutions. The goal of the studies was to generate data to support and optimize the field design. The following is a highlight of the lab work. More details are presented in Zhong et al. (2013).

The shear thinning behavior of the xanthan in DI water solutions is shown in **Figure 5.4a**. The viscosity at high shear rate (200 s^{-1}) was more than one order of magnitude lower than that at low shear rate (0.3 s^{-1}). At low shear rate the solution viscosity increased linearly with the increase of xanthan concentration within the range from 300 mg/L to 2000 mg/L (**Figure 5.4b**). This concentration range should cover the concentrations that will be applied in field remediation injections.

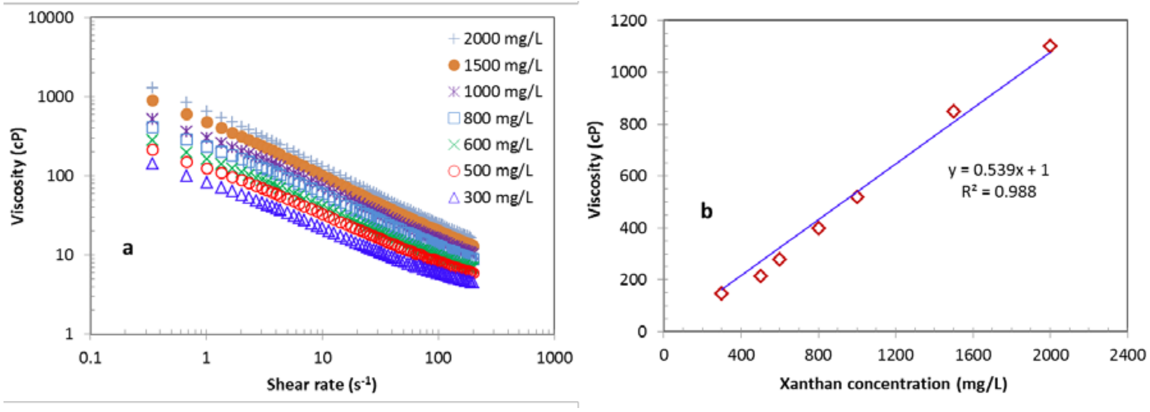


Figure 5.4. Xanthan gum concentration influence on fluid viscosity and rheology. (a) Viscosity as a function of shear rate, and (b) Viscosity at low shear rate (0.3 s^{-1}) for several xanthan concentrations. All solutions were made in de-ionized water.

Xanthan rheology was influenced by solution ionic strength and specific ions in solution. The influence of sodium and calcium ions on the rheology of 600 mg/L xanthan solutions is shown in

Figures 5.5a and **5.5b**, respectively. When cations were initially added to the ion-free xanthan solution, the viscosity decrease was significant, and further addition of ions to the system resulted in less impact on viscosity. For Na^+, when concentration increased from 0 to 25 mg/L, the viscosity at a shear rate of 0.3 s^{-1} decreased from 282 cP to 80 cP (72% decrease). However, an additional concentration increase from 25 mg/L to 50 mg/L only resulted in a viscosity decrease from 80 cP to 64 cP (5.7% decrease). The impacts of NaCl and $CaCl_2$ solutions on rheology behavior over a large range of shear rates are similar. The similarity between the two salts is also obvious for the relation between ionic strength and viscosity at low shear rate (**Figure 5.5c**), indicating that for ionic strengths in the tested range greater than ~1.5 mmol/L, the low-shear rate viscosity is not negatively affected. The influence of Na^+ and Ca^{2+} on xanthan solutions at 300, 500, 800, and 1000 mg/L polymer concentrations were also tested and similar influence patterns were observed.

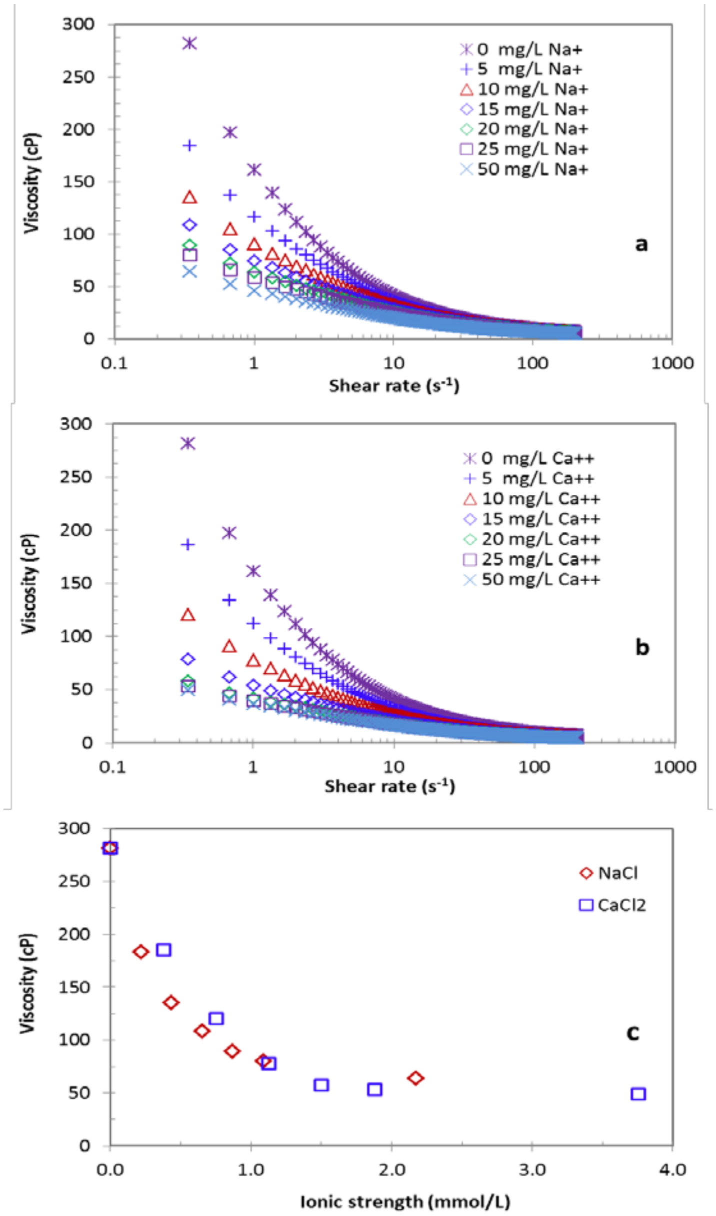


Figure 5.5. Influence of Na^+ and Ca^{2+} ions on 600 mg/L xanthan solution rheology: (a) shear thinning curve for solutions with Na^+; (b) shear thinning curves for solutions with Ca^{2+}; (c) viscosity of solutions with different ionic strength at shear rate = 0.3 s^{-1}.

The rheological behavior of the xanthan solutions is well described by the power law model:

$$\eta(\gamma) = K\gamma^{-n}$$

The rheology flow curves of different xanthan solutions were fitted to this power law to obtain the parameters of *K* and *n* for each solution. The *K* and *n* values are plotted against the xanthan concentration (**Figure 5.6a**) and solution ionic strength (**Figure 5.6b**). Linear trend lines with high R^2 values could be fitted to the *K* vs. xanthan concentration data for the DI water and tap water (TW) solutions, which were forced through intercept of (0, 1) to recognize that for a xanthan concentration of 0 mg/L, the DI water and the TW viscosity is approximately 1 cP (**Figure 5.6a**). The consistency index, *K*, representing the solution viscosity at 1.0 s^{-1} shear rate, is smaller than the viscosity value at γ = 0.3 s^{-1} for the same DI water solutions, as shown in **Figure 5.4a.** This observation was resulted from the shear thinning behavior of the solutions, i.e. the viscosity was lower at higher shear rate. The slopes of the fitted lines in **Figure 5.4a** and **Figure 5.6a** are 0.539 and 0.315, respectively. The higher slope in lower shear rate indicated that the shear thinning degree was higher at higher xanthan concentration. In other words, the viscosity drop from γ = 0.3 s^{-1} to γ = 1.0 s^{-1} is larger for solution with a higher xanthan concentration. This observation was also indicated by the relationship of fitted *n* with xanthan concentration plotted in **Figure 5.6a.** In **Figure 5.6a**, the slope of line fitted to TW (0.096), demonstrates again the impact on salt concentrations on rheology. This result strongly indicates that interested users should independently determine the *K* – concentration relationship if a water source containing salt will be used. As is also shown in **Figure 5.6a**, the *n* vs. xanthan concentration data were best fitted with logarithmic trend lines. The value of plots shown in **Figure 5.6a** is that over a range of xanthan concentrations, fitted *K* and *n* value can be computed that can be directly used in field application designs.

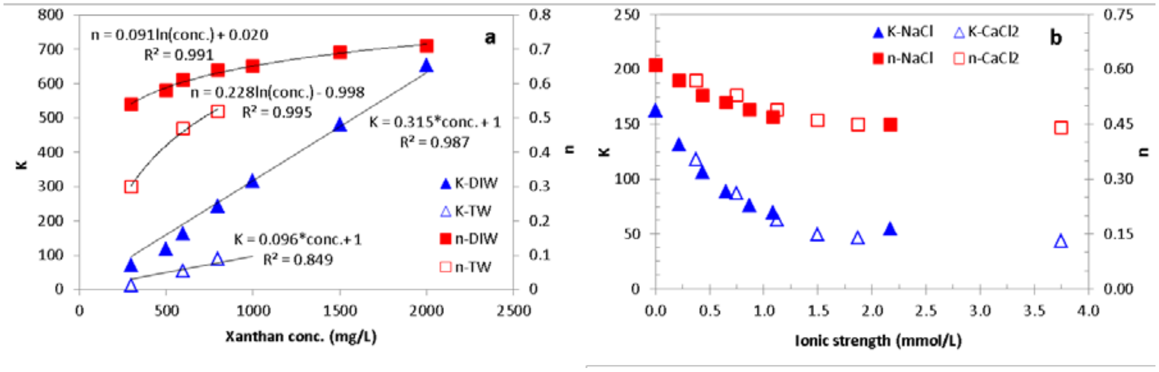


Figure 5.6. Power law fitting parameters K and n vs. (a) xanthan concentration and (b) ionic strength. The xanthan concentration for both cases is 600 mg/L.

Remedial amendments to xanthan solutions might contain ionic and non-ionic compounds and change the ionic strength, therefore alter their rheological behavior. Of interest in this contribution is to test specific amendments to see if their impacts are different than just the type of compounds present in GW or TW.

Sodium lactate and ethyl lactate (both at 10 g/L) lowered the viscosity of 700 mg/L xanthan gum solutions while the solutions still showed shear thinning behavior (**Figure 5.7**). Sodium lactate lowered the viscosity at 0.3 s^{-1} shear rate by 76% and the ethyl lactate decreased the viscosity by 25% (**Figure 5.7**). The significant difference between the viscosity impacts of the two substrates was presumably due to the presence of Na^+ in the sodium lactate ($C_3H_5NaO_3$) while there was no salinity in ethyl lactate ($C_5H_{10}O_3$). When higher viscosity is desired for substrate delivery in corresponding to the aquifer heterogeneity settings, ethyl lactate is preferred over sodium lactate. Therefore ethyl lactate was selected for the JBLM site demonstration.

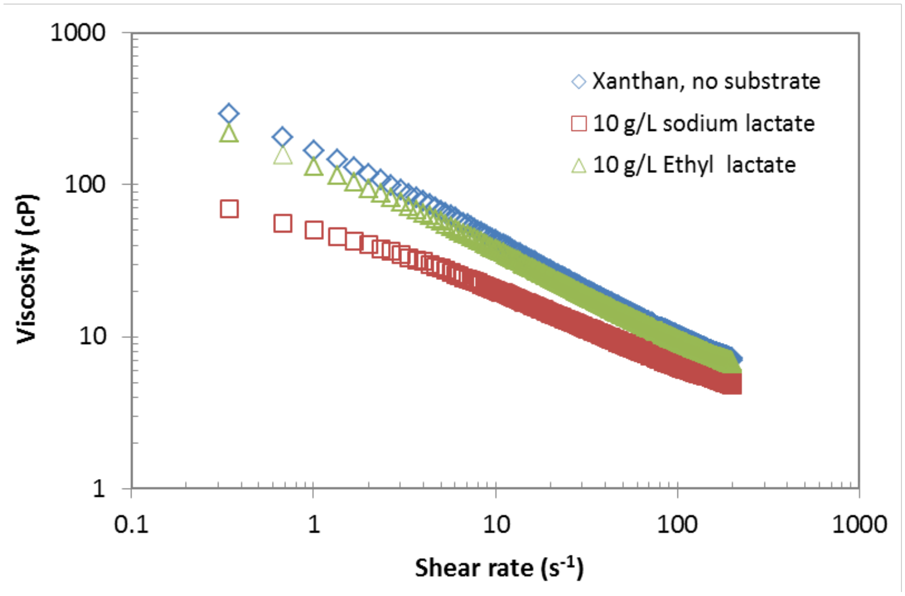


Figure 5.7. Influence of remedial amendment lactate on xanthan solution rheology.

5.3.2 Design Factors

Key design considerations for use of STF are managing the injection pressure and inducing distribution of amendment into lower-permeability zones in the subsurface. These design considerations impact selection of the appropriate STF rheology, and therefore, concentration of STF polymer (e.g., xanthan) to use.

Injection pressure is important to manage to enable injection within the constraints of the subsurface and well construction for the site. The data required is an estimate for the injection pressure at the design injection flow rate, or for a range of possible injection flow rates, for water-only injection. This information can be obtained by a water-only injection test or from step-drawdown and constant rate extraction test data evaluated in terms of expected injection pressures. The injection pressure for the STF will be this base injection pressure multiplied by the viscosity of the STF under the injection conditions. There is typically high shear rate near the injection well such that an upper bound for the viscosity is the measured viscosity at a shear rate of 150/s. In the field, observed initial pressure increases from STF have been only about 20% of this value, although the injection pressure increases with time. Thus, this range of injection pressures should be considered in the design. For pressure management in the field, monitoring of pressure to a pre-determined maximum based on system constraints may be needed where pressure can be decreased, if needed, by decreasing the injection flow rate. At some point pressure may become a limiting factor for the injection processes.

While the injection pressure consideration leads to the need for keeping viscosity as low as possible, viscosity is needed to induce distribution of amendment into low-k layers (e.g., through the cross flow phenomena). Generally, more viscosity leads to more cross flow between layers. However, there are diminishing returns as viscosity increase. **Figure 5.8** shows results of simulations examining the relation between viscosity and improved distribution to low-k layers. In these simulations, using a radial simulation grid to approximate fluid movement from an injection well, a 5-ft thick low-k layer was imposed at the middle of a 20-ft well screen interval. The contrast between the high-k and low-k zone hydraulic conductivities was either 10 (Figure 5.8A) or 100 (Figure 5.8B). STF was injected at 30 gpm to a target ideal cylindrical injection radius of 15 ft (12 hours). The swept volume fractions are computed by dividing the swept volume of STF delivered in the low-k layer by the total volume of this layer out to a 15 ft radius. The red line represents the total swept volume fraction and the blue line represents the swept volume fraction resulting from cross flow only. The difference between the two lines represents the swept volume fraction resulting from direct well flow into the low-k zone. It is difficult to explicitly model most sites due to uncertainties in the actual layer permeability contrasts and the configuration of layering. Thus, a rule of thumb for applying STF with a static viscosity of near 100 cP is suggested. If more detailed assessment is warranted for a specific site, modeling approaches such as described by Oostrom et al. (2014) or Silva et al. (2012) can be applied.

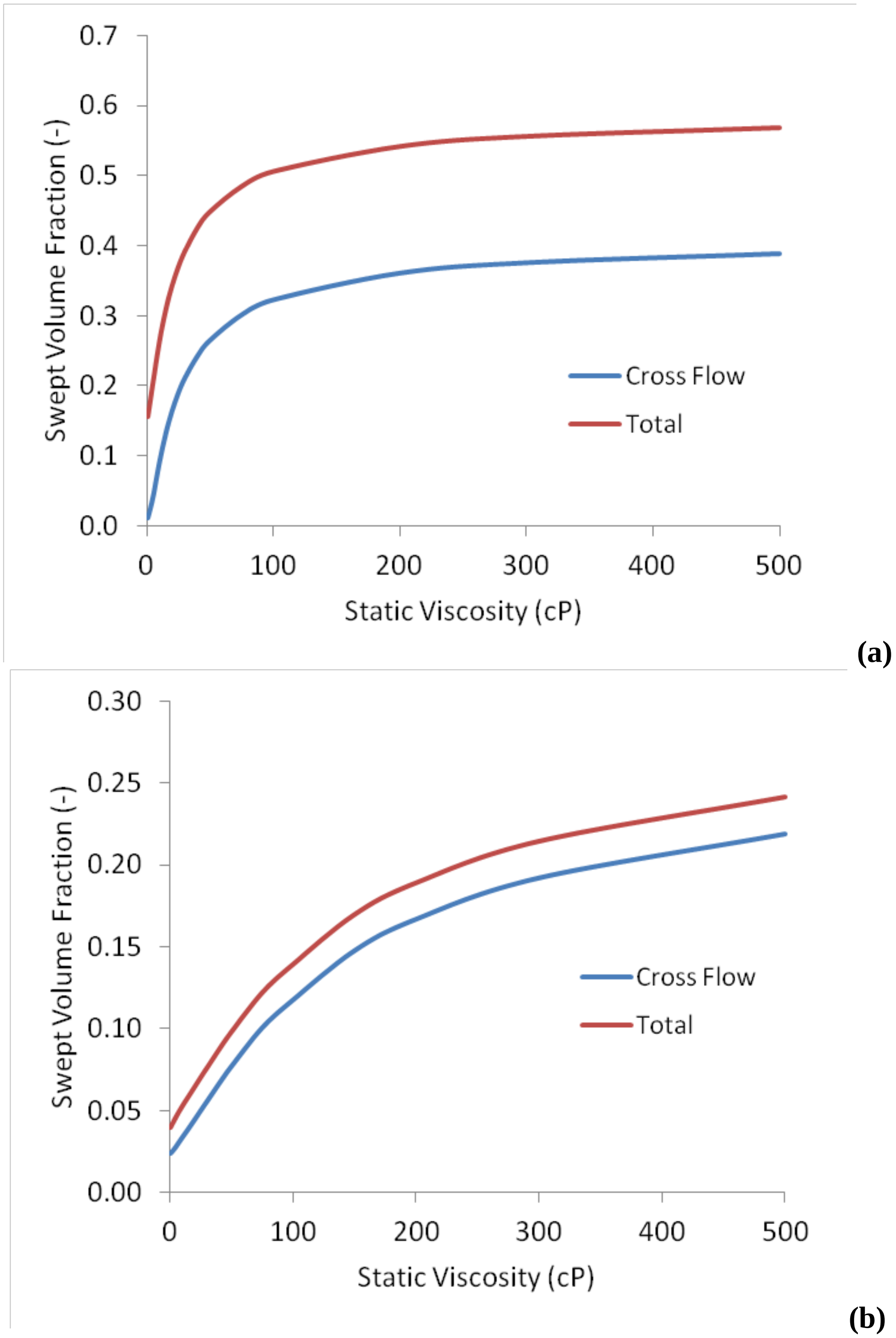


Figure 5.8. Results of simulations examining the relation between viscosity and improved distribution to low-permeability layers. The contrast between the high-k and low-k zone hydraulic conductivities was either 10 (Figure 5.8a) or 100 (Figure 5.8b). The red line represents the total swept volume fraction and the blue line represents the swept volume fraction resulting from cross flow only. See text for simulation details.

It is important to set appropriate expectations for how much STF will improve amendment distribution into lower-permeability zones. A primary factor is the thickness of the low-k layer (or lens). Except near the injection well, STF promotes distribution of amendment to lower-permeability zones by cross flow from fluid in the higher-permeability zones. As the distance from the low-high permeability interface increases, cross flow is less effective in moving fluid into the low-k layer. Thus, it is difficult to distribute amendment to the center of thicker layers. In terms of overall treatment effectiveness, distributing amendment within a thick low-k layer in a thin zone along the interface with the higher permeability layer may still be useful for reducing matrix diffusion. However, each site should consider the treatment goals, the permeability contrasts, and the thickness of lower-permeability layers when evaluating use of STF approaches. A rule of thumb would be to have caution with expectations when permeability contrasts are greater than two orders of magnitude and/or for low-k layers thicker than about 0.5 m if distribution to the center of the layer is necessary to meet goals.

5.4 Design and Layout of Technology Components

5.4.1 System Layout

As described in previous sections, the test site is located within the American Lake Garden Tract Area D at JBLM. The test cell layout is provided as **Figure 5.9**. The components of this system are described in the following subsections.

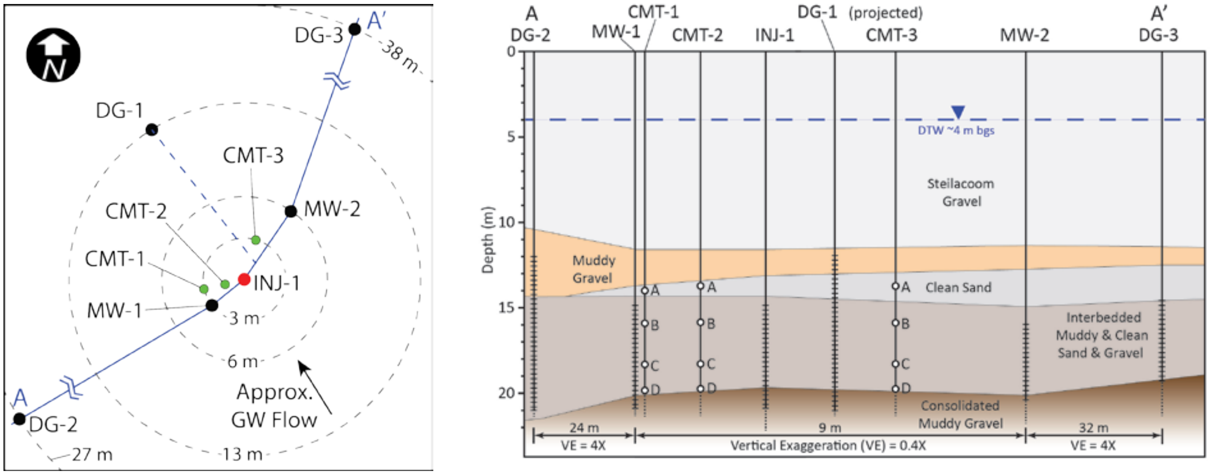


Figure 5.9. Layout of treatment cell. Three CMT wells were installed at distances between 1.5 and 3 m from the injection well. CMT screened interval depths were selected to monitor higher permeability and lower permeability zones within the 15-21 m depth interval, as well as the higher permeability sediments in the 10-15 m depth interval.

5.4.1 Well Installation

An injection well that was suitable for the purposes of this demonstration was available at the test site (INJ-1; note that this well also served as an additional monitoring well following injection). In addition, there were two other fully-screened wells within the expected area of influence of the injection (MW-1 and MW-2), and additional surrounding monitoring wells.

Wells that were installed as part of the demonstration were three multilevel (CMT) wells within the treatment zone, placed in a pattern with one or two on each side of the injection well. Because of the non-uniform pattern of outwash and till, both standard fully-screened monitoring wells and CMT wells were used for monitoring contaminant concentrations and solutions injected during the tests. Screened intervals for the three CMT wells were selected to monitor within a sandy layer above the targeted treatment zone (Channel A) and then within three relatively evenly spaced vertical locations (Channels B, C, and D) within the treatment zone.

An overview of the CMT well installation process is shown in **Figure 5.10**. Wells were installed using the rotosonic method per the drilling and well installation protocol detailed below:

- Six-inch diameter temporary carbon steel casing were advanced until the total drill depth was encountered (70 ft bgs). Well locations were staked by project personnel prior to beginning of work. The wells are located on a level driving range area within the Whispering Firs Golf Course, so no clearing or leveling of these well locations was necessary.
- Cores collected during well installation were inspected by project personnel to confirm that the geology at these locations was consistent with that observed during previous investigations. This information was also used to determine the completion depths. Boring logs for these locations are included in **Appendix C**.
- Six-inch diameter temporary carbon steel casing were advanced until the total drill depth was encountered (70 ft bgs). Well locations were staked by project personnel prior to beginning of work. The wells are located on a level driving range area within the Whispering Firs Golf Course, so no clearing or leveling of these well locations was necessary.
- Installation and completion of these wells was conducted in accordance with *Washington Administrative Code*, Chapter 173-160 standards ("Minimum Standards for Construction and Maintenance of Wells"). Well construction details are presented in **Table 5.1**.

Table 5.1. Summary of Well Installations

Well Type	Depth to Water (ft bgs)	Drill Depth (ft bgs)	CMT Tubing Diameter (in)	Stainless Steel Screen Mesh Size	CMT Monitoring Ports	Silica Sand Filter Pack Size	Flush Mount Vault Size (in)
CMT monitoring well	20 ± 3	70	1.7	100	7	20-40 mesh	8

- Boreholes drilled at designated monitoring well locations were completed as nominal 2-in-diameter 7-port CMT well completions. Immediately prior to installation of the well, each borehole was developed using an appropriately sized pump to decrease the sediment load within the temporary casing water column. At each location, the pump was near the bottom of the borehole and operated 10 to 15 minutes. During the installation of each monitoring well, a CMT multilevel system will be preassembled at the surface, suspended in the borehole and installed over a designated depth interval.

- The monitoring well installations were constructed using 1.7-in diameter Solinst Model 403 7-port CMT multilevel system components, and assembled and installed per the manufacture's guidelines: (http://www.solinst.com/Downloads/Inst/403cmt/403cmtManual.pdf). No glues or solvents were used. Based on available data, 100 mesh stainless steel screen having an open area of ~0.006 in. (0.15 mm) were selected. At each location, CMT tubing extended from the deepest port completion depth to approximately 0.5 feet below ground surface and was supported with a minimum 2-foot-length of 2-in. schedule 40 PVC and fitted with a Solinst 7 port CMT wellhead.

- CMT port completion depths were finalized based on observed site conditions, but in general, the same depths were used at each location (**Table 5.2**). Of the seven available ports, one to two port completions were used at each depth, such that there were a total of four port completions per location.

Table 5.2. Summary of CMT Port Completions

Well ID	Port Depth (ft bgs)	Port Number[1]	Lateral Distance from Injection Well (ft)	Sampling ID[2] (ft)
CMT-1	45.6	3	10	C1A
CMT-1	52.6	4/1	10	C1B
CMT-1	61.6	5/2	10	C1C
CMT-1	66.1/66.7	6/7	10	C1D
CMT-2	45	3	5	C2A
CMT-2	52	4/1	5	C2B
CMT-2	60	5/2	5	C2C
CMT-2	64.2/64.7	6/7	5	C2D
CMT-3	45	3	10	C3A
CMT-3	52	4/1	10	C3B
CMT-3	60	5/2	10	C3C
CMT-3	64.2/64.7	6/7	10	C3D

Notes: (1) Port number describes which of the 7 available CMT ports was used in completion of that well; (2) Sampling ID refers to identification used during the collection of groundwater samples from that location/depth.

- Bentonite pellets or chips (i.e., "hole plug") were used to seal the borehole from total depth to approximately 0.5 ft below the bottom of the deepest port interval. The filter pack consisted of 20-40 Colorado silica sand that extended from 0.5 ft below to 0.5 ft above the center of each port interval. Coated bentonite pellets were used for the seals between each port interval. The remaining annular seal material consisted of hydrated bentonite chips, extending to approximately 2 ft bgs (**Figure 5.11**).

- After each filter pack installation (prior to installation of subsequent bentonite seals), a submersible pump was installed to purge the well and develop the filter pack material. During low flow purging, drawdown and filter pack stability was closely monitored to minimize the risk of formation sediments encroaching the filter pack and/or coming up the well bore. Each filter pack interval was purged for approximately 15 minutes, totaling approximately 1 hour of purge time per CMT well completion with 4 port completion depths.

- Flush-mount surface completion (**Figure 5.11**), consisting of well vault, cement pad and French drain were installed at each well location. Concrete used in the surface completions contained an air entraining agent to prevent freeze/thaw cracking (6% +/- 2%) but no other additives. Steel-reinforcement was used in the concrete pad construction.

- Surface protection was installed in “flush-mount” manner per WAC 173-160-420 with the following additions/modifications:
  - Each protective vault was 8-inch diameter with a lockable well cap.
  - Four inch schedule 40 protective PVC casing was installed around each CMT wellhead and rose to within 0.3 ft of the top of the protective vault, leaving sufficient room for a locking j-plug to be installed with the vault lid in place.
  - Concrete pads were 2 feet by 2 feet by 6 inches thick, reinforced with 6” X 6” W1.4 x W1.4 welded wire fabric or comparable.
  - A brass survey marker (3-in. diameter, domed), stamped with the well identification number and well name was installed on the north side of each pad.

Figure 5.10. CMT well installation during field demonstration. Photos illustrate several key steps (not all steps shown).

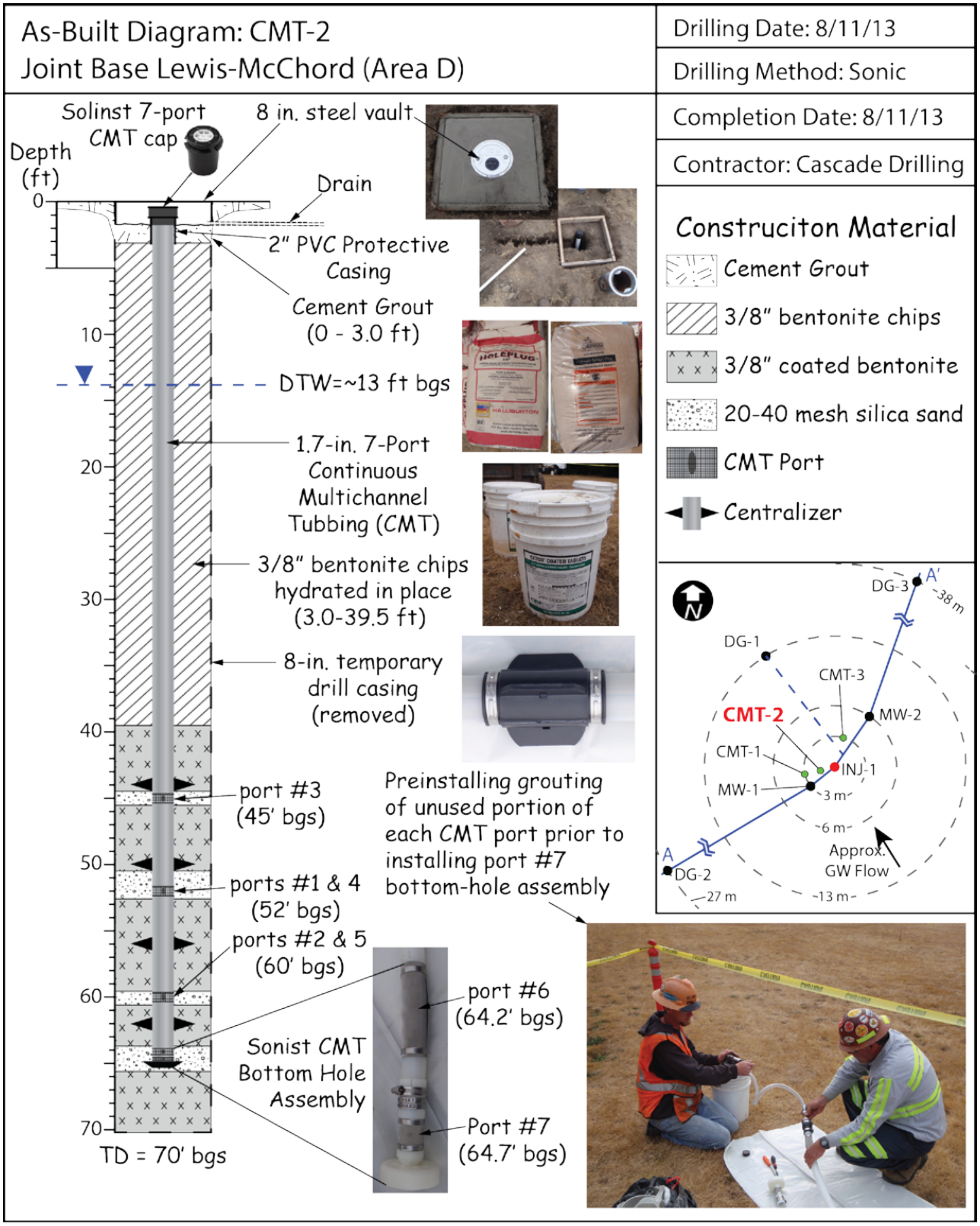


Figure 5.11. CMT monitoring well construction and flushmount surface completion (modified after Solinst, 2012). Details for CMT-2 are shown; remaining CMT wells completed in similar manner.

5.4.2 Electronic Borehole Flowmeters

Electronic borehole flowmeters (EBFs) are a second downhole device that was used to provide a vertical hydraulic profile of the intervals of interest. These devices were employed during the pre-test baseline characterization. The EBF probe provided data to evaluate the relative flow rate and thereby associated permeability for different depth intervals in the well.

The theory that governs the operation of the EBF is Faraday's Law of Induction, which states that the voltage induced by a conductor moving at right angles through a magnetic field is directly proportional to the velocity of the conductor moving through the field. Flowing water is the conductor, the electromagnet generates a magnetic field, and the electrodes are used to measure the induced voltage. For sign convention, upward flow represents a positive voltage signal and downward flow represents a negative voltage signal. More detailed descriptions of the EBF instrument system and field test applications are provided in Young and Pearson (1995).

The concept of the field test design is illustrated in **Figure 5.12**. The EBF probe consists of an electromagnet and two electrodes 180 degrees apart inside a hollow cylinder. The inside diameter (ID) of the hollow cylinder is 2.5 cm (1 in.) and the outside diameter (OD) of the probe cylinder was just under 5.1 cm (2 in.). The probe (Quantum Engineering Corporation, Loudon, Tennessee) is capable of measuring flow ranging from 0.04 L/min (0.01 gpm) to 40 L/min (10.6 gpm). The probe will be connected to an electronics box at the surface with a jacketed cable. The electronics attached to the electrodes transmit a voltage signal directly proportional to the velocity of water acting as the conductor.

An inflatable packer was used to isolate specific depth intervals in the well for testing. Both ambient and dynamic (i.e., pump-induced) flowmeter tests were performed. Flowmeter measurements will be acquired at 0.3-m (1-ft) depth intervals within the well screen. During data collection, the device is raised to a new depth interval following signal stabilization (1 to 5 minutes per interval), and data is compiled on a portable laptop computer for processing. The EBF probe was calibrated according to the manufacturer's calibration procedure described in Young and Pearson (1995) over a range of flow rates planned for the field.

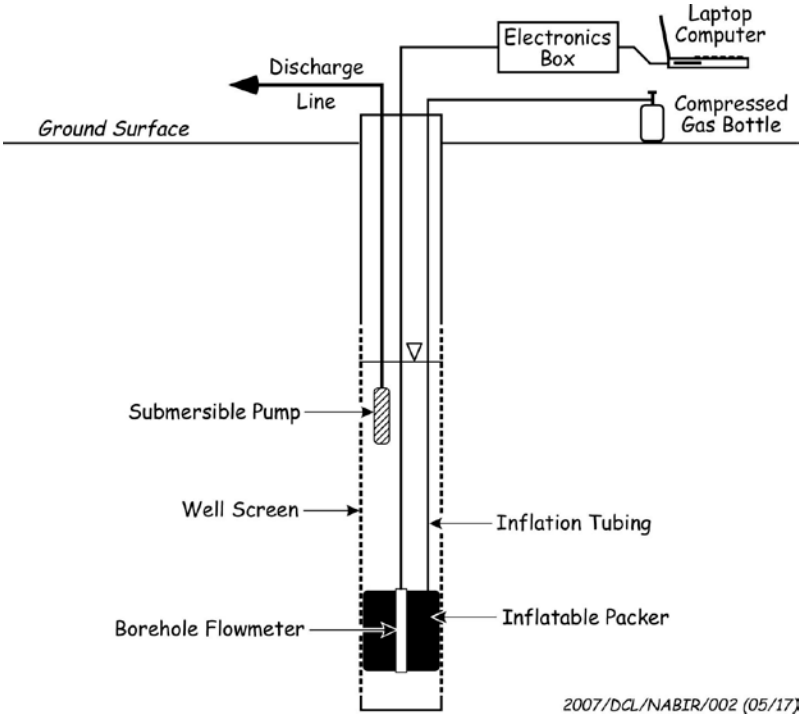


Figure 5.12. Electromagnetic Borehole Flowmeter (EBF) general configuration

5.4.3 Electrical Resistivity Tomography

Distribution of the injection solutions for the baseline and STF injections was also evaluated for a 2-D cross section between the injection well and MW-1 using electrical resistivity tomography (ERT). ERT is a method whereby the electrical resistivity of the subsurface is imaged between arrays of electrodes, which are used to inject current and measure resulting electrical potentials in a strategically chosen measurement pattern (Cassiani et al., 2006; Kemna et al., 2002). The resulting data set is then analyzed using a computational tomography algorithm that reconstructs subsurface electrical resistivity (the reciprocal of which is electrical conductivity); a process formally known as inversion (Johnson et al., 2010). In this case, 10 electrodes were placed within the screened intervals of the injection well and MW-1 at 0.61 m (2 ft) intervals ranging from approximately 15 m (49.2 ft) to 21 m (68.9 ft) bgs, providing the capability to image electrical conductivity between these two wells over the same depth interval. As more electrically conductive tracer solutions replaces native pore water during injection, the bulk subsurface electrical conductivity increases. Changes in electrical conductivity produced by time-lapse ERT imaging therefore serve as useful proxy for injection fluid distribution within the imaging plane at a given point in time. The changes are calculated by subtracting the post injection ERT image from the pre-injection ERT image, thus revealing the change in conductivity caused by the tracer present in the injection solution. During the baseline stage, bromide tracer was added to a concentration that approximately doubled the specific conductance of the injected solution compared to native groundwater electrical conductivity. For subsequent STF injection, a chloride tracer was added which has a higher conductance to concentration ratio so that the amendment solution specific conductance was double the conductance of the previous bromide tracer solution.

A comprehensive ERT survey was conducted prior to each injection stage to characterize the distribution of resistivity in the subsurface. Time-lapse ERT was conducted during baseline and STF injection stages to monitor the progressive distribution of the injected solution and augment well data with respect to the uniformity of distribution within the heterogeneous subsurface conditions.

5.4.4 Injection Equipment and Configuration

The distribution of injection solutions was evaluated in a phased approach. The initial test - the baseline injection - consisted of injecting water (obtained from the fire hydrant system at the site) amended with, on average, 250 ppm Br- tracer (320 mg/L sodium bromide). The objective of this first test was to monitor the distribution of a tracer solution (i.e., not STF modified and representative of a standard amendment injection approaches) within the heterogeneous formation. The second test - the shear-thinning fluid (STF) injection - consisted of injecting water containing 800 mg/L xanthan gum polymer (Kelco Oil Field Group, Houston, TX), 1 g/L ethyl lactate (JRW Bioremediation, Lenexa, KS), and, on average, 230 mg/L Cl- tracer (480 mg/L potassium chloride). Prior to the baseline and STF injections, a stainless steel inflatable packer and tubing string (perforated over the injection interval) were installed in the injection well to isolate the screened interval and facilitate pressurized injection in this shallow aquifer system.

For the baseline injection, the concentrated sodium bromide stock solution was prepared in a 1900 L polyethylene tank. The solution was delivered into the injection stream via a stainless-steel 2-horsepower centrifugal pump, mixed with water from a nearby fire hydrant, and routed through an inline static mixer prior to injection (**Figure 5.13**).

STF injection required pre-mixing of a xanthan stock solution with sufficient hydration to ensure appropriate rheological properties and uniformity of the solution. The xanthan stock solution was mixed with hydrant water, potassium chloride, and ethyl lactate in 1900-L batches and then transferred to an 18,900-L temporary storage tank (**Figure 5.14**). Mixing and hydration of each batch was accomplished using two electric variable-speed mixers with multi-bladed impellers. The xanthan stock solution was recirculated within the storage tank for several hours to provide additional mixing using the same inline static mixer and centrifugal pump setup used in the baseline injection, and then allowed to hydrate overnight prior to the injection. The xanthan stock was delivered into the injection stream using the same equipment configuration as the baseline injection (**Figure 5.13**).

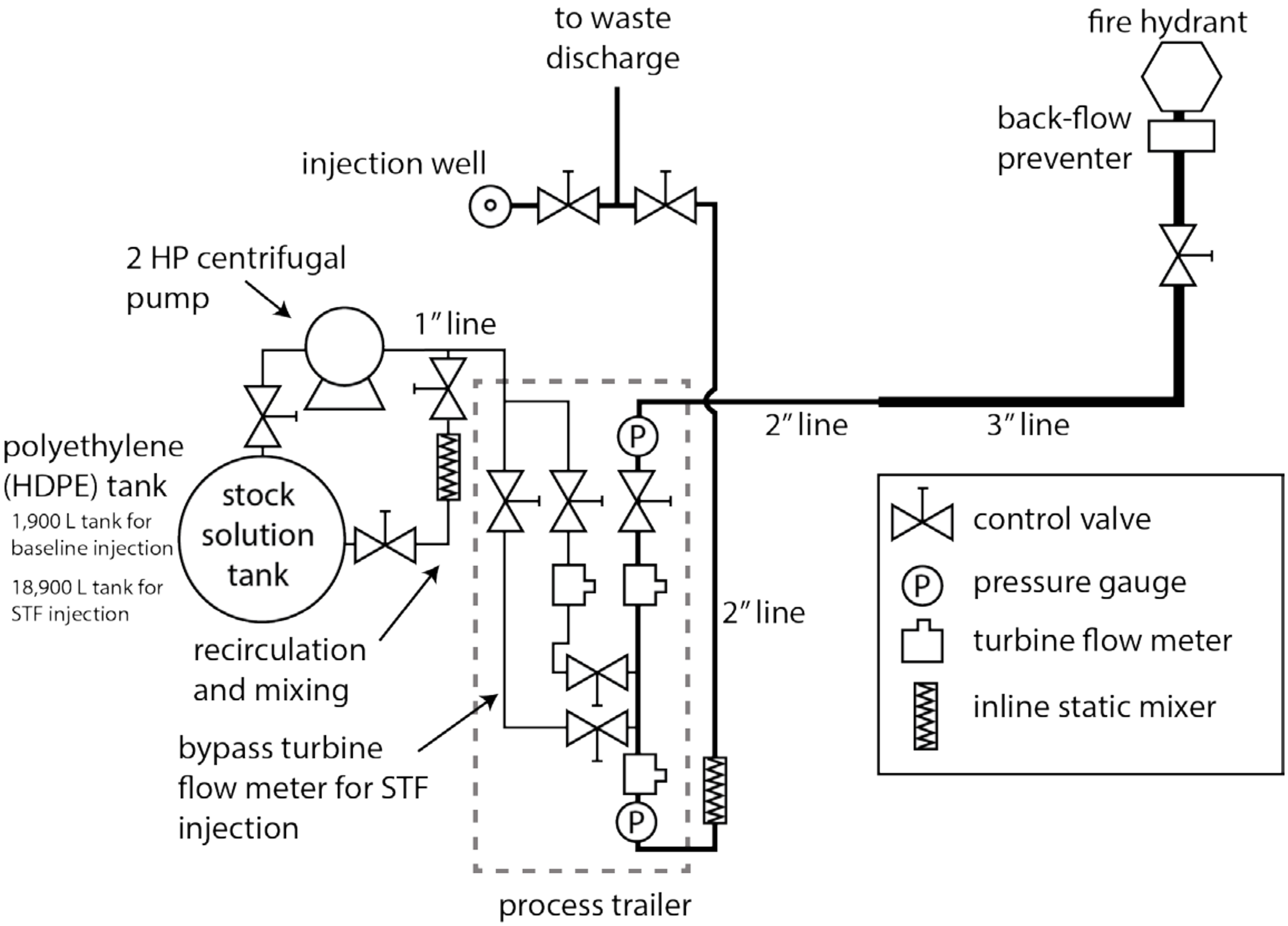


Figure 5.13. Schematic of the process and injection equipment for the baseline and STF injections.

For the baseline injection, the bromide stock solution feed rate was measured using a ½-inch diameter turbine flow meter (FT4-8 with Linear Link flow linearizer; accuracy ±0.1% of reading; Flow Technology Inc., Tempe, AZ). The injection stream hydrant water and total injection flow rates were measured using two 2-inch diameter turbine flow meters (FT-32 with Linear Link flow linearizer; accuracy ±0.1% of reading; Flow Technology Inc., Tempe, AZ). During the STF injection, an attempt was made to monitor the xanthan stock solution feed rate directly with an inline ultrasonic flow meter; however, the flowmeter malfunctioned and could not be used to provide independent a reliable flow measurement for the viscous xanthan stock solution. Because the xanthan stock solution would have plugged the ½” diameter turbine flow meter, the stock solution feed rate was calculated as the difference between the hydrant water and the total injection flow rate measurements made with the two 2-inch diameter turbine flow meters (**Figure 5.13).** Flow meter measurements were recorded using a CR1000 data acquisition system (Campbell Scientific, Inc., Logan, UT). Pressures in the injection and observation wells were measured and recorded with submersible pressure sensors (CT2X; 30 PSIG range; accuracy ±0.1% of full-scale output; Instrumentation Northwest Inc., Kirkland, WA). A picture showing the layout of the injection equipment (i.e., tanks, process trailer, and injection line) and onsite mobile laboratory is provided in **Figure 5.15**.

Figure 5.14. Preparation of the xanthan stock solution: a) initial mixing and b) continued hydration with additional recirculation mixing in the storage tank.

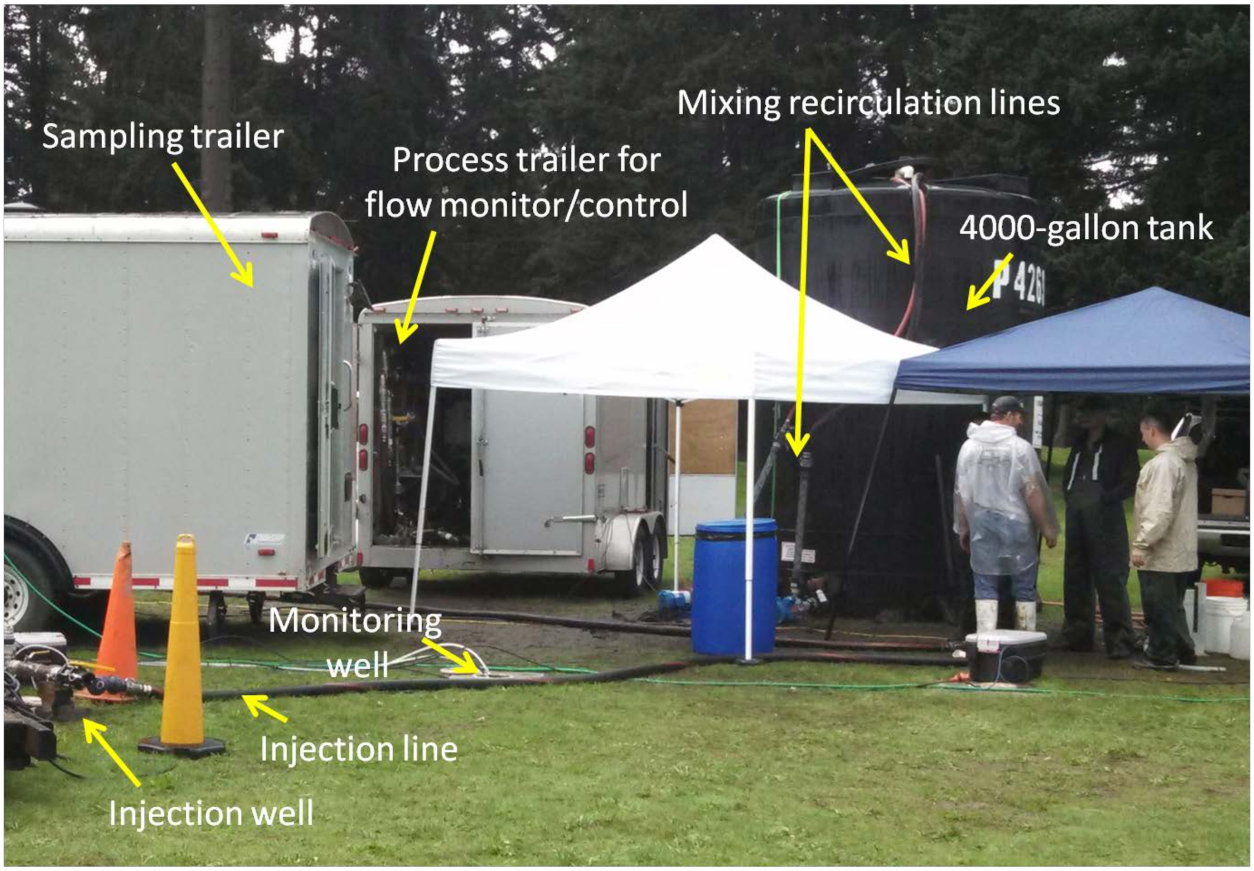


Figure 5.15. Injection and monitoring equipment layout.

5.5 Field Testing

The field portion of this project involved three stages as outlined in Section 5.1. The implementation schedule for each of these project stages (as well as the characterization efforts) for the field program at JBLM is presented as a Gantt chart (**Figure 5.16)**. Further description of each of these field testing phases is provided below:

5.5.1 Baseline Injection Stage

The objective of the baseline injection stage of the demonstration was to evaluate the distribution of an injected aqueous solution in the absence of a shear-thinning polymer. In this regard, it mimics a conventional injection approach for in situ bioremediation, with the distribution of amendments highly influenced by the heterogeneity near the injection well.

Following the site characterization (described in Section 5.2), the first step was completion of step and constant-rate injection tests. The injection well was sealed with an inflatable packer, fitted with a pressure gauge and pressure relief valve, and connected to the injection water supply via flexible tubing. Injection solutions were transferred via this line using a centrifugal pump.

To minimize the potential for formation fracturing, the injection pressure was checked against allowable injection pressures estimated based on pore pressures within the formation.

Hydraulic properties were estimated during these initial injection trials by monitoring pressure heads in nearby monitoring wells. A step injection test was conducted first by sequentially increasing the injection flow rate and observing the pressure response. Based on these data, an injection rate for the constant-rate test was selected. During the constant-rate injection test, pressure heads were monitored for analysis of aquifer hydraulic properties. The change in the water level is a function of the spatial distance between the observation well and the injection well, aquifer thickness, storativity/specific yield, and the aquifer hydraulic conductivity. Data from the field tests during injection was used to establish the hydraulic properties of the groundwater-bearing unit (Kruseman and de Ridder 1991).

The second and primary step during the baseline injection stage involved the injection of a bromide tracer solution to monitor the distribution of soluble compounds in a heterogeneous formation in the absence of a shear-thinning polymer.

The test consisted of the injection of bromide at a concentration of 250 mg/L (320 as sodium bromide) at a rate of approximately 30.4 gpm. Solution preparation was completed on-site and utilized make-up water supplied by the site (fire hydrant). As described in Section 5.4.4, separate tanks with appropriate mixing capabilities were used for stock solutions and injection solutions. All solutions were metered separately to reach the desired injection concentrations.

The tracer (bromide) was injected to ensure that a target radius of influence of 10 to 20 ft was achieved. Injection occurred until breakthrough was observed at MW-2 and sufficient volume was injected (61,300 L) for distribution of the injection solution to an ideal cylindrical radius of ~13 ft (i.e., clearly past the radial distance of MW-1 and the CMT wells). At the conclusion of the tracer injection, a clean water flush was completed using 40,000 L of bromide-free water injected at an average rate of 29 gpm.

Downhole ion-specific or specific conductance probes were used to monitor tracer arrival in the field; aqueous samples were also collected periodically at these locations as guided by the probe results. Arrival at locations within lower and higher permeable intervals were compared using aqueous samples collected from the CMT wells. Sampling frequency was adjusted as required based on observed arrival response during injection; less frequent sampling was completed for wells screened within the less permeable zones. At the end of injection, a complete round of samples was collected.

During and at the conclusion of the tracer test, cross-hole ERT surveys were conducted as a time series to evaluate tracer movement (using the tracer as a resistivity signal).

5.5.2 STF Injection Stage

Following the completion of the baseline injection stage, injection of the shear-thinning solution was completed to start the treatment phase of the demonstration. The injection rate and nominal injection duration were evaluated in advance using design simulations with adjustments based on aquifer response to injection flow during the tracer test. The lactate-xanthan gum solution was prepared at a polymer concentration to provide rheological properties determined based on pre-injection numerical simulations. The shear-thinning fluid amendment consisted of diluted ethyl lactate, potassium chloride tracer, and xanthan gum polymer. The target lactate concentration in the aquifer (following injection) was 1000 mg/L. This represents a relatively low concentration injection solution that is well-suited to stimulate the desired reductive dechlorination reactions for the site contaminant levels and also to provide a reasonable response in fermentation and terminal electron acceptor processes to track biological processes. Xanthan was added at a final (mixed solution) concentration of 800 mg/L. Chloride was used as the tracer for this phase at a concentration of 230 mg/L (480 mg/L as potassium chloride).

The injection process and monitoring followed the protocol described previously, using an injection rate of 31.7 gpm. At the conclusion of the test, the injection volume (106,400 L) was about twice the injection volume for the baseline injection, resulting in a targeted cylindrical radius of ~17 ft. During injection, downhole ion-specific or specific conductance probes were used to monitor tracer arrival in the field. Arrival at locations within lower and higher permeable intervals were compared using aqueous samples collected from the CMT wells. At the end of injection, a complete round of samples was also collected. Once the desired amendment volume was injected, a small volume (< 500 L) of xanthan solution with no lactate was pumped to flush out the distribution lines and well casing. During and at the conclusion of the STF injection test, surface and cross-hole ERT surveys were also conducted as a time series to evaluate tracer/amendment movement (using the tracer as a resistivity signal).

At the conclusion of the injection test, groundwater samples for VOC analysis were collected from each of the monitoring locations (as well as the injection well).

5.5.3 Performance Monitoring (Treatment Stage)

Performance monitoring was completed in the period following the amendment injection to determine if the amendment were effective in achieving treatment of contaminants. In addition, the persistence of the amendment within the treatment area using the temporal

Performance monitoring events were completed in February 2014 and May 2014. Scheduling for the performance monitoring events was intended to be dynamic, and relied on an assessment of progress of the test. Ultimately, the duration of the monitoring period (8 months) was consistent with the duration that was assumed prior to the start of the test (approximately 6 to 9 months). The last performance monitoring event essentially replaced any separate post-test characterization step.

During performance monitoring, groundwater samples were collected and analyzed as outlined in **Table 5.3** and **Table 5.4**. Samples were collected from all available monitoring locations and depths. All performance monitoring was completed by members of the project team.

Figure 5.16. Gantt chart for implementation of field activities

FIELD ACTIVITY	**2013**					**2014**							
	A	**S**	**O**	**N**	**D**	**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**
Baseline characterization – EBF testing of existing wells	■												
CMT well installation	■												
Baseline characterization – Pre-test groundwater sampling	■												
Baseline characterization – ERT survey	■												
Baseline injection stage	■												
Post-baseline injection ERT survey	■												
STFinjection stage		■											
Post-STF injection ERT survey		■											
Post-STFinjection groundwater sampling		■											
Performance monitoring – groundwater sampling (1st event)							■						
Performance monitoring – groundwater sampling (2nd event)										■			
Well decommissioning[1]													■

Notes: (1) Well decommissioning has yet to be completed but is anticipated to occur in August 2014.

5.5.4 Demobilization

All injection equipment was provided by the project team or rented. Therefore, all equipment was removed from the site following the end of each injection phase.

Well abandonment was completed following the end of the performance monitoring phase. In order to install continuous multichannel tubing (CMT) in the demonstration area, the project team was required to submit a variance request to the Washington Department of Ecology ("Ecology"). The specific parts of the Washington Administrative Code (WAC) related to well installation that Ecology cited as requiring a variance are listed in the letter from Ecology that granted the variance (attached as **Appendix D**). Ecology granted the variance on 5 August 2013 on an accelerated schedule, with their approval contingent upon several requirements for installing and decommissioning the CMT wells:

> *"Within 1 year of the completion of the CMT wells, all 4 wells must be decommissioned by a licensed resource protection well driller. Appropriate notice must be submitted to Ecology prior to decommissioning. The CMT wells must be decommissioned by overdrilling the entire CMT well and the entire borehole is properly sealed per WAC 173-160-460. The drill bit for overdrilling must be a minimum of 8 inches in diameter. All overdrilled materials (including broken CMT material) must be removed before sealing the borehole. Enough seal material shall fill any voids from the bottom of the borehole to land surface".*

The CMT wells were installed based on this variance and the injection tests were completed. During the post-test performance monitoring period, the project team provided Ecology with additional information to justify that the overdrilling requirement was unnecessary given the site conditions. In late June 2014 (after the completion of all characterization activities), Ecology granted this request for a modified variance, and instead requested that the CMT wells be decommissioned by pumping cement grout into each channel and using additional cement to fully encase each well within the individual monuments. Note that these are the decommissioning procedures recommended by the CMT vendor (Solinst).

Decommissioning of the wells via the above procedures is scheduled for completion in August 2014.

5.5.5 Investigation-Derived Waste

Drill cuttings generated during well installation were transported by the drilling contractor to a designated area within the Fort Lewis East Gate Disposal Yard (EGDY) and spread on the ground. This procedure was pre-approved by the site manager and was in accordance with accepted protocols.

Purge water generated during groundwater sampling was either returned to adjacent wells or collected in buckets for disposal at the water treatment facility (designed for handling aqueous waste from a stripper). Because low-flow purging was used as the sampling method throughout all project phases, minimal volumes (< 5 gallons per event) were generated.

5.6 Sampling Methods

5.6.1 Groundwater Sampling and Analysis

Comprehensive groundwater sampling was completed as part of the baseline characterization phase, the pre-test (**Table B.1 in Appendix B**). This included samples from each of the 20 monitoring locations installed within the treatment area (each of the 12 CMT ports plus wells MW1, MW2, INJ1, and DA31 – DA35). Samples were collected using low-flow purging protocols (using the CMT ports for those wells and tubing for the remaining wells) with flow cells for measuring geochemical parameters. Water was purged until relevant field parameters stabilize, and well purge records will be maintained at each well.

Similar sampling protocols were followed for three additional comprehensive groundwater monitoring events: 1) event completed immediately after the end of the shear-thinning fluid amendment injection; 2) performance monitoring event completed in February 2014; and 3) performance monitoring event completed in May 2014.

During the injection tests, groundwater samples were also collected at frequent intervals (every 2 to 10 minutes) to quantify tracer concentrations. While these samples were typically collected using low-flow purging techniques, the high frequency of sampling occasionally necessitated the use of grab sampling to ensure that no data were missed.

Samples were analyzed following the program outlined in **Table 5.4.** This includes the analysis of CVOCs, field parameters (using a flow-through cell), methane, ethene, ethane, sulfate, chloride, bromide, organic carbon, and rheological properties. Labels for all samples identified the sampling location and time, and shipments were prepared in a manner consistent with method and laboratory protocols (e.g., proper containers and preservatives, cooled to 4°C to minimize volatilization and other losses). As described in **Table 5.4**, all analyses were completed at appropriate commercial laboratories.

5.6.2 Quality Assurance Procedures

The integrity of the data generated during this demonstration was ensured by adherence to a Quality Assurance Project Plan (QAPP) prepared for this investigation (**Appendix E**). The QAPP identified the requirements necessary to obtain high quality data and included requirements for QA/QC sampling, detection limits, methods, and field and laboratory performance. Highlights of the quality assurance procedures include the following:

- *Calibration of Analytical Equipment.* The majority of project data was generated by fixed analytical laboratories with acceptable quality control programs to assure proper operation of analytical equipment. Measurements of groundwater quality parameters, including specific conductance during the injection tests, were collected using handheld meters that were properly calibrated before use. Photoionization detector (PID) was used to evaluate VOC levels in the workspace sample points and was calibrated per the manufacturer's instructions prior to use.
- *Quality Assurance Sampling.* General quality assurance guidelines of a minimum of one duplicate sample per ten samples collected was followed for all groundwater samples. If less than 10 samples are collected then at least one duplicate sample was collected. A field blank sample was collected to demonstrate appropriate sampling techniques, and trip blanks accompanied all soil vapor samples submitted for laboratory analysis.
- *Decontamination Procedures.* During the well installation process, all down-hole boring equipment was decontaminated using water and a suitable detergent to avoid transferring

contaminants between borings. All sampling equipment was single-use, disposable material (tubing, sample containers).

- *Sample Documentation.* Field documentation was facilitated by pre-printed tables, labels, and logs that allowed precise notation of sample collection and field conditions. Samples were identified using pre-determined sample IDs that were consistent with date and location of the samples and conducive to assembly of data into databases. Sample labels were prepared prior to the field investigation to minimize errors and keep sample collection orderly. Data collected during the sampling events was recorded on pre-printed data sheets developed specifically for this application. All samples submitted for laboratory analysis were submitted under chain-of-custody control and all laboratory reports included a narrative that discussed any quality control excursions. Photographic documentation of the project activities was collected throughout the project for inclusion in the final report.

Table 5.3. Summary of Sampling Plan for Field Demonstration

Project Component	Matrix	Collection Method	Number of Samples	Analyte(s)	Location(s)
Pre-Test Baseline Characterization	Groundwater	Low-flow w/ peristaltic pump	20	CVOCs, ethene, methane, sulfate, TOC, bromide, field parameters[1,2]	4 intervals at each CMT well, MW1, MW2, INJ1, DA31-DA35,
	Groundwater	Pressure transducer	Up to 6	Static water level	All fully screened wells in test area
	Soil/groundwater resistivity	Electrical Resistivity Tomography	NA	Resistivity	Surface electrodes and in-well electrodes at INJ1, MW1, MW2
	Groundwater	Electronic Borehole Flowmeter	Every 0.3 vertical m per location	Relative Hydraulic Conductivity	INJ1, MW1, MW2
Injection Monitoring	Groundwater	Low-flow w/ peristaltic pump	2-20 per screen interval to assess tracer arrival during each injection test	Bromide (during baseline test), chloride (during amendment injection)	4 intervals at each CMT well, MW1, MW2, DG1
	Groundwater	Down-well probe	NA	Bromide (during baseline test), chloride (during amendment injection)	MW1, MW2, MW3
	Injection solution	Sample valve	Minimum of 3during each injection test	Bromide (during baseline test), TOC, chloride (during amendment injection)	Injection line
	Groundwater	Low-flow w/ peristaltic pump	Up to 20 at end of amendment injection	CVOCs, ethene, methane, sulfate; bromide/chloride, TOC, field parameters[1,2]	4 intervals at each CMT well, MW1, MW2, INJ1, DA31-DA35
	Soil/groundwater resistivity	Electrical Resistivity	NA; repeated at end of each injection test	Resistivity	Surface electrodes and in-well electrodes at INJ1, MW1, MW2
	Groundwater	Low-flow w/ peristaltic pump	Up to 15 collected at the end of amendment injection	Rheologic properties	4 intervals at each CMT well, MW1, MW2, INJ1
Performance Monitoring	Groundwater	Low-flow w/ peristaltic pump	Up to 20 per event (2 events; conducted 5 and 8 months after injection)	CVOCs, ethene, methane, sulfate; bromide/chloride, TOC, field parameters[1,2]	4 intervals at each CMT well, MW1, MW2, INJ1, DA31-DA35

Notes: (1) Field parameters for groundwater include temperature, pH, oxidation-reduction potential, electrical conductivity, and dissolved oxygen; (2) Not all analytes may be included in all monitoring events at all locations; (3) CVOCs = chlorinated volatile organic compounds; TOC = total organic carbon.

Table 5.4. Summary of Analytical Methods for Samples Collected During Field Demonstration

Matrix	Analyte	Method	Container and Preservative	Laboratory
Groundwater	CVOCs	EPA 8260	3 40-mL glass vials; HCl to pH < 2	ESC Lab Sciences
	Ethene, ethane, methane	RSK175	3 40-mL glass vials; no preservative	ESC Lab Sciences
	Inorganic anions (sulfate, chloride, bromide)	EPA 300.0	500 to 1000 mL plastic bottle; no preservative	ESC Lab Sciences
	Bromide/Chloride	Specific conductance meter	> 100 mL; no preservative	Not applicable (field measurement)
	Field parameters (dissolved oxygen, electrical conductivity, oxidation-reduction potential, pH, temperature)	YSI Mulitmeter or equivalent	> 100 mL; no preservative	Not applicable (field measurement)
	Rheology	rotational rheometer Physica MCR 101	20 mL; no preservative	PNNL
	Total organic carbon (TOC)	EPA 9060A or SM 5310D	500 mL plastic bottle; H_2SO_4 to pH < 2	ESC Lab

5.7 Sampling Results

Results related to the performance of the shear-thinning fluid amendment relative to the baseline control test are presented in this section. Note that the results of the baseline characterization were presented in an earlier section (Section 5.2) and are used here for comparative purposes.

5.7.1 Field Testing and Injection Data

Data from initial injection of only water were used to estimate a ~3 m/d bulk hydraulic conductivity of the targeted injection interval. Injection pressure and flow rate monitoring during the field injections demonstrated that, at the same rate of injection, the STF resulted in approximately 1.75 times greater injection pressure than for the baseline solution near the end of the injection period (**Figure 5.17**). Thus, the high shear rate from injection resulted in shear thinning that significantly reduced the viscosity of the STF solution from its static viscosity of about 130 cP, as would be expected based on the shear-thinning response of the injection solution determined using laboratory rheological measurements using a rotational rheometer (Physica MCR 101, Anton Paar USA Inc., Ashland, VA) (**Figure 5.18**). Under these field injection conditions, the STF injection pressure was approximately 10 m (~14 psi) above ground surface at the injection well. It was expected that the well seal would be sufficient for this pressure range. However, after injection of about 58,300 L (528 minutes elapsed injection time), the injection pressure dropped abruptly, a strong indication that the well seal was breached and that part of the injected fluid was being discharged into the upper, high-k Steilacoom Gravel formation. Thus, while pressure increases during STF injection are much lower than would be predicted from the static STF viscosity, the additional pressure for injection puts stresses on the injection well seal that need to be considered in design of the injection well.

As observed in **Figure 5.17**, the STF injection pressure increases over time, in comparison to a stable pressure for the baseline injection. This effect is attributed to 1) lower interstitial velocities, and therefore lower shear rates, causing viscosity of the injected solution to increase as a function of distance to the well, and 2) an increasing volume of viscous fluid in the subsurface over time as the injection volume expands radially. These conditions lead to higher pressures required to maintain the same flow rate.

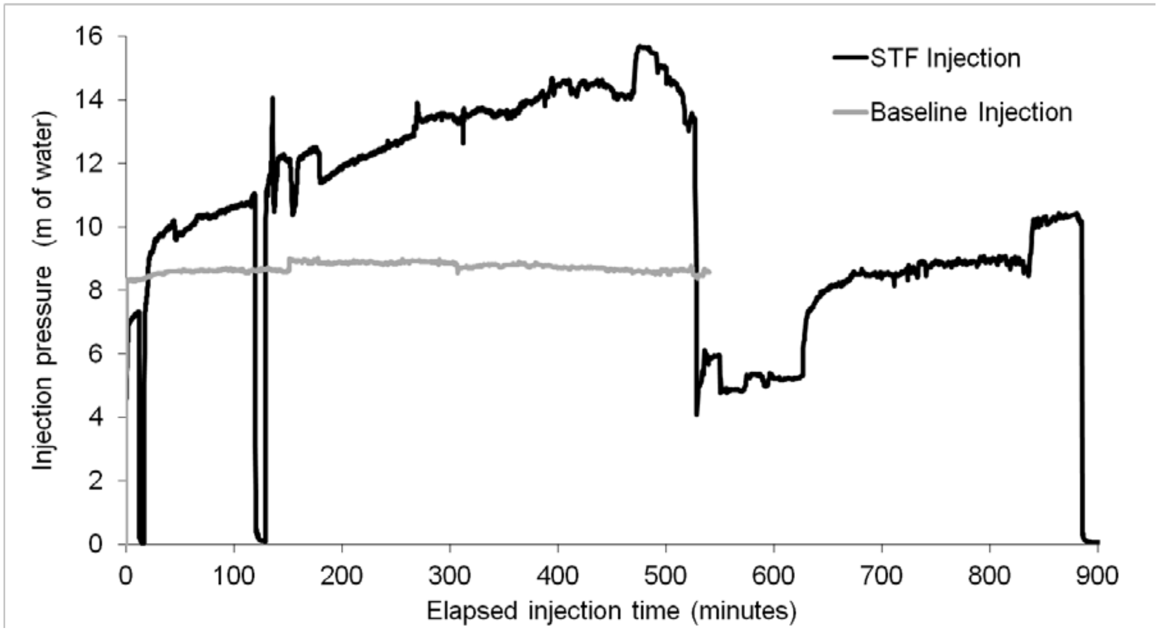


Figure 5.17. Injection pressure recorded during the baseline (control) and STF injection tests. Pressure is reported as meters of water above the static water table. The STF injection pressures are normalized to the average injection flow rate for the baseline injection of 115 L per minute. The average flow rate for the STF injection was 120 L per minute.

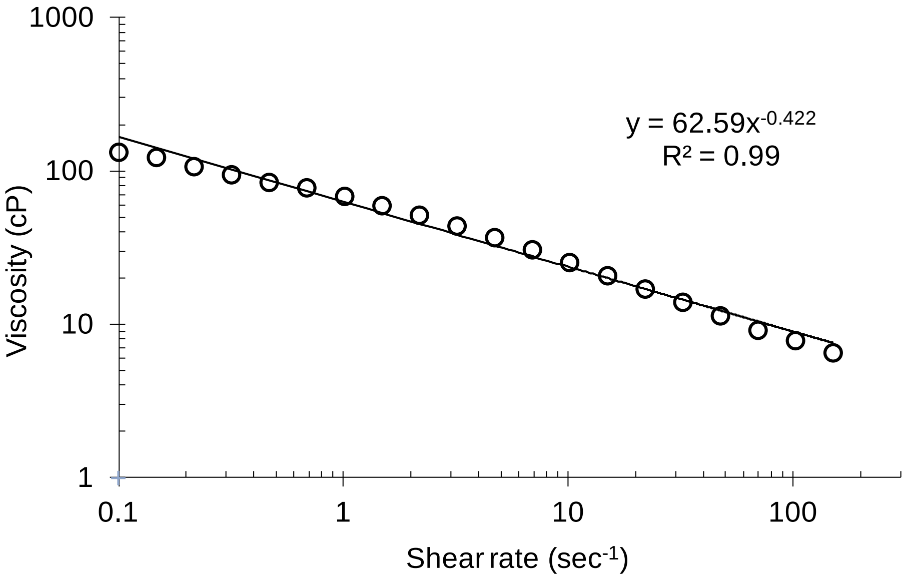
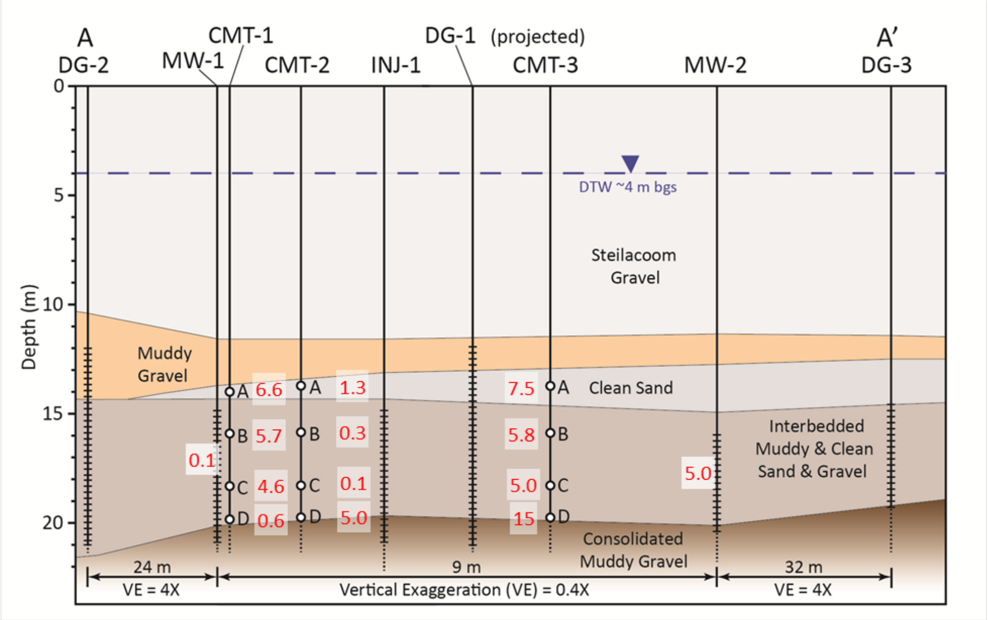


Figure 5.18. Rheology of STF injection solution used in the field demonstration. The data in the power-law region have been fitted with an Ostwald-De Waele relationship according to Lopez et al. (2003).

5.7.2 Distribution During Baseline Injection

A volume of 61,300 L of tracer solution was injected during the baseline test. Tracer arrival at the various sampling points was monitored throughout the injection period. Breakthrough was defined as the volume associated with reaching 50% of the observed arrival concentration at a given well location after fitting data to a Sigmoid curve (TableCurve 2D, Systat Software Inc., San Jose, CA) or, where appropriate, using in a linear fit. **Figure 5.19** displays the volume of the tracer solution that had been injected at the time of tracer breakthrough at the most relevant monitoring locations and depths, as well as the observed tracer concentration at the end of the test relative to the concentration in the injection solution. The breakthrough curves for each sampling point are included in **Appendix F**.

(a) Tracer breakthrough volumes (in 1000s of gallons)



(b) Tracer concentration at end of test volumes (% of injection concentration)

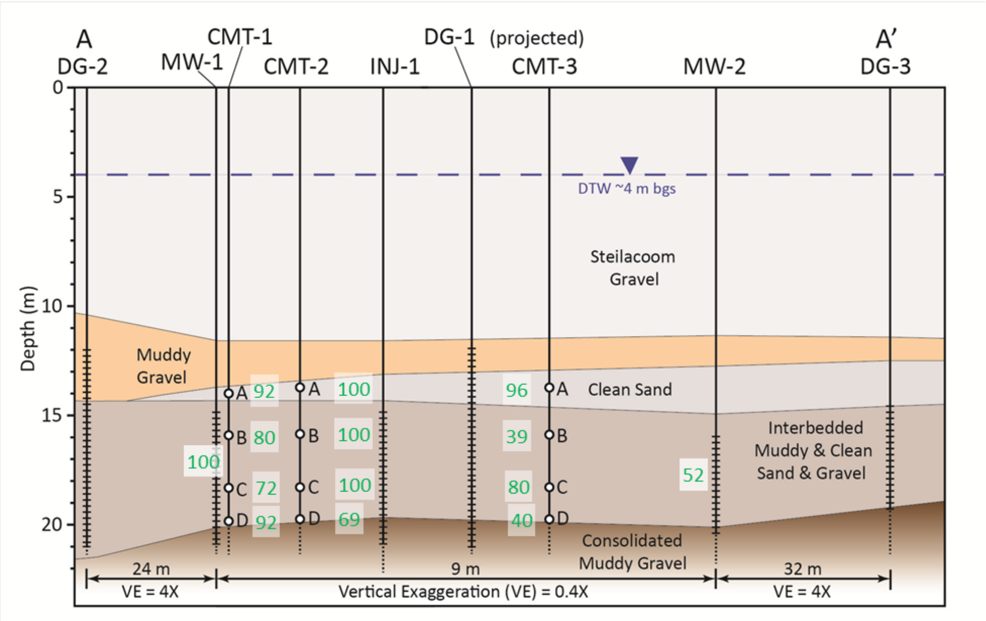


Figure 5.19. **Cross-section of treatment zone with tracer distribution during baseline injection test.** (a) tracer breakthrough volumes; (b) tracer concentration.

Breakthrough and distribution of injected solutions were evaluated in relation to the ideal cylindrical volume required to reach monitoring locations. Based on the 6.1-m (20-ft) well screen length and a porosity of 0.2 (Truex et al. 2006; USACE 2002), 8,900, 35,600, and 142,300 L are needed to reach monitoring radii of 1.52, 3.05, and 6.1 m (5, 10, and 20 ft), respectively. Breakthrough of injected solution at a given monitoring location was computed based on a percentage of the idealized cylindrical injection volume required to reach the location. The idealized volume represents a cylindrical pore volume extending to the radial distance of the monitoring location from the injection well. Percentages lower than 100% provide indication of faster transport and tracer arrival than would be expected for a homogeneous and radially symmetric system. A larger percentage is indicative of slower transport and a delayed tracer arrival. Assuming an ideal cylindrical distribution, the total volumes injected during both the baseline and STF tests were sufficient to fully reach the monitoring locations at 1.52- and 3.05-m (5 and 10 ft), but not the 6.1-m (20-ft) location. Observed tracer concentrations at the end of the injection period were compared to the injection concentration and percentages were computed to provide a metric for distribution effectiveness. The “A” zone monitoring locations are above the injection well screen and, ideally, injected fluid would not reach these locations. A summary of these metrics is provided in **Table 5.5**.

CMT monitoring locations were categorized using the data from the baseline injection (the control test) as representing a relatively high-k transport pathway, a low-k pathway, or as monitoring within the sand “A” zone location above the targeted treatment zone (**Table 5.5, Figure 5.20**). This approach was selected because sediment type and associated permeability vary significantly over short vertical and lateral distance (i.e., the subsurface is not comprised of laterally-extensive layers). Therefore, the breakthrough response to the baseline tracer injection was the best method for classifying the locations.

Table 5.5. Summary of Tracer Distribution During Baseline Injection Test

Location ID	**Screen/Port Depth** (ft bgs)	**Breakthrough Volume** (as % of Idealized Volume)	**Tracer Concentration** (as % of Injection Solution Concentration)	**Permeability Classification**
C1A	45.6	70%	93%	Overlying Sand (High K)
C1B	52.6	61%	81%	Low K
C1C	61.6	49%	73%	Low K
C1D	66.1/66.7	6%	93%	High K
C2A	45	56%	100%	Overlying Sand (High K)
C2B	52	14%	100%	High K
C2C	60	2%	100%	High K
C2D	64.2/64.7	213%	69%	Low K
C3A	45	80%	97%	Overlying Sand (High K)
C3B	52	62%	39%	Low K
C3C	60	53%	81%	High K
C3D	64.2/64.7	165%	40%	Low K
MW-1	48.5-68.5	1%	89%	NA (screened in multiple zones)
MW-2	48.5-68.5	13%	53%	NA (screened in multiple zones)

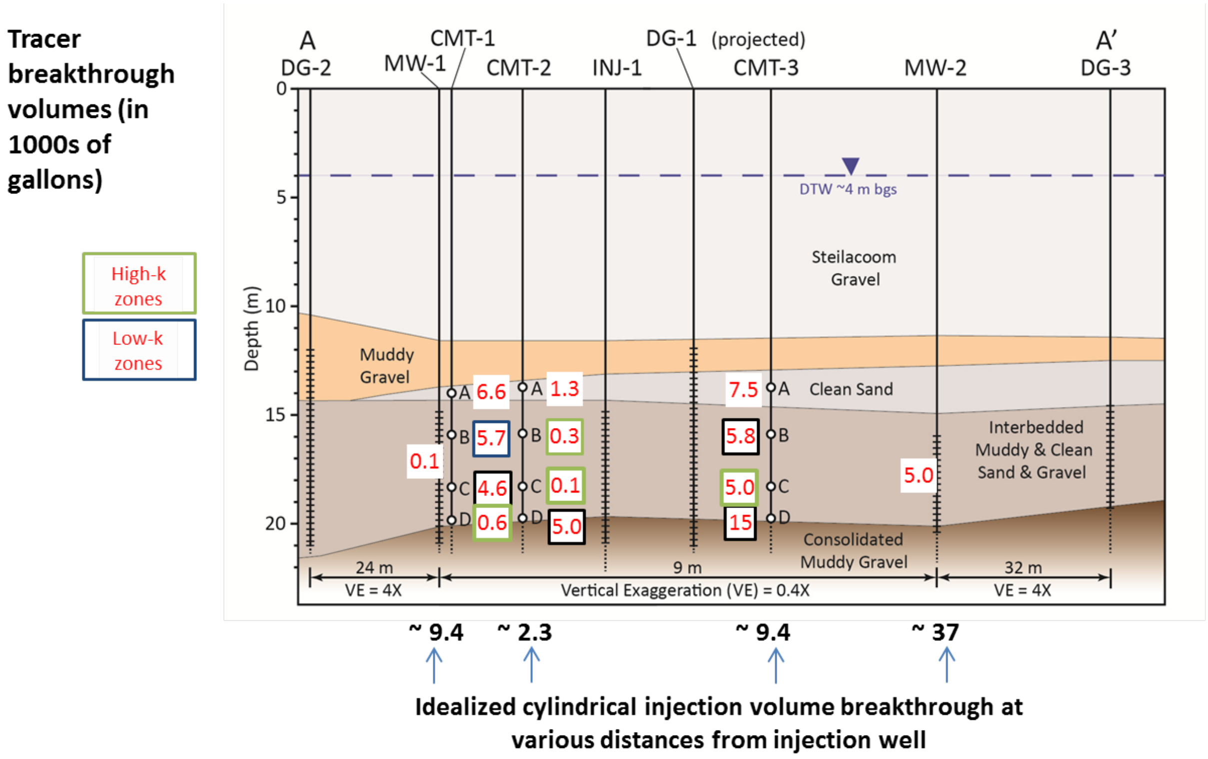


Figure 5.20. Classification of locations as high-permeability vs. low-permeability zones based on tracer distribution during baseline injection test.

Based on this approach, CMT locations C1D, C2B, and C2C were categorized as representing relatively high-k transport pathways because the breakthrough volume for the baseline injection was 7 to 50 times lower than the ideal cylindrical volume required to reach these monitoring locations (**Table 5.5**). Consistent with the results for breakthrough at well MW-1, these CMT location results indicate that significant high-k pathways in the radial direction toward MW-1 exist at the test site. A similar, though less pronounced, pathway is also evident in the radial direction toward MW-2 (**Table 5.5**). At the CMT-3 well, positioned in approximately the same radial direction as MW-2, monitoring location C3C was categorized as residing within a higher-permeability pathway based on relative response during the baseline injection where breakthrough volume was lower (faster arrival) and a higher percentage of the injection concentration was observed than at the other sampling depths for CMT-3. Adjacent monitoring locations C3B and C3D were categorized as low-k pathways because of the lower percentage of the injection concentration and the higher breakthrough volumes (slower arrival) than were observed at location C3C. Similarly, monitoring locations C1B and C1C were categorized as low-k pathways because of the lower percentage of the injection concentration and the higher breakthrough volumes (slower arrival) than were observed at location C1D and the adjacent well

MW-1. Monitoring well C2D was categorized as a low-k pathway because of the high breakthrough volume (slow arrival) during the baseline test.

Electrical resistivity data were collected for the 2D cross section between the screened intervals of the injection well and well MW-1 during the injection using a streamlined survey approach compared to the pre-injection and post-injection full surveys. This approach allowed several surveys to be completed during the injection period, though with lower resolution than the full pre- and post-surveys. Survey results during the baseline test are shown in **Figure 5.21** where the panels show the areas of the cross section with elevated conductivity (red/yellow shades) caused by the higher ionic strength of the injected solutions compared to the background. For this analysis, regions with a conductivity increase greater than $0.5x10^3$ S/m are considered to show the presence of injection solution. At both the approximate mid-point (25,700 L) and end (61,300 L) of the injection test, the dominant paths of injected fluid distribution for the baseline injection were in interval between 18-19 m below ground surface, likely indicating a high-k pathway is present causing the very early tracer breakthrough at well MW-1. The pathways where the change in conductivity was observed are consistent with the high conductivity zones identified in the baseline image. Note that there is an approximate 1 PV difference between the volumes represented in the panels. The finding that there is little change in distribution after the injection of an additional PV illustrates the difficulty in trying to deliver fluid throughout a formation when preferential pathways exist. More quantitative assessment of the ERT results using the post-injection full survey are presented in Section 5.6.4.

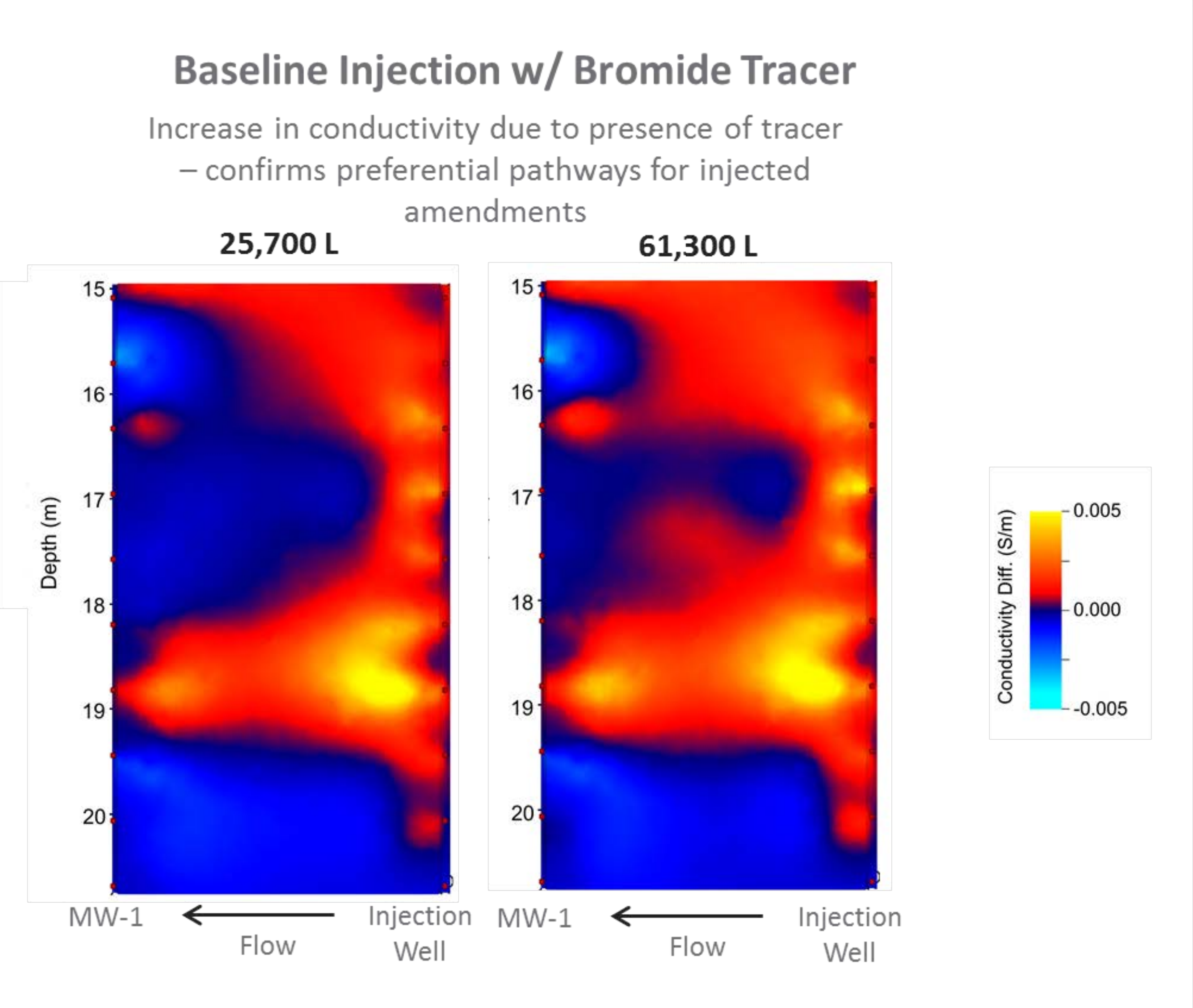


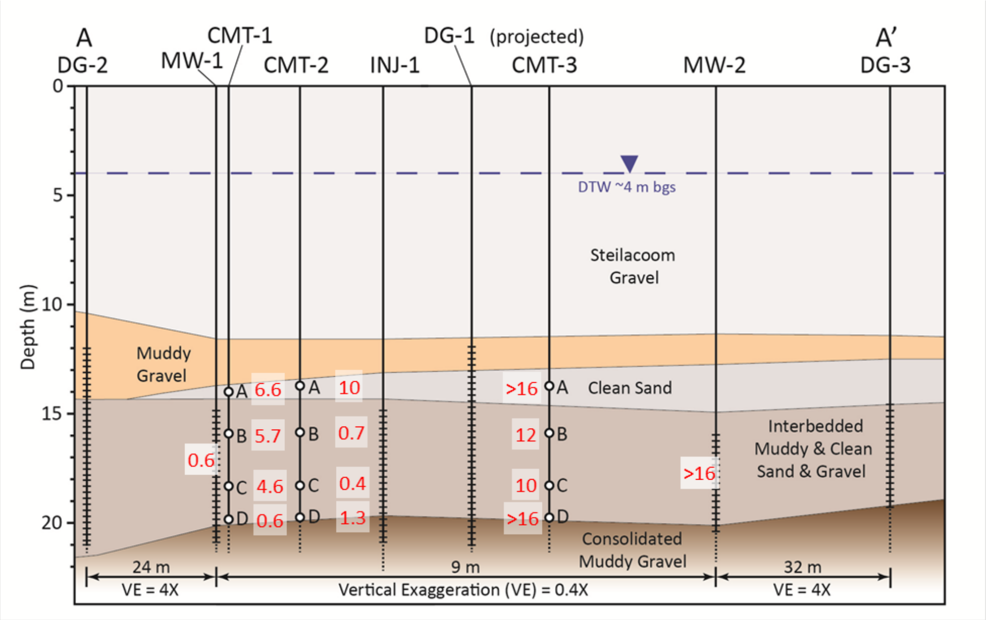
Figure 5.21. ERT image during baseline injection test. Distribution of the higher electrical conductivity (red/yellow shades) solutions as a conductivity difference during injection with bromide is shown over the depth interval of the screen from MW-1 to the injection well.

5.7.3 Distribution During Shear-Thinning Fluid Amendment Injection

A total of 106,400 L of tracer solution containing the lactate-xanthan gum amendment was injected during the shear-thinning fluid test. Due to the well seal breach discussed in section 5.6.1, the STF breakthrough analysis focuses on data up to that time with a corresponding injection volume of 58,300 L, comparable to the baseline injection volume of 61,300 L. Based on the pressure in the injection and monitoring wells after the breach it was estimated that about 33% of the injected solution was distributed to the targeted well screen interval and 67% flowed into the overlying high-k Steilacoom gravel formation. Using this estimate, the total STF volume injected to the targeted well screen interval was 74,200 L of the total 106,400 L injected.

Figure 5.22 displays the volume of the tracer solution that had been injected at the time of tracer breakthrough at the various monitoring locations and depths. **Figure 5.22** also shows the observed tracer concentration at each sampling point at the end of the test relative to the concentration in the injection solution, as well as the viscosity relative to the injection solution. The breakthrough curves for each sampling point are included in **Appendix F**, along with the tabulated tracer data from the entire test. A full set of samples was collected after the end of the injection test for measurement of tracer concentration, as well as CVOC, TOC, and various other geochemical and field parameters. These latter data are tabulated in **Appendix B (Table B.2)**.

(a) Tracer breakthrough volumes (in 1000s of gallons)



(b) Tracer concentration and viscosity at end of test volumes (% of injection concentration)

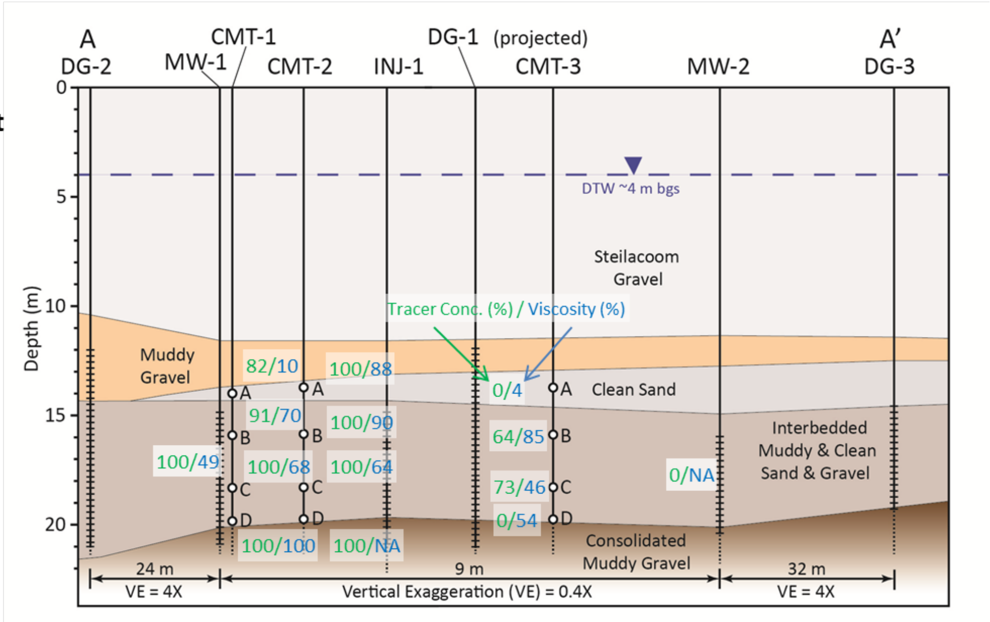


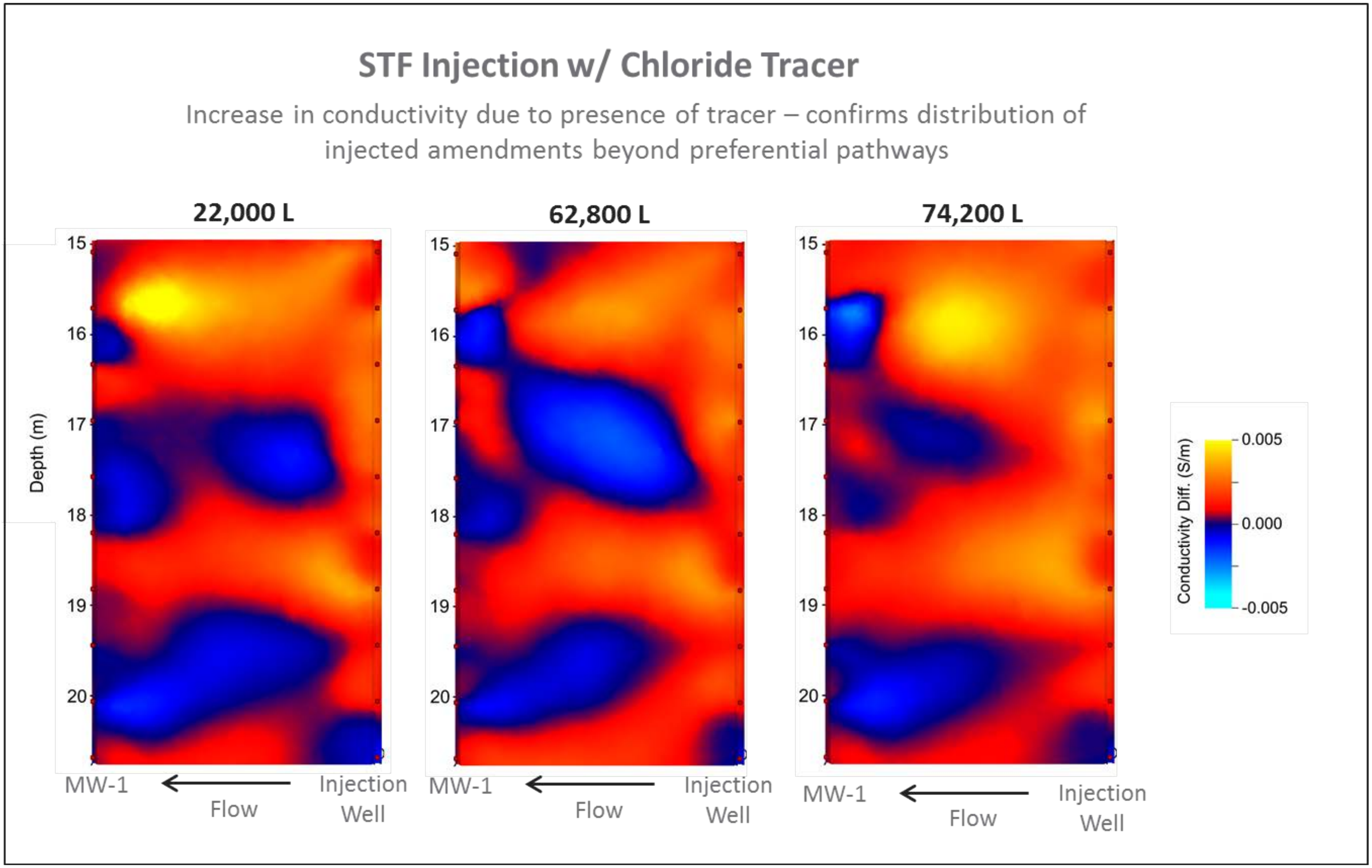
Figure 5.22. **Cross-section of treatment zone with tracer distribution during shear-thinning fluid (STF) injection test:** (a) tracer breakthrough volumes; (b) tracer concentration and viscosity.

As described in the previous section, breakthrough and distribution of injected solutions were evaluated in relation to the ideal cylindrical volume required to reach monitoring locations, as well as the concentration and viscosity (relative to the injection solution) measured at each location at the end of the test. A summary of these metrics is provided in **Table 5.6**. The results from a comprehensive post-test groundwater monitoring event are included in **Table B.2** in **Appendix B.**

Electrical resistivity data were also collected for the 2D cross section between the screened intervals of the injection well and well MW-1 during the STF injection using a streamlined survey approach compared to the pre-test and post-test full surveys. This approach allowed several surveys to be completed during the injection period, though with lower resolution than the full pre- and post-surveys. Survey results during the baseline test are shown in **Figure 5.23** where the panels show the areas of the cross section with elevated conductivity (red/yellow shades) caused by the higher ionic strength of the injected solutions compared to the background. While the dominant paths of injected fluid distribution for the injection remain in the interval between 18-19 m bgs, there is clearly a more even distribution throughout the area between the injection well and well MW-1 (as discussed below). An additional quantitative assessment of the ERT results using the post-injection full survey is presented in Section 5.6.4.

Table 5.6. Summary of Tracer Distribution During STF Injection Test

Location ID	**Screen/Port Depth** (ft bgs)	**Breakthrough Volume** (as % of Idealized Volume)	**Tracer Concentration** (as % of Injection Solution Concentration)	**Viscosity** (as % of Injection Solution Viscosity)	**Permeability Classification**
C1A	45.6	96%	82%	10%	Overlying Sand (High K)
C1B	52.6	30%	91%	70%	Low K
C1C	61.6	38%	100%	68%	Low K
C1D	66.1/66.7	12%	100%	100%	High K
C2A	45	450%	100%	88%	Overlying Sand (High K)
C2B	52	29%	100%	90%	High K
C2C	60	17%	100%	64%	High K
C2D	64.2/64.7	56%	69%	No data	Low K
C3A	45	>170%	2%	4%	Overlying Sand (High K)
C3B	52	124%	65%	85%	Low K
C3C	60	104%	74%	46%	High K
C3D	64.2/64.7	>170%	5%	54%	Low K
MW-1	48.5-68.5	7%	100%	No data	NA (screened in multiple zones)
MW-2	48.5-68.5	>43%	2%	No datta	NA (screened in multiple zones)



STF Injection w/ Chloride Tracer

Increase in conductivity due to presence of tracer – confirms distribution of injected amendments beyond preferential pathways

Figure 5.23. ERT image during STF injection test. Distribution of the higher electrical conductivity (red/yellow shades) solutions as a conductivity difference during injection with chloride is shown over the depth interval of the screen from MW-1 to the injection well. Note: ERT survey resolution was lower for the 22,000 L and 62,800 L events.

5.7.4 Comparison Between STF and Baseline Amendment Distribution

Table 5.7 shows the breakthrough and distribution data for the baseline injection and the STF amendment injection tests. A graphical representation of this information is shown in **Figure 5.23**.

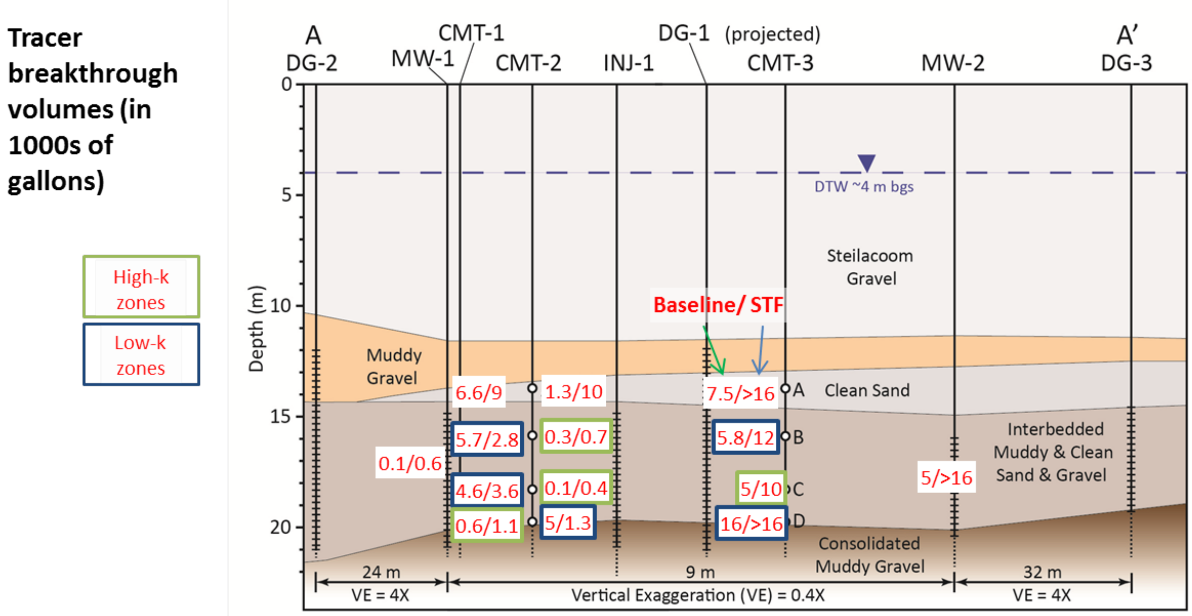


Figure 5.24. Cross-section of treatment zone with tracer distribution during baseline injection test vs. STF injection test. Volumes for baseline test represent breakthrough of bromide tracer while volumes for shear-thinning test represent breakthrough of chloride tracer.

Data from the two injection tests at the fully-screened monitoring wells MW-1 and MW-2 demonstrate key differences in injected fluid movement in a heterogeneous subsurface environment induced by the use of a STF injection solution. These data are based on injected volumes of 61,300 to 74,200 L. This volume range represents 1.7 to 2.1 pore volumes for a cylinder extending to the MW-1 radius and 0.43 to 0.52 pore volumes extending to the MW-2 radius. Thus, an ideal injection would fully distribute solution to MW-1, and no solution would reach MW-2. As shown in **Table 5.7**, 100% distribution of STF was achieved at MW-1 compared to 89% distribution of tracer from the baseline injection. While the breakthrough volumes for both the baseline solution and the STF solution indicate rapid tracer movement between the injection well and MW-1 (i.e., very early tracer arrival), the STF slowed flow in the dominant flow paths (**Table 5.7**: 7% versus 1% of the idealized cylindrical volume at 50% breakthrough) and improved the final distribution (percent of injected concentration) of the injected solution. At MW-2, breakthrough during the baseline test was achieved at a volume that was equivalent to 13% of the idealized radial volume, reaching a final tracer concentration 53% of the injected concentration. In contrast, during the STF injection, tracer arrival was not observed at MW-2, consistent with a more uniform distribution of the injected solution within the heterogeneous formation due to the presence of the shear-thinning fluid.

Table 5.7. Summary of Differences Between Amendment Distribution During Baseline Injection Test and STF Injection Test

Location ID	**Permeability Classification** (based on results from baseline test)	**Breakthrough Volume** (as % of Idealized Volume)		**Tracer Concentration** (as % of Injection Solution Concentration)		**Viscosity** (as % of Injection Solution Viscosity)
		Baseline	***STF***	***Baseline***	***STF***	***STF***
C1A	Overlying Sand (High K)	70%	96%	93%	82%	10%
C1B	Low K	61%	30%	81%	91%	70%
C1C	Low K	49%	38%	73%	100%	68%
C1D	High K	6%	12%	93%	100%	100%
C2A	Overlying Sand (High K)	56%	450%	100%	100%	88%
C2B	High K	14%	29%	100%	100%	90%
C2C	High K	2%	17%	100%	100%	64%
C2D	Low K	213%	56%	69%	69%	No data
C3A	Overlying Sand (High K)	80%	>170%	97%	2%	4%
C3B	Low K	62%	124%	39%	65%	85%
C3C	High K	53%	104%	81%	74%	46%
C3D	Low K	165%	>170%	40%	5%	54%
MW-1	NA (screened in multiple zones)	1%	7%	89%	100%	No data
MW-2	NA (screened in multiple zones)	13%	>43%	53%	2%	No datta

A comparison of breakthrough and distribution at the CMT monitoring locations for the baseline and STF injections is summarized in **Table 5.8**. The table presents the relative percent difference in the breakthrough volume between the STF and baseline tests, as well as the relative percent difference in the percentage of the injected tracer concentration for each test. Representative breakthrough data at the CMT-2 location for the three categories of pathways are shown in **Figure 5.25**.

Table 5.8. Comparison of Baseline (Control) Injection vs. STF Injection Performance.

Location ID	RPD for Breakthrough Volumes	RPD for % Injected Tracer Concentration
Above Treatment Zone		
C1A	36%	-11%
C2A	709%	0%
C3A	>113%	-98%
Low-Permeability Zones		
C1B	-51%	13%
C1C	-21%	38%
C2D	-74%	46%
C3B	100%	67%
C3D	>3%	-88%
High-Permeability Zones		
C1D	89%	8%
C2B	108%	0%
C2C	572%	0%
C3C	96%	-9%

Notes: (1) Values are the relative percent difference (RPD) of the STF data compared to the baseline data (calculated as [[STF-baseline]/baseline] x 100); (2) Positive values represent a larger breakthrough volume (slower arrival) or higher percent of injected concentration for STF versus baseline injection; (3) Yellow shaded cells show where the metric indicates STF performance was not equal to or better than baseline performance.

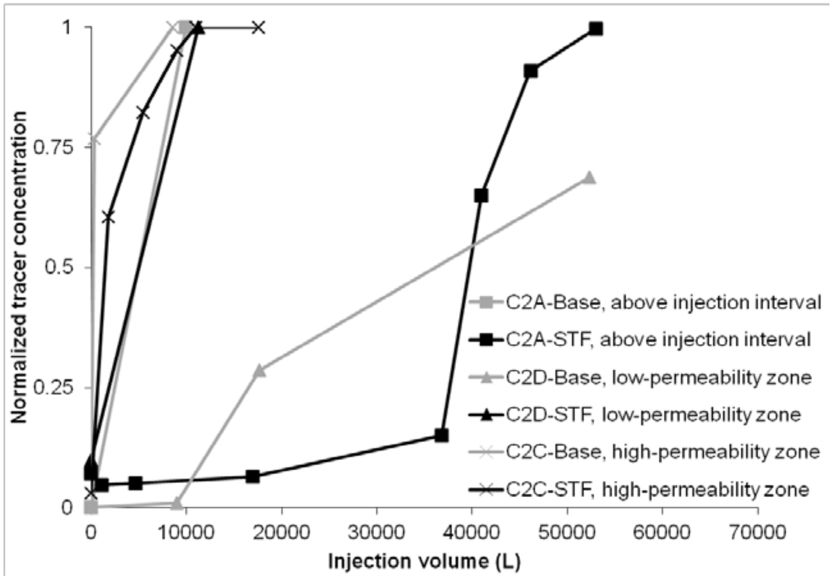


Figure 5.25. Representative breakthrough data at the CMT-2 location for the three categories of pathways for the baseline (Base) control injection and the shear-thinning fluid (STF) injection.

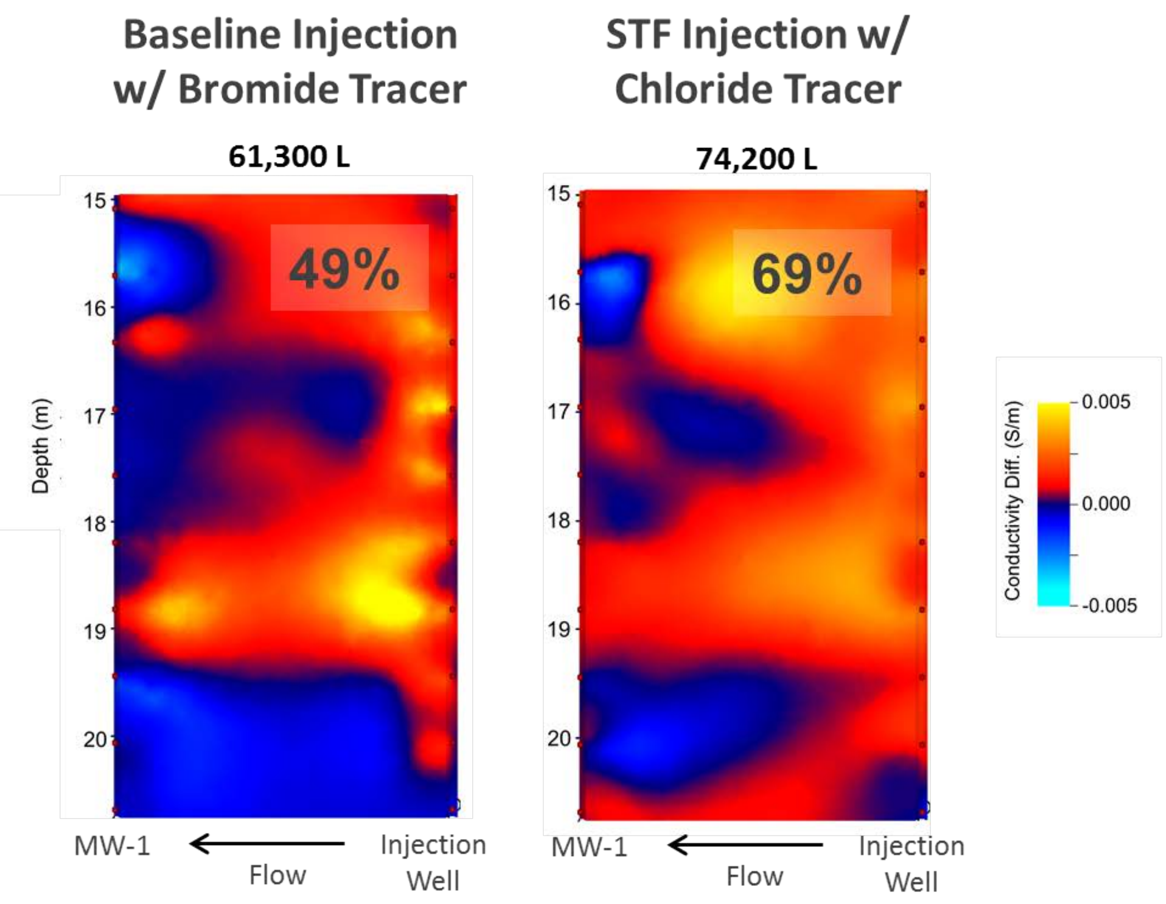
To evaluate the potential benefit of the STF on distribution, it is important to distinguish between the anticipated shear-thinning response for higher-k zones versus those anticipated for lower-k zones within a radius of 3.05 m (10 ft) from the injection well:

- For higher-k zones, the inclusion of an STF would be expected to cause slower transport than observed for the baseline injection and the same or better distribution of the injected solution.
- For lower-k zones: the inclusion of an STF would be expected to cause faster transport and a higher percentage of the injected tracer concentration (i.e., better delivery of injected solution to low-k zones) than observed for the baseline injection.

All of the high-k monitoring locations showed higher breakthrough volumes (slower arrival) with the STF injection (**Table 5.8**). Distribution (based on an evaluation of the percentage of injected concentration) was the same for the STF versus the baseline test at the CMT-2 monitoring locations, all of which are 1.52 m (5 ft) from the injection well. At the 3.05-m (10-ft) monitoring radius (CMT-1 and CMT-3), the STF showed improved distribution at location C1D, but worse distribution at location C3C. For the lower-permeability pathways represented by the C1B, C1C, C2D locations, the STF injections achieved the expected improvements of faster transport and a higher percentage of the injected tracer concentration (**Table 5.8**). At location C3B, STF injection transport was slower but resulted in a higher percentage of the injected tracer concentration. STF injection showed slower transport and worse distribution than the baseline injection at location C3D, contrary to the positive results at the other locations. Finally, slower transport and a lower percentage of the injected tracer solution are the preferred outcome for the "A" zone wells, which are located in a relatively higher-permeability sand layer above the well screen and outside the targeted treatment zone. The STF injection showed these improvements for all "A" zone wells, except that 100% of the injected concentration was observed at the C2A location 1.52 m (5 ft) from the injection well for both STF and baseline injections (**Table 5.8**).

A second method for demonstrating the impact of the STF on remedial amendment distribution and delivery effectiveness is to examine the ratios between the fastest and slowest breakthrough at each monitoring location. The inclusion of a STF is expected to promote a more uniform sweep of the injected solution through the heterogeneous formation, such that the ratio between the fastest and slowest breakthrough would be less than that observed during the baseline test. Evidence of this positive effect was observed at both CMT-1 and CMT-2. At CMT-2, a 50:1 ratio between the fastest and slowest breakthrough volumes was observed during the baseline test, followed by a decrease to 25:1 during the STF injection. At CMT-1, the ratio during the baseline test was 11:1 and decreased to 8:1 during the STF injection. Note that at CMT-3, the lack of breakthrough at all monitoring locations during the STF injection precludes this evaluation.

A third method for demonstrating the improved distribution following the STF amendment injection is the electrical resistivity data. **Figure 5.26** shows ERT data collected for the 2D cross section between the screened intervals of the injection well and well MW-1 at the end of the baseline and STF injections. Areas of the cross section with elevated conductivity (red/yellow shades) are caused by the higher ionic strength of the injected solutions compared to the background. In both cases, a dominant path of injected fluid distribution is observed in the interval between 18-19 m bgs. However, the injected fluid distribution for the STF injection is more uniform across the cross section, although regions remain where the formation materials are bypassed by the amendment solution. Based on integrating the electrical resistivity data at the end of the injection period, the percentages of the ERT cross section indicating the presence of injected tracers are 49% and 69% for the baseline and STF injections, respectively. This demonstrates the improved distribution of amendment into the lower-permeability zones of a heterogeneous aquifer using the shear-thinning fluid.



Baseline Injection w/ Bromide Tracer

STF Injection w/ Chloride Tracer

Areas of elevated conductivity reflect improved distribution of tracer using STF

STF improved distribution from 49% to 69%

Figure 5.26. Comparison of amendment distribution using the ERT images. Each panel shows the distribution of the higher electrical conductivity (red/yellow shades) solutions as a conductivity difference between the baseline injection (left panel) and STF injection (right panel) over the depth interval of the screen. Well MW-1 is located at a radial distance of 3.05 m from the injection well. At the time of these measurements, the injection volumes for both baseline and STF injections were sufficient to reach a cylindrical radial distance of 4.0 and 4.4 m, respectively.

5.7.5 Performance Monitoring

As noted previously, post-injection performance monitoring was completed to assess amendment persistence as well as effectiveness in achieving treatment of contaminants. Performance monitoring events were completed in February 2014 and May 2014, such that the total duration of the monitoring period was 8 months. The results are summarized in **Figure 5.27** (February 2014) and **Figure 5.28** (May 2014). Data supporting the performance objectives are tabulated in **Tables 5.9 - 5.11** (complete data are in **Appendix B)**.

Important findings include the following:

- In locations where substrate was distributed during the STF injection, there was evidence that a portion of the substrate persisted through the 8 month monitoring event. For this evaluation, TOC concentration was used as a surrogate for the STF. Within the CMT wells in the treatment zone, TOC concentrations were consistently greater than pre-test background levels, and generally greater than 20 mg/L. The exceptions were C3C and C3D, which also saw relatively low levels immediately following STF injection. The measured TOC concentrations are suitable for supporting sustained treatment via biological reductive dechlorination. The finding that a portion of the substrate persisted for 8 months is promising given that the primary substrate (ethyl lactate) is readily degradable, although the presence of the shear-thinning polymer likely improved amendment persistence. It should be noted that the design of the shear-thinning amendment was based primarily on rheologic properties during injection and not long-term stability.
- There was evidence of increased persistence in lower-k zones relative to higher-k zones. After 8 months, the average TOC concentration in the 5 low-k CMT locations was 153 mg/L, while the average TOC concentration in the 4 high-k CMT locations was 71 mg/L. In addition, the average TOC concentration in the low-k locations had changed little between 5 months (151 mg/L) and 8 months (153 mg/L), while a significant decrease in the average TOC concentration was observed in the high-k CMT locations between 5 months (201 mg/L) and 8 months (71 mg/L). This pattern highlights the benefits of improving distribution to lower-k zones through the use of shear-thinning fluids; once amendment has been delivered to the lower-k zones, it is less subject to flushing and thus should persist for longer periods.
- Little TOC was measured in downgradient wells (e.g., DG-1, DG-2, DG-3), a pattern which is consistent with the persistence of the amendment within the treatment zone.
- Relatively rapid tracer breakthrough was observed during the baseline injection test at MW-2, a well that is located in a direction lateral to the regional groundwater flow direction. In contrast, tracer breakthrough was not observed at MW-2 during the STF injection test, and the TOC concentration immediately after injection was only 22 mg/L. This provided evidence that the STF resulted in a more uniform distribution that minimized preferential pathways in the direction of MW-2. However, a significant increase in the TOC concentration at the side-gradient well MW-2 was observed during

the 5 month performance monitoring event (200 mg/L), and only a slight decrease was observed after 8 months (140 mg/L). This indicates a portion of the amendment was being transported out of the treatment zone via advection due to localized hydraulic gradients.

- The presence of TOC was positively associated with the establishment of proper reducing conditions for reductive dechlorination. The majority of locations maintained ORP readings that were well below zero throughout the 8-month performance monitoring period.
- Sulfate was below detection limits at the majority of locations throughout the performance monitoring period. While pre-injection sulfate levels were generally low (24 to 200 mg/L in the treatment zone), the fact that nearly 100% removal was achieved and maintained is promising with respect to controlling influx of competing electron acceptors.
- Methane production within the treatment zone was relatively limited, although there were some notable increases in several high-k locations in the period between 5 and 8 months. Given the low baseline concentration of methane and slow methanogenic growth rates, the data suggest that the methanogenic population within the treatment zone is initially low.
- Complete removal of TCE was observed in the majority of wells in the treatment zone by 5 months, and no rebound in TCE concentrations was observed after 8 months of monitoring. TCE concentrations in downgradient wells were largely similar to pre-injection levels, while the TCE concentration in the upgradient well increased slightly (from an initial level of 9.4 μg/L to 14 μg/L after 8 months).
- Increases in cDCE concentration in all treatment zone wells provided confirmation that the reductions in the parent compound (TCE) were attributable to reductive dechlorination rather than dilution. At both the 5-month and 8-month monitoring events cDCE represented 100% of the total CVOCs measured in the majority of wells in the treatment zone. The exceptions were C3C and C3D, which were locations that saw lower TOC concentrations immediately after the end of the STF injection (i.e., poor distribution). However, these two wells were still characterized by increased cDCE concentrations after injection, such that cDCE represented 70% or more of the total CVOC concentration by the end of the 8-month monitoring period.
- Vinyl chloride was detected in only one location (C3A) during both the 5-month (3 μg/L) and 8-month (3.4 μg/L) monitoring events. Similarly, ethene was detected at a limited number of locations (C2A and C2D) at trace levels. This pattern was observed even though TCE had been largely removed from the treatment zone within 5 months. The results suggest a limitation in the native microbial population with respect to the capacity for complete dechlorination given that other commonly-cited factors for cDCE stall (e.g., TCE inhibition, competing electron acceptors, pH) were not applicable. Consequently, bioaugmentation would likely need to be evaluated for a full-scale design for this site.

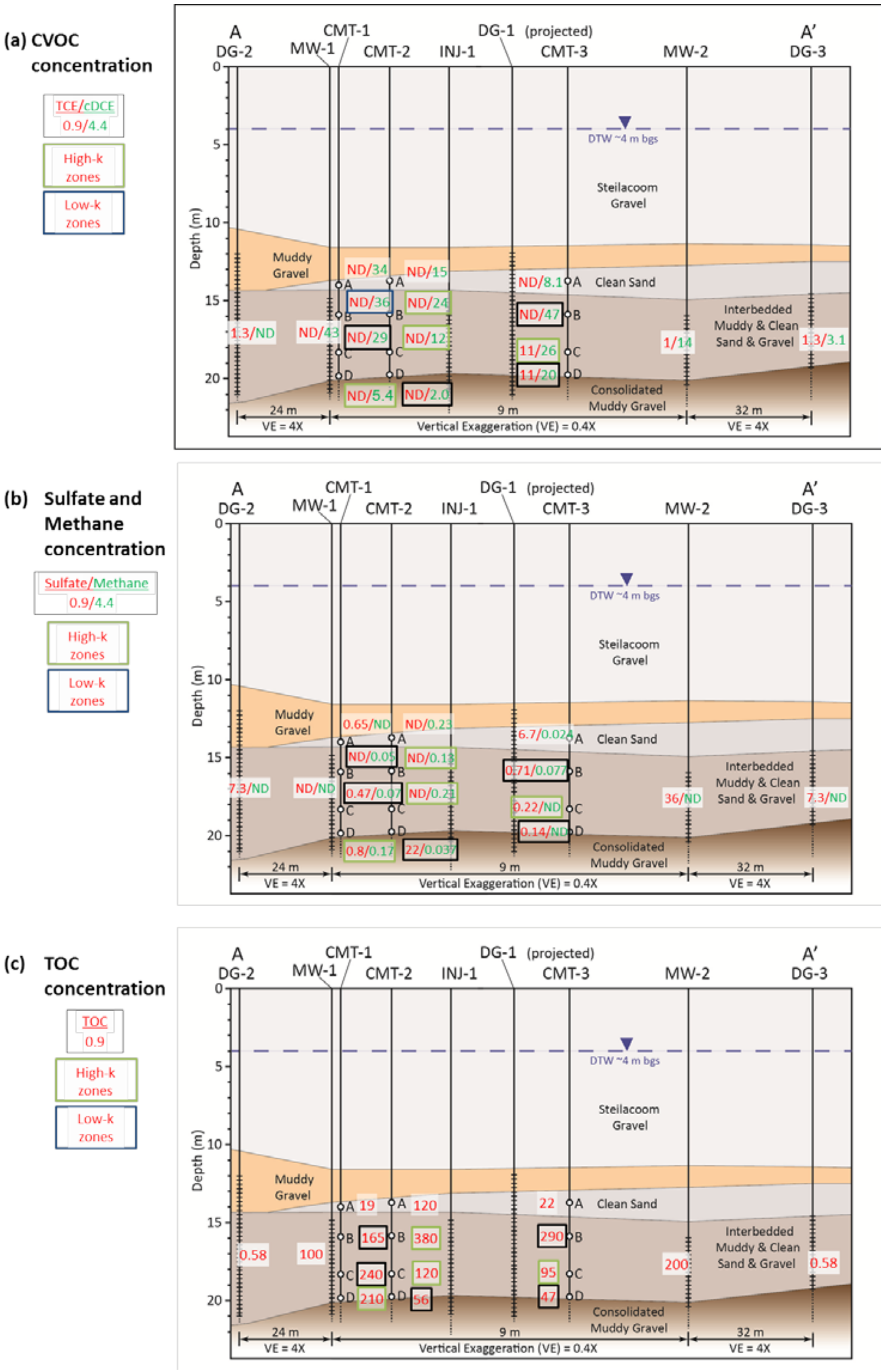


Figure 5.27. Groundwater sampling results from performance monitoring – 5 months post injection. The location of cross-section A-A' is shown in **Figure 5.2**.

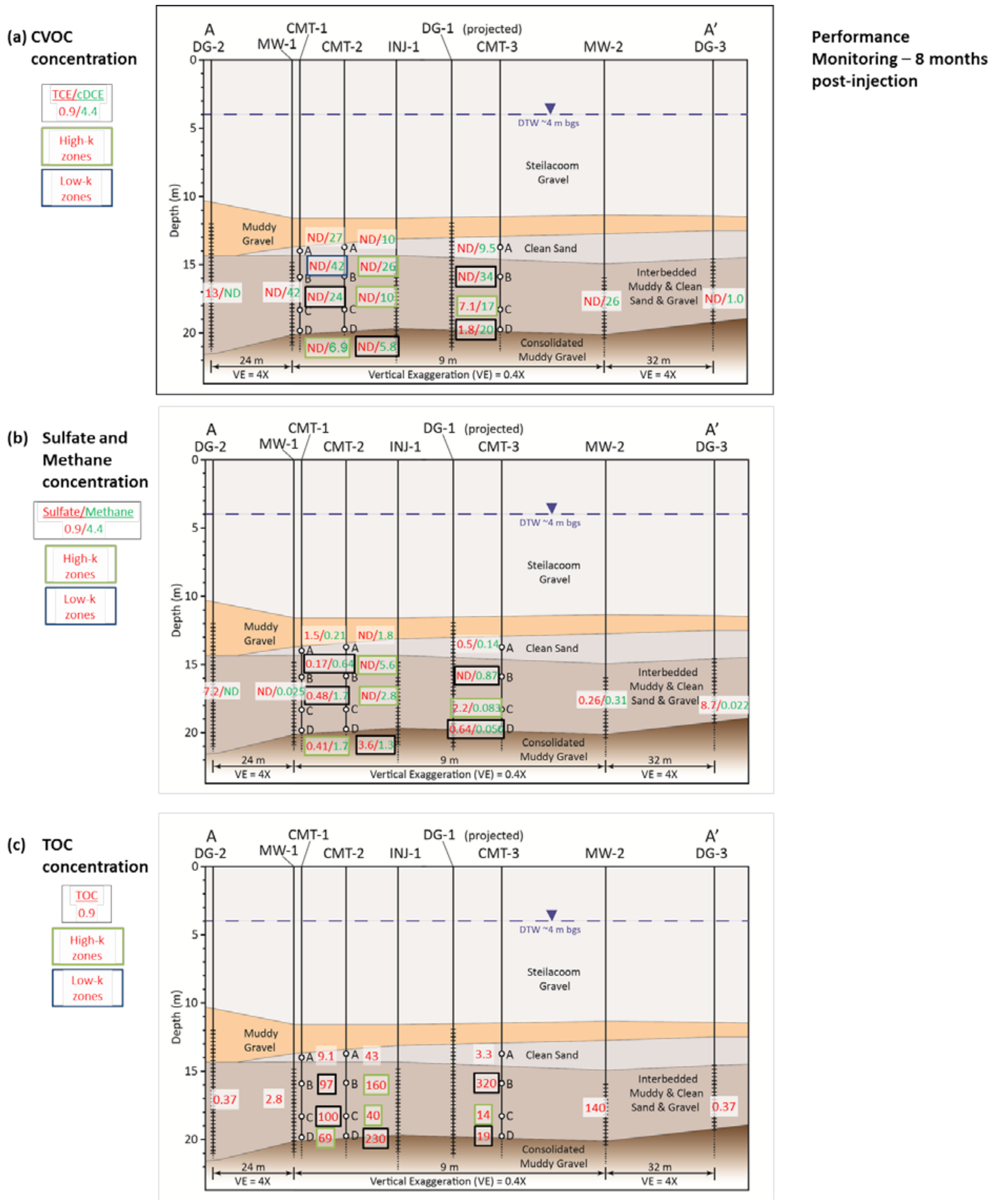


Figure 5.28. Groundwater sampling results from performance monitoring – 8 months post injection. The location of cross-section A-A' is shown in **Figure 5.2**.

Table 5.9. Comparison of Parent Compound Concentration Reductions Achieved During Post-Injection Performance Period.

Location ID	Pre-Injection: August 2013	5 Months Post-Injection: February 2014		8 Months Post-Injection: May 2014	
	Parent Concentration (µg/L)	Parent Concentration (µg/L)	% Change from Initial Parent Concentration	Parent Concentration (µg/L)	% Change from Initial Parent Concentration
Above Treatment Zone					
C1A	1.9	0.86 J	-55%	ND	-100%
C2A	8.6	0.7 J	-92%	ND	-100%
C3A	0.9	0.96 J	+7%	ND	-100%
Low-Permeability Zones					
C1B	7.9	0.6 J	-92%	2.8	-65%
C1C	13	ND	-100%	ND	-100%
C2D	ND	0.48	+100%	ND	-100%
C3B	14	ND	-100%	ND	-100%
C3D	28	11	-61%	1.8	-94%
High-Permeability Zones					
C1D	4.2	ND	-100%	ND	-100%
C2B	7.5	0.51 J	-93%	ND	-100%
C2C	7.8	ND	-100%	ND	-100%
C3C	27	11	-59%	7.1	-74%
Multiple Zones (Fully-Screened Wells)					
MW-1 (side-gradient)	11	ND	-100%	ND	-100%
MW-2 (side gradient)	7.6	1	-87%	ND	-100%
MW-3 (side-gradient)	14	NS	--	NS	--
DG-1 (down-gradient)	5	4.2	-16%	3.9	-22%
DG-2 (down-gradient	9.9	18	+82%	13	+31%
DG-3 (down-gradient)	1.1	1.3	+18%	ND	-100%
DA-31 (up-gradient)	9.4	16	+70%	14	+49%

Notes: (1) ND = non-detect; NA = not available (sample damaged upon receipt at lab); NS = not sampled; (2) Concentrations include J flag results where indicated (estimated values below the detection limit).

Table 5.10. Comparison of Daughter Product Ratios Achieved During Post-Injection Performance Period.

Location ID	**Pre-Injection: August 2013**			**5 Months Post-Injection: February 2014**			**8 Months Post-Injection: May 2014**		
	Parent Conc. (µg/L)	**Sum of Daughter Conc. (µg/L)**	**% Daughter Relative to Total CVOCs**	**Sum of Daughter Conc. (µg/L)**	**% Daughter Relative to Total CVOCs**	**% Daughter Relative to Initial Parent**	**Sum of Daughter Conc. (µg/L)**	**% Daughter Relative to Total CVOCs**	**% Daughter Relative to Initial Parent**
Above Treatment Zone									
C1A	1.9	27	93%	34	100%	>100%	27	100%	>100%
C2A	8.6	45	84%	15	100%	>100%	10	100%	>100%
C3A	0.9	6.7	88%	11.1	100%	>100%	12.9	100%	>100%
Low-Permeability Zones									
C1B	7.9	6.1	43%	37	100%	>100%	42	100%	>100%
C1C	13	6.8	34%	29	100%	>100%	24	100%	>100%
C2D	ND	1.2	100%	2	100%	>100%	5.8	100%	>100%
C3B	14	7.7	35%	47	100%	>100%	34	100%	>100%
C3D	28	6.2	18%	20	65%	71%	21	93%	75%
High-Permeability Zones									
C1D	4.2	8.5	67%	5.4	100%	>100%	6.9	100%	>100%
C2B	7.5	12	62%	24	100%	>100%	26	100%	>100%
C2C	7.8	4.3	36%	12	100%	>100%	10	100%	>100%
C3C	27	8.9	25%	26	70%	96%	17	71%	63%
Multiple Zones (Fully-Screened Wells)									
MW-1 (side-gradient)	11	4	27%	43	100%	>100%	42	100%	>100%
MW-2 (side gradient)	7.6	4.1	35%	36	93%	>100%	26	100%	>100%
MW-3 (side-gradient)	14	5.5	28%	NS	--	--	NS	--	--
DG-1 (down-gradient)	5	1.3	21%	1.8	70%	84%	ND	0%	0%
DG-2 (down-gradient)	9.9	ND	0%	ND	0%	0%	ND	0%	0%
DG-3 (down-gradient)	1.1	4.5	80%	3.1	70%	>100%	1	100%	91%
DA-31 (up-gradient)	9.4	0.4	4%	0.48	ND	0%	1.8	11%	19%

Table 5.11. Comparison of Amendment Persistence Indicators During Post-Injection Performance Period.

Location ID	Pre-Injection: August 2013				5 Months Post-Injection: February 2014				8 Months Post-Injection: May 2014			
	TOC (mg/L)	ORP (mV)	Sulfate (mg/L)	Methane (mg/L)	TOC (mg/L)	ORP (mV)	Sulfate (mg/L)	Methane (mg/L)	TOC (mg/L)	ORP (mV)	Sulfate (mg/L)	Methane (mg/L)
Above Treatment Zone												
C1A	6.8	-196	43	0.03	19	-150	0.65	ND	9.1	-110	1.5	0.21
C2A	12	82	78	0.027	120	-110	ND	0.23	43	-79	ND	1.8
C3A	6.1	-135	24	0.04	22	-170	6.7	0.024	3.3	-115	0.5	0.14
Low-Permeability Zones												
C1B	10	-222	95	0.027	170	-175	ND	0.053	97	-56	0.17	0.64
C1C	5.5	-195	72	0.024	240	-168	0.47	0.07	100	-105	0.48	1.7
C2D	NA	NA	NA	NA	56	-293	22	0.037	230	-90	3.6	1.3
C3B	21	-43	200	0.021	290	-159	0.71	0.077	320	-47	ND	0.87
C3D	7.9	-72	62	0.02	47	-188	0.14	ND	19	-112	0.5	0.058
High-Permeability Zones												
C1D	5.1	-165	61	0.015	210	-116	0.8	0.17	69	-45	0.41	1.7
C2B	22	-78	120	0.031	380	-109	ND	0.13	160	-65	ND	5.6
C2C	4.6	-17	26	0.016	120	-165	ND	0.21	40	-68	ND	2.8
C3C	13	-69	74	0.021	95	-180	0.22	ND	14	-55	2.2	0.083
Multiple Zones (Fully-Screened Wells)												
MW-1 (side-gradient)	0.62	525	13	ND	100	-46	ND	ND	32	19	ND	0.25
MW-2 (side gradient)	0.46	240	12	ND	200	-107	0.094	ND	140	-33	0.26	0.31
MW-3 (side gradient)	0.63	160	16	ND	NS	NS	NS	NS	NS	NS	NS	NS
DG-1 (down-gradient)	0.48	142	8.4	ND	3.3	26	7.3	ND	0.48	83	17	ND
DG-2 (down-gradient)	0.49	266	6.7	ND	0.21	88	6.2	ND	0.48	351	7.2	ND
DG-3 (down-gradient)	0.95	162	8.6	ND	0.58	-60	7.3	ND	0.37	89	8.7	0.022
DA-31 (up-gradient)	0.46	246	8.1	ND	0.2	6	7.4	ND	0.51	-20	10	ND

Notes: (1) ND = non-detect; NA = not available (sample damaged upon receipt at lab); NS = not sampled; (2) Concentrations include J flag results (estimated values below the detection limit).

6.0 PERFORMANCE ASSESSMENT

A summary of the performance objectives for this demonstration, along with an overview of technology performance, was presented in Section 3. This section includes a detailed assessment of technology performance based on the quantitative data presented in Section 5. Following completion of the sampling and analysis program, the data were reviewed to determine whether the success criteria for each performance objective have been met. The evaluation of each individual performance objective is discussed below, with references to relevant supporting results in Section 5.

6.1 Quantify Improved Distribution of Amendment to Lower-Permeability Zones

Success Criteria Achieved? **YES**

The highest-priority objective of this technology was to demonstrate that the injection of amendments as a shear-thinning fluid results in improved distribution to lower permeability zones relative to conventional approaches (e.g., lactate or other carbon source diluted in water). Distribution was monitored for both baseline (conventional injection) and STF injection using a tracer solution (baseline and STF) and TOC and viscosity measurements (STF only) that were measured at the multiple radial distances from the injection well and, at selected locations, within vertically discrete monitoring intervals. ERT data was also collected as part of both injection phases for a 2-D cross section between the injection well and monitoring well MW-1 located 10 ft from the injection well. The ERT monitored the screen depth interval (20 ft) within this cross section and provided an indication of the 2-D distribution of injected solution based on the increased electrical conductivity of the injection solution compared to the background.

The objective was considered achieved if the shear-thinning fluid injection results in measurable evidence that the STF and associated amendments and tracer has penetrated the low-k zones and at higher concentrations (>50% volumetric improvement in distribution) relative to the water-only injection. Another related criterion was to demonstrate an improvement (> 50% decrease) in the ratio of tracer arrival between high- and low-k zones during the STF stage relative to the baseline stage, an indicator of improved uniformity of distribution (sweep efficiency). Success was also evaluated based on whether the concentration of the tracer and amendment in monitored low-k zones reached 10% of the concentration of the tracer in the injection solution. Indications of success in meeting these objectives are listed below.

- An ideal injection would fully distribute solution to MW-1, and no solution would reach MW-2. 100% distribution of STF was achieved at MW-1 compared to 89% distribution of tracer from the baseline injection. At MW-2, tracer arrival was not observed at MW-2 during the STF, but breakthrough during the baseline test was achieved at a volume that was equivalent to 13% of the idealized radial volume. Monitoring in a sandy zone above the targeted injection interval showed less STF distribution upward than was observed for the baseline injection. Thus, more of the injected volume was maintained within the targeted injection radius, including low-k zones, with use of STF. ERT data show that injection solution, as measured by increased bulk conductivity, was present in 69% of a 2-D cross section over the first 3-m from the injection well for STF versus 49% for the baseline injection. This is equivalent to a ~41% improvement in distribution for the STF stage.

- At CMT-2, a 50:1 ratio between the fastest and slowest breakthrough volumes was observed during the baseline injection, followed by a decrease to 25:1 during the STF injection, a 50% decrease. At CMT-1, the ratio during the baseline injection was 11:1 and decreased to 8:1 during the STF injection, a 28% decrease. Thus, this criteria was met in CMT-2 and partially met in CMT-1
- Tracer concentrations in 4 of 5 monitored low-k zones were >10% of the injected concentration and were improved with STF versus baseline and worse at one. Tracer concentrations in 4 monitored low-k zones as a % of injected tracer concentration were for the STF and baseline stage were (STF/baseline) 91%/81%, 100%/73%, 100%/69%, 65%/39% and 5%/40%.
- Amendment concentration (as TOC) in 4 of 5 monitored low-k zones were >10% of the injected concentration. Amendment concentration (as TOC) in monitored low-k zones were 84%, 91%, 41%, 33%, and 1% of the injected concentration.

6.2 Determine Effectiveness in Enhancing Concentration Reduction in Low-Permeability Zones

Success Criteria Achieved? **YES**

A primary goal of any remediation effort is to achieve a reduction in the concentration (or mass) of the target contaminant. In the case of the shear-thinning technology, the improved distribution of the amendment should lead to an improved ability to treat contaminants present in the lower permeability zones of the treatment area. Therefore, the performance evaluation focused on data from the CMT wells screened in locations that had been identified as lower-permeability zones. Concentrations from the pre-treatment monitoring event were then compared to concentrations measured during performance monitoring events, particularly during the final event (8 months after the shear-thinning fluid injection). The primary objective was to achieve > 50% reduction in parent compound concentration in the majority of low-k zone locations. A second objective was based on achieving a daughter product concentration that was > 25% of the initial (pre-treatment) parent compound concentration.

Both of these sub-objectives were successfully achieved. A 100% reduction in the parent compound (TCE) concentration occurred in 3 of the 5 locations screened in low-k zones. Even at the locations where TCE was still present after 8 months, the reduction from pre-treatment concentrations was 65% to 94%. Similar patterns were observed in the fully-screened wells and in the CMT wells screened in higher-permeability zones, confirming that treatment effectiveness was relatively uniform. Importantly, there was no evidence for rebound in parent compound concentrations in the period between the final two monitoring events. The wells where incomplete parent compound reduction was achieved were wells where lower TOC concentrations were measured after injection (C3C and C3D). This confirmed that treatment effectiveness was a function of amendment distribution.

The success criterion for the second sub-objective was also met. Specifically, the daughter product concentration at each low-k zone monitoring location was > 25% of the initial parent compound concentration during each monitoring event. The same condition was met at all other monitoring locations within the treatment zone. Since this criterion was developed prior to the pre-treatment monitoring event, and it eventually became clear that it was a relatively low threshold for success. Therefore, secondary metrics for success that were evaluated were: 1) the daughter concentration was also > 25% of the parent compound concentration measured during individual monitoring events; and 2) the percentage of the the total CVOC concentration represented by daughter compounds increased throughout the performance monitoring period. Both of these secondary criteria were also successfully achieved.

Note that in addition to the amendment distribution, the treatment effectiveness is a function of site-specific conditions. At Area D of JBLM, pre-demonstration data suggested that there was dechlorination beyond cDCE. Therefore, the fact that complete dechlorination to ethene was not observed following injection of the shear-thinning fluid reflects deficiencies in the native microbial population, rather than a limitation in the technology.

6.3 Determine Effectiveness in Enhancing Persistence of Amendment and Effects

Success Criteria Achieved? **YES**

The purpose of this performance objective was to evaluate if the beneficial influence of the shear-thinning fluid persisted over an extended period of time. Conventional amendments for in situ treatment technologies typically require repeated injections. In the case of enhanced bioremediation, soluble substrates such as lactate are often injected at intervals of several weeks to several months. The shear-thinning fluid that was used as the amendment for this demonstration was not specifically designed to serve as a long-lasting substrate; if so, a semi-soluble or emulsified carbon source would have been more appropriate choice than ethyl lactate. However, the technology is designed to improve delivery of the substrate to the lower-permeability intervals within the treatment area. As such, the technology takes advantage of the relative persistence of amendments that have been successfully delivered into low-k zones because advective flushing is minimized.

The sub-objectives that were developed for this evaluation used a minimum of a 6-month period that these benefits persisted; the final monitoring event was completed 8 months after the STF injection. Success was based on the continued presence of the amendment (in the form of TOC concentrations) and dechlorination products, as well as favorable geochemical conditions and diverted electron acceptors throughout the entire performance monitoring period. As such, this objective focused on the temporal patterns in the monitoring data, with particular attention to the impacts in the lower-permeability zones.

All sub-objectives that were developed as part of this evaluation were met. The primary criterion was elevated TOC concentration in monitoring locations in low-k zones relative to the TOC concentrations that were present prior to injection. In these 5 monitoring locations, the average concentration increased from 11 mg/L (pre-injection) to approximately 600 mg/L immediately after injection. During the performance monitoring period, the average concentration in these 5 locations dropped to 151 mg/L after 5 months but was maintained at 153 mg/L after 8 months. The pattern in the 4 CMT locations screened in high-k zones was slightly different, with a decrease from approximately 900 mg/L immediately post-injection to 200 mg/L after 5 months of monitoring and then 71 mg/L after 8 months of monitoring. Consequently, the results confirmed enhanced persistence of the shear-thinning fluid within low-k zones. In addition, there was no indication that groundwater entering the treatment zone was resulting in more rapid decreases in TOC concentrations in wells located in the upgradient portions of the treatment cell relative to those located farther downgradient.

Other sub-objectives were based establishing proper reducing conditions within the treatment area due to the long-lasting presence of the amendment and its ability to divert competing electron acceptors. Sulfate concentrations decreased to nearly non-detectable levels during the performance monitoring events. At most monitoring locations, the oxidation-reduction potential were relatively similar to pre-treatment readings, but consistently negative and supportive of reductive dechlorination. Methane concentrations were relatively low (generally < 1 mg/L) but did increase at the majority of locations as a result of the amendment injection.

Finally, treatment effectiveness via amendment persistence was part of this performance objective. The criterion of increased cDCE production throughout the entire monitoring period was achieved. There was a notable lack of rebound in parent compound concentrations during the demonstration despite the fact that the test consisted of a single injection with a relatively limited footprint. Despite these constraints, there was sustained activity within the treatment zone for at least 8 months.

6.4 Ease of Use

Success Criteria Achieved? **YES**

The purpose of this performance objective was to confirm that the methods could be implemented with minimal additional effort relative to more conventional methods. While there are certain extra steps that are necessary in including shear-thinning polymers as part of an amendment solution, the techniques are not highly dissimilar to those already familiar to practitioners. Because the use of shear-thinning amendments require slightly more time (and material/equipment costs) relative to conventional injection, the success criterion for this performance objective was demonstrating that the shear-thinning fluid injection could be completed in a single mobilization using standard equipment.

The success criterion was met. The shear-thinning injection was completed in a single mobilization, using a pumping period of approximately 15 hours to achieve an idealized radius of influence of > 4 m. A pumping rate of 30 gpm was sustainable, and this rate is within the typical range for amendment injections based on the project team's experience. Hydration of the xanthan gum to create the shear-thinning fluid was completed the day before pumping started, but this type of 1-day preparation period is typical for any in situ injection-based technology (and in the case of this demonstration, it overlapped with the equipment set-up period). Collectively, the project demonstrated that the field methods are easy to implement and can be completed in a timely manner.

7.0 COST ASSESSMENT

A key objective of this project was to track costs associated with this technology demonstration in order to provide a basis for estimating costs of a full-scale implementation of the technology. To aid the evaluation, implementation costs were incorporated into various scenarios and then compared to various alternatives.

7.1 Cost Model

As part of the demonstration, the cost of implementing the field program was carefully tracked and this cost data was used to estimate the cost that would be associated with implementing this methodology at a generic site. These are summarized in **Table 7.1**. Only those elements that are unique to this technology were included as part of the cost assessment and comparison. This means that costs that are standard to injection-based treatment methods (e.g., in situ enhanced bioremediation) were tracked but have not been included in the cost assessment. Finally, costs that were incurred during this demonstration with the objective of obtaining a more comprehensive dataset than would be expected during a standard implementation were tracked but not included in the cost model.

7.1.1 Technology-Specific Cost Elements

The following descriptions focus on the cost elements that are specifically associated with the shear-thinning technology. There are other cost elements associated with the various scenarios that were part of the scenario-based cost model, but these are not discussed separately here.
Laboratory and/or Modeling Studies: In order to determine the optimum polymer formulation and injection design, a limited set of studies are recommended. Costs associated with this task are primarily labor required to complete laboratory studies and/or modeling, but also include materials and analytical costs. Bench-scale studies to understand the rheologic properties, or at minimum the static viscosity, of various potential amendment formulations are recommended. Supplemental studies using multi-phase flow modeling (STOMP, UTCHEM) may be beneficial for understanding the expected distribution of injected amendments, using known or estimated bulk permeability values within relevant layers of the targeted groundwater-bearing unit. However, it is anticipated that this step may not be included in many applications. Therefore, the cost estimate includes only bench-scale testing of amendment formulation rheology or static viscosity. Static viscosity may be sufficient if a formulation similar to those for which rheological properties are published in scientific literature. Otherwise, testing of rheological behavior is important to ensure that the formulation will perform as expected in the field injection.

Baseline Characterization: A complete understanding of the site stratigraphy and contaminant distribution is a required element prior to implementing this technology. For the purposes of the cost model, it is assumed that sufficient characterization data has been collected to develop a conceptual site model that supports the remedy being implemented, i.e., in situ bioremediation.

Table 7.1. Cost Model for the Shear-Thinning Technology

Cost Element	Tracked Data
Laboratory and/or Modeling Studies	Labor, materials, analytical costs
Baseline Characterization	Detailed vertical stratigraphic characterization of targeted groundwater-bearing unit using one of several different methods • Electronic Borehole Flowmeter (EBF) used for this demonstration • Cost model assumed that high-resolution baseline data was available for either STF application or conventional in situ bioremediation
Injection/Monitoring Well Installation	No unique requirements, although multi-level monitoring well clusters are recommended if not otherwise installed for conventional in situ bioremediation applications
Amendment Injection	Labor associated with shear-thinning amendment injection as basis for comparison to conventional amendment injection • Includes labor associated with amendment preparation • All other costs are standard for injection
Material Cost	Polymer as component of amendment formulation • Cost for conventional substrate (ethyl lactate) not included Tank and other equipment rental
Long-Term Monitoring	No unique requirements
Operations and Maintenance	No unique requirements
Waste Disposal and Decommissioning	No unique requirements

Further, the cost model assumes that existing characterization efforts indicate that a level of geologic heterogeneity exists at the site, such that the use of the shear-thinning technology would be beneficial. Therefore, it is anticipated that a full-scale implementation would rely on existing data from groundwater and soil sampling.

The only recommended addition to conventional characterization efforts would be the use of one or more high-resolution methods to provide more detailed spatial information (particularly in the vertical direction) on contaminant distribution and permeability within the treatment area (Adamson et al, 2013, Sale et al., 2013). Depending on the site, there are a number of methods that may be appropriate, including (but not limited to) CPT, MIP, GeoProbe HPT or MiHPT, Waterloo^{APS}, passive flux meters, and various geophysical approaches. For this demonstration site, the presence of very coarse-grained soils precluded the use of tools that rely on direct-push methods. Therefore, the primary characterization method utilized during this project was the Electronic Borehole Flowmeter (EBF) to obtain a vertical permeability profile within several of the monitoring wells at the site. These data proved useful for identifying permeability contrasts and preferential flowpaths, such that the cost model assumed that a similar level of effort would be included in most applications of this technology. For the purposes of the cost comparison, however, it was assumed that both conventional in situ bioremediation and in situ bioremediation with STF would rely on existing baseline characterization data. Note that the high-resolution data are of interest because the STF is targeting treatment of those lower-permeability zones that are not effectively treated with conventional in situ bioremediation.

Injection/Monitoring Well Installation. Shear-thinning fluids can be injected through wells that are designed for conventional amendment solutions. As such, there are no unique cost considerations relative to most in situ bioremediation applications. However, careful attention to the well annular seal is needed to accommodate the injection pressures. In addition, the use of permanent injection wells—as opposed to temporary wells and/or direct-push boreholes—is strongly recommended due to the higher injection pressures that will be experienced in comparison to conventional injection. Monitoring requirements are also similar to conventional in situ bioremediation, although the use of multi-level wells is generally recommended to better evaluate amendment distribution.

Amendment Injection: The techniques used for injecting the shear-thinning polymer solution are identical to those for soluble (and most semi-soluble carbon substrate amendment solutions), assuming that a strategy of monitoring tracer breakthrough is employed to confirm that the desired radius of influence is achieved. The primary unique cost for this technology is polymer preparation, which requires additional time for sufficient hydration of the xanthan gum within the polymer solution. The cost model include labor for experienced personnel to complete the polymer preparation and injection, as well as assumptions of injection duration and frequency over the course of the project lifetime (see Sections 7.1.2 and 7.1.3).

In addition, the technology requires pressure testing of the injection well using using a step-injection test along with monitoring of adjacent wells, and it can be completed within a short period of time (<1 day) prior to the start of the full-scale amendment injection. Since similar procedures are used during most injection-based remedial technologies to test the efficacy of the well design, separate cost tracking for these tests were not included. Other applications of this technology may include a limited tracer test or comprehensive tracer test using a water-based (non-shear thinning) solution as a first step to confirm flow in the absence of the polymer. However, this option was not included in this cost model.

Material Cost: The primary costs associated with materials are the shear-thinning polymer and the equipment required to prepare the shear-thinning polymer solution. All other costs (e.g., purchase of a carbon substrate for bioremediation) are not unique to this technology. For this demonstration, these costs included xanthan gum, an additional tank and metering pump (for preparation of the concentrated polymer solution), and proper mixing equipment.

Note that the cost model assumes that there are no permanent installations at the site. Injections were completed as one-time events using rented equipment that required no automated process control system. As such, there were no additional labor costs for installation (labor associated with polymer preparation was included in the *Amendment Injection* cost element described above.

Long-Term Monitoring: Monitoring requirements are identical those for most in situ bioremediation applications. The analyte list for all monitoring programs should include TOC measurements (in groundwater samples) as a surrogate for the shear-thinning fluid.

Operations and Maintenance: There are no unique cost associated with operations and maintenance of the technology. As noted above, the cost estimates presented here are based on the assumption that injections were completed as discrete events (i.e., not continuous) without the use of automated process control systems.

Waste Disposal and Decommissioning: The technology generates no additional waste beyond that typical of in situ bioremediation projects, assuming that the entire volume of shear-thinning fluid is injected into the subsurface. There are no special decommissioning requirements since the technology utilizes conventional injection and monitoring wells. Note that there were several requirements for decommissioning the CMT wells installed as part of this demonstration (based on Washington Department of Ecology regulations). However, these were specific to the monitoring network installed as part of this demonstration—which is not required for all applications of this technology. Consequently, these costs are not included in this model.

7.1.2 Cost Scenarios

The cost elements described above were incorporated into several scenarios for illustrating the costs associated with this technology.

- ***Scenario 1: Cost of Single Injection of Shear-Thinning Fluid Amendments vs. Conventional Amendments for In-Situ Bioremediation***. The goal was to establish how much additional short-term cost would be associated with implementing the shear-thinning technology relative to similarly-sized treatment systems that used conventional amendments. In this case, the potential long-term benefits of the technology are not incorporated into the evaluation.
- ***Scenario 2: Project Lifetime Costs of In-Situ Bioremediation using Shear-Thinning Fluid vs. Conventional Amendments.*** This scenario assumes that the better distribution of substrate achieved through the use of shear-thinning fluids results in fewer injection events over the project lifetime and leads to site closure within 5 years. Conventional in situ bioremediation also leads to an alternative outcome, where post-treatment management of the site using MNA is required over the course of the next 25 years.

7.1.3 Assumptions

The various assumptions used to develop the cost model and generate cost estimates for the various scenarios are described below:

- Site characteristics and the scale of the treatment system were assumed to be similar to those for this demonstration project. This ensured that cost tracking performed for the project would be useful and representative. This means that the treatment consisted of a single injection well with sufficient volume to achieve an idealized radius of influence of 10 ft based on pore volume estimates and 20-ft thick treatment interval. As a result, the soil treatment volume was estimated to be 6280 ft^3 (233 yd^3) for the baseline case.

- Distribution to the entire treatment zone (i.e., 100% sweep efficiency) could be achieved by injecting 2 pore volumes of STF. This is based on the finding that a sweep efficiency of 69% was achieved during this demonstration using an injection volume that represented slightly greater than 1 pore volume, as well as the relatively moderate permeability contrasts at the test site. For the case in Scenario 2 where STF is compared to conventional amendments, it is assumed that a 2 pore volume injection of conventional amendments would not achieve 100% sweep efficiency, such that incomplete treatment would occur.
- An injection rate of 30 gpm could be achieved, such that the entire amendment volume could be injected over the course of two work shifts (16 hours). Note that the cost model includes injection rate as an input parameter for the purposes of sensitivity analysis.
- An additional day was required for initial preparation of the STF. Injection testing was assumed to occur during the prep day, and process monitoring was completed during the course of the amendment injection period. During the 2-day, 3-shift work phase (preparation plus injection), a total of 3 people were needed (1 engineer/geologist, 2 technicians).
- For Scenario 1, the unit cost for conventional in situ bioremediation was assumed to \$100/yd^3. This value is based on median technology-specific unit costs compiled as part of ESTCP ER-201120 (involving several PIs from this project; McGuire, 2014) and represents primarily the treatment phase of full-scale in situ bioremediation projects. Therefore, we feel that this typical unit cost represents an appropriate baseline. Given that the scale of the project evaluated here is smaller than the majority of projects in the ESTCP ER-201120 cost and performance survey, additional evaluation of the influence of scale is presented in Section 7.3. Since the cost model used the injection frequency as an input value, the \$100/yd^3 unit cost was assumed to apply to two full-scale injection events for a moderately persistent substrate. A unit cost adjustment of 25% per injection event was used to account for scenarios with less than or greater than 2 injection events (e.g., the single injection envisioned in Scenario 1).
- For Scenario 2, the unit cost for in situ bioremediation using shear-thinning fluid amendments was again estimated in terms of the incremental cost associated with the technology. In other words, the costs associated with those elements unique to the technology were added to the typical unit cost for more conventional applications.
- For Scenario 2, two injections of the STF and four injections of the conventional substrate (lactate without polymer) were assumed. The STF amendment was expected to persist for approximately one year, such that the second injection for each case occurred approximately one year after the first injection. The conventional amendment was expected to be less persistent, such that additional injection events were necessary over the same project lifetime.
- For Scenario 2 that involves a comparison of outcomes, the costs associated with any additional characterization efforts during the remedy selection period were not considered. For example, additional characterization may occur immediately prior to the

start of in situ bioremediation to optimize the design. These costs can vary widely based on site-specific considerations and thus were not included in this cost assessment.

- For Scenario 2, long-term monitoring involved bi-annual (twice yearly) monitoring of wells for CVOCs and TOC. The number of wells is based on the size of the treatment area (1 well per 1600 ft^2, plus 1 background and 1 downgradient compliance well). The monitoring period for MNA was assumed to be 30 years (i.e., including monitoring during the active treatment period). For the case where the use of STF led to site closure, long-term monitoring to provide confirmatory evidence for site closure was assumed to be 5 years.

7.2 Cost Analysis

This section provides a cost comparison for each of the scenarios described above. The costs were compiled using a combination of the demonstration data, information from similar projects, vendor quotes, literature values, and the Remedial Action Cost Engineering and Requirements (RACER) software. Drillers and analytical laboratories that were part of the demonstration were used where applicable. The cost breakdown for each scenario is presented in **Table 7.2** and summarized below.

Scenario 1: The cost of implementing a small-scale injection of the shear-thinning technology (single well, single injection event) was estimated to be approximately $40,000. Approximately 51% of this cost was associated with conventional enhanced bioremediation, 31% was associated with the extra field time for preparing the STF and injection testing, and the remaining 18% was associated with lab-scale tests and other work to support the STF formulation and design. In other words, the inclusion of STF increased the cost of conventional bioremediation by approximately a factor of 2 for this scenario. It should be noted that this cost estimate is highly scale-dependent. For example, increasing the treatment volume by a factor of 3 (i.e., 3 injection wells required) would increase the total cost to $81,000. However, the cost associated with using STF is approximately $21,000 in this case, representing an incremental cost of 34% over conventional enhanced bioremediation.

Scenario 2: For the case where the shear-thinning technology was used (at a single site at a scale similar to that used for this project) to support site closure after 5 years, the total life-cycle cost was $96,000 (or $412 per yd^3). Approximately 33% of this cost was associated with the use of the STF (including costs for lab-scale testing), while long-term monitoring represented 39% of the cost. The total life-cycle cost associated with the alterative—conventional enhanced bioremediation leading to MNA—was estimated to be $194,000 (or $834 per yd^3). For the latter option, approximately 79% of the cost was associated with long-term monitoring obligations. As a result, the total life-cycle cost of the remedy that incorporated the shear-thinning technology was 51% less than the baseline case.

The primary cost benefit of the shear-thinning technology is the decrease in the remediation timeframe for the site, which greatly reduce the long-term monitoring obligations. For the scenario evaluated here, the cost savings more than compensates for the short-term incremental costs of adding the shear-thinning polymer to the in situ bioremediation design. These benefits are largely the result of providing enhanced treatment of the contaminants in the low-k zones, such that only a short monitoring period (4 years after the end of active treatment) is required for compliance purposes. Under the alternative scenario, a 26-year period of MNA is required to ensure that mass diffusing from low-k zones has decreased below the acceptable endpoint. An additional cost benefit of the shear-thinning technology is the reduction in the number of injection events to complete the active treatment phase.

Table 7.2. Summary of Cost Modeling Results

COST ELEMENT	SCENARIO 1	SCENARIO 2	
	Single Injection of STF (Duration = 3 days)	STF Injections Followed by Site Closure (Duration = 5 years)	Conventional Amendment Injections Followed by MNA (Duration = 30 years)
TASK 1. Laboratory Study and Amendment Selection	$6,200	$6,200	$0
TASK 2. Conventional In Situ Bioremediation	$17,444	$23,259	$34,889
TASK 3. Shear-Thinning Fluid Preparation and Injection (costs beyond conventional in situ bioren	$10,736	$21,472	$0
TASK 4. Modeling	$0	$0	$0
TASK 5. Other Characterization/Reporting in Support of Remedy Selection/Design	$0	$0	$0
TASK 6. Well Installation (monitoring wells, injection wells, extraction wells)	$0	$0	$0
TASK 7. Treatment System Design and Installation	$0	$0	$0
TASK 8. Treatment System Operations and Maintenance	$0	$0	$0
TASK 9. Long-Term Monitoring	$0	$32,310	$133,860
TASK 10. Closeout and Decomissioning	$0	$0	$0
TASK 11. Final Reporting	$0	$0	$0
CONTINGENCY (15%)	$5,157	$12,486	$25,312
TOTAL COST	**$39,538**	**$95,728**	**$194,061**
COST PER INJECTION LOCATION	**$39,538**	**$95,728**	**$194,061**
COST PER FT	**$1,977**	**$4,786**	**$9,703**
LIFE-CYCLE COST PER CUBIC YD TREATED	NA	**$412**	**$834**

Notes: (1) Costs were not included for tasks that are not applicable or where there were no unique costs for the STF technology relative to conventional in situ bioremediation.

7.3 Cost Drivers

The total costs of implementing this technology are primarily associated with the scale of the remediation performed at a site. Key cost drivers include the volume of the treatment zone, the injection rate for the STF, and the polymer concentration used in the STF. All of these parameters were included in the following sensitivity analysis for Scenario 1. In addition, the effect of treatment volume was evaluated for Scenario 2.

7.3.1 Sensitivity to STF Injection Rate

The baseline scenario in the cost model used an STF injection rate (30 gpm) that was identical to that for non-STF injections. This condition was met during the demonstration project, with the understanding that site-specific injection pressures may dictate using lower injection rates for the STF. This sensitivity analysis compared costs using the injection rate for an STF relative to the injection rate for a non-STF. Assuming all other inputs remained unchanged, the estimated costs associated with the STF injection rate were evaluated for Scenario 1. The results are shown in **Figure 7.1**:

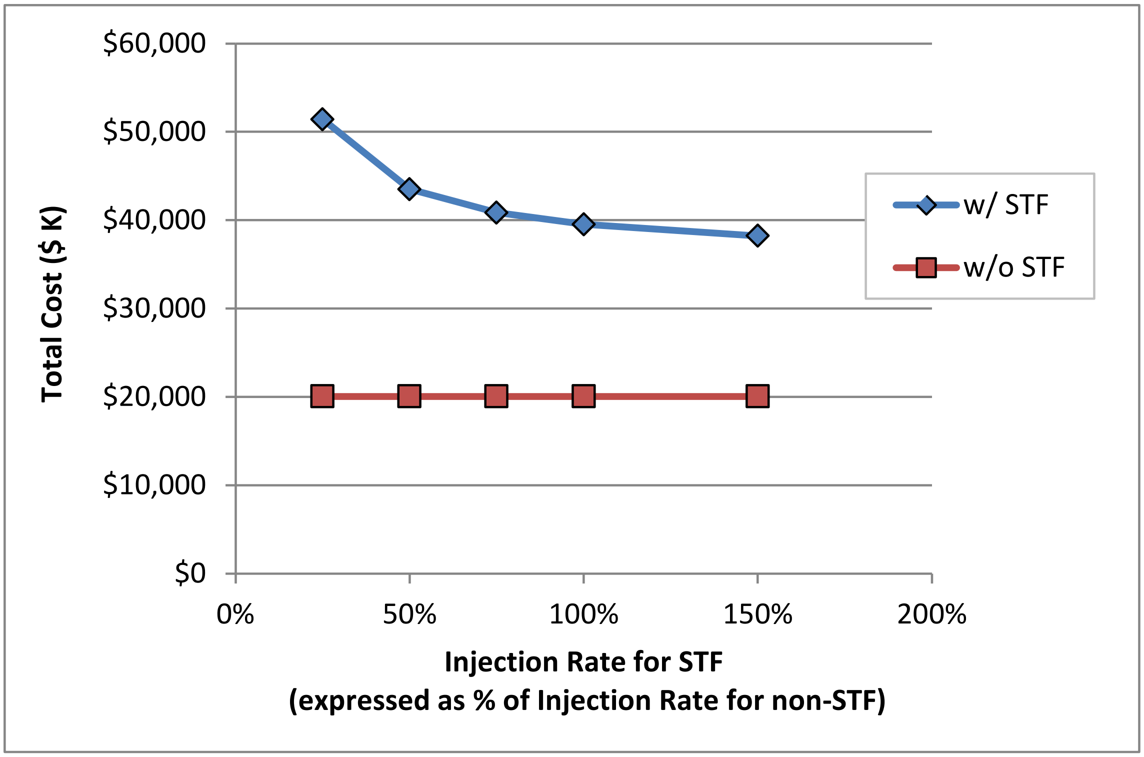


Figure 7.1. Sensitivity of cost of shear-thinning technology to injection rate (Scenario 1: single injection)

As expected, the total costs increase if the injection rate must be decreased to compensate for the inclusion of the STF. However, the cost increases are relatively marginal (10%) even if the injection rate is halved, primarily because the materials cost remain constant regardless of the injection rate. More significant changes in the cost curve can be observed when the STF injection rate decreases to 25% of the baseline rate. This injection rate corresponds to 7.5 gpm, which is on the lower-end of what would be considered technically practical for selecting injection-based in situ treatment technologies.

7.3.2 Sensitivity to Polymer Concentration

The baseline scenario in the cost model assumed that a polymer concentration of 800 mg/L was selected for the STF, i.e., the same concentration used for this demonstration project. Purchasing polymer represents an incremental cost relative to conventional bioremediation, and the results of the sensitivity analysis on this input parameter for Scenario 1 are shown in **Figure 7.2**:

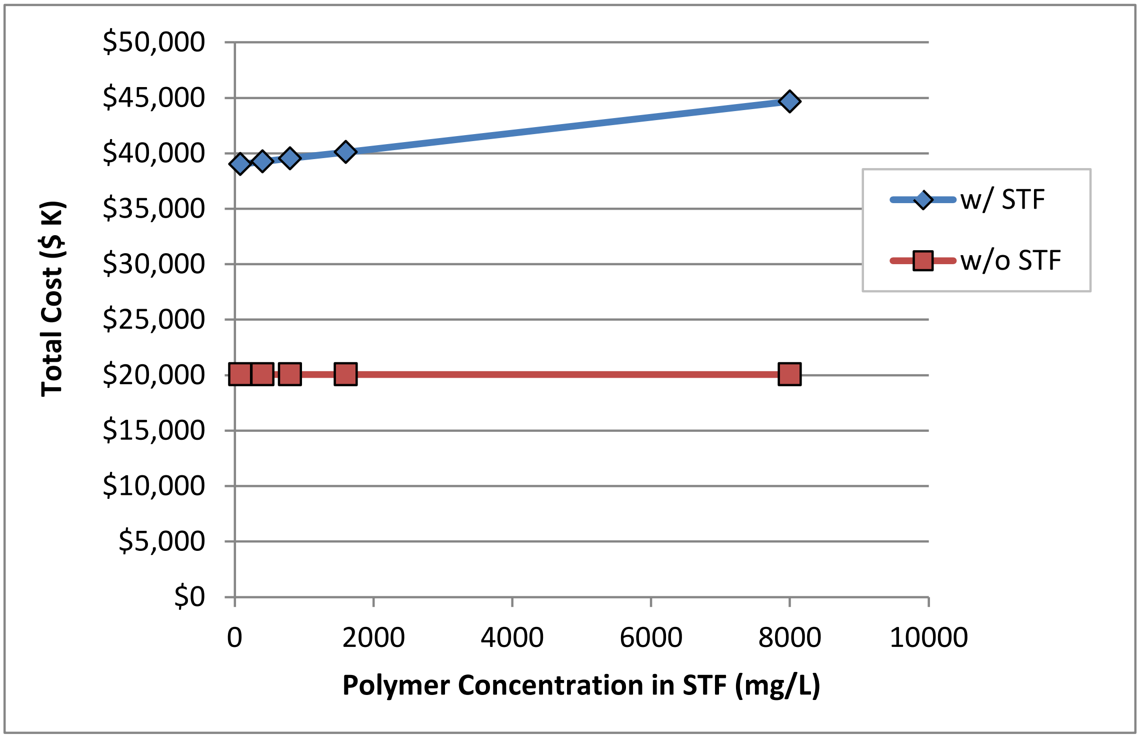


Figure 7.2. Sensitivity of cost of shear-thinning technology to polymer concentration (Scenario 1; single injection)

The cost curve clearly demonstrates that the impact of material costs on the total project costs are relatively minimal for the scenario that was evaluated. In part, this is a function of the scale of the project being considered. While site-specific considerations might dictate a higher or lower polymer concentration than the concentration used during this project, it is our experience that greater than order-of-magnitude adjustments would be unusual.

7.3.3 Sensitivity to Volume of Treatment Zone

To provide a basis for comparison to the demonstration project, the baseline scenario in the cost model assumed that the site represented a relatively small treatment volume of 6280 ft^3 (233 yd^3). The unit costs that resulted from this assumption (**Table 7.2**) are a reflection of the limited scale. At larger sites, a higher number of injection points and greater amendment quantities would be required. Larger sites would also require a more intensive monitoring program during the long-term monitoring phase of the project. The impacts of changes to the treatment volume for Scenario 1 are shown in **Figure 7.3a**, while the changes for the costs in Scenario 2 are shown in **Figure 7.3b**:

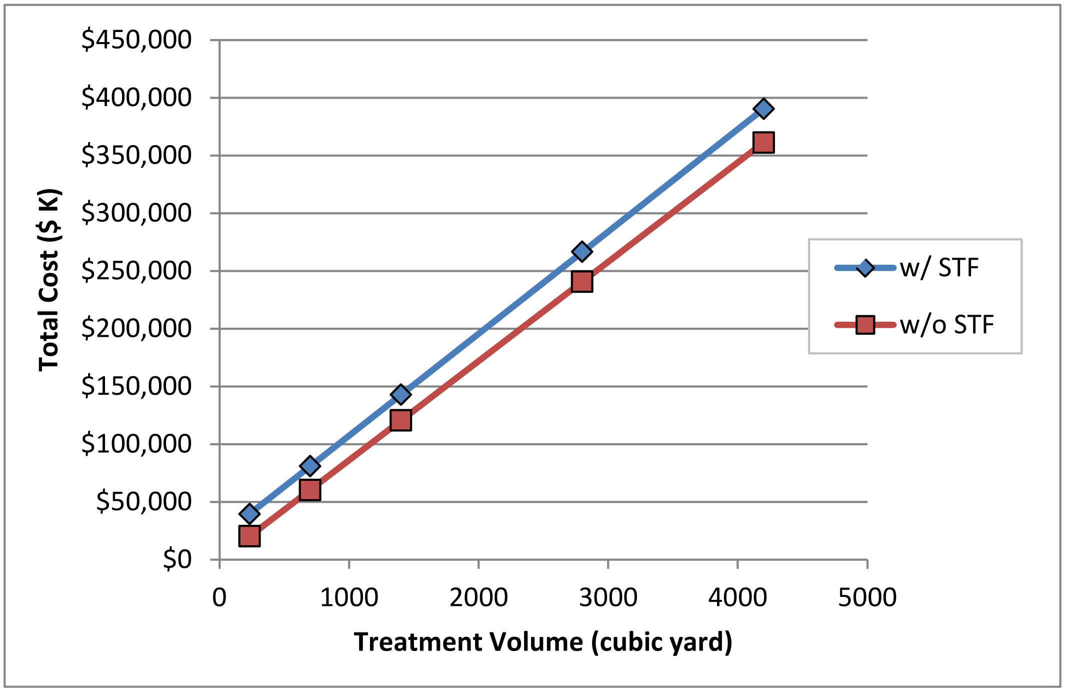


Figure 7.3a. Sensitivity of cost of shear-thinning technology to volume of treatment zone (Scenario 1: single injection)

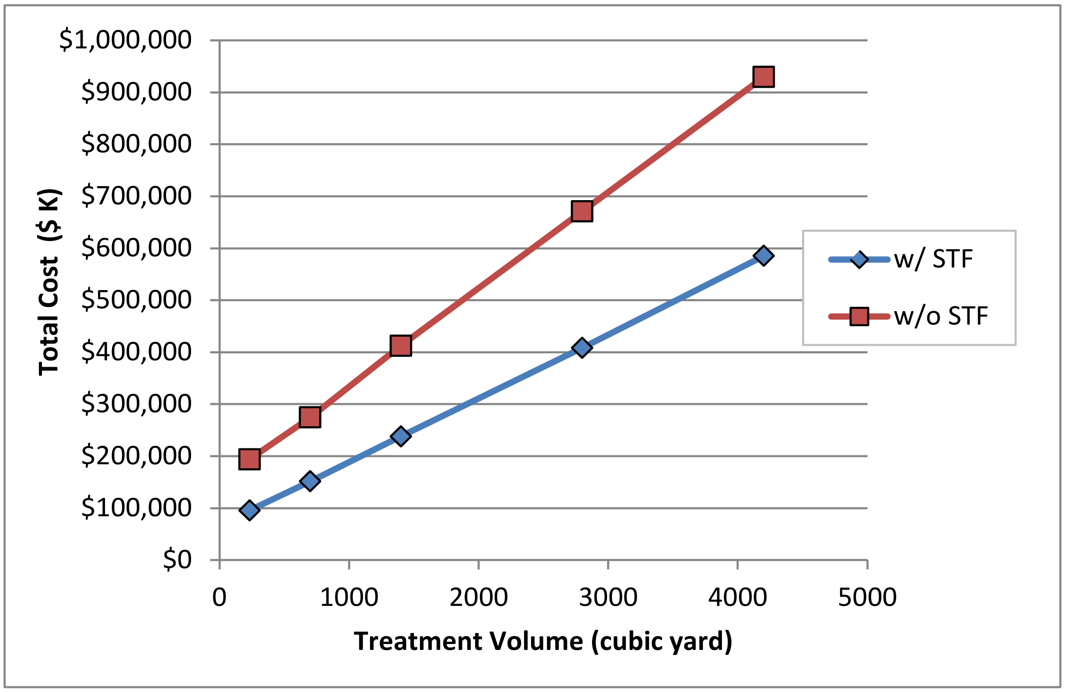


Figure 7.3b. Sensitivity of cost of shear-thinning technology to volume of treatment zone (Scenario 2: life-cycle cost comparison between 2 outcomes)

As expected, increasing the treatment volume has significant cost implications. However, relative to the baseline case, increasing the treatment volume has limited direct cost impacts for the shear-thinning technology (assuming that the similar injection rates are possible). This is because material costs, including the incremental costs from using the shear-thinning polymer (xanthan gum), represent a modest percentage of the overall project costs. In Scenario 1 (**Figure 7.3a)**, the marginal difference in the slopes between the baseline case vs. the STF injection reflects that changes in treatment volume have a similar influence over both cases.

For Scenario 2 (**Figure 7.3b**), there is always a life-cycle cost savings when the STF is used. The incremental cost savings becomes progressively higher when the size of the site increases from the combined effects of fewer injection events and a shorter monitoring period. When the cost savings is expressed as a percent of total cost, the effect diminishes at larger sites. This is because the shorter-term costs associated with the treatment itself represent a larger portion of the total costs as the treatment volume increases, while the longer-term beneficial effects of the STF (reduced monitoring costs) become a less important cost driver.

8.0 IMPLEMENTATION ISSUES

8.1 Regulations and Permits

The project demonstrated the use of shear-thinning fluids to improve subsurface distribution of remedial amendments. Shear-thinning fluids are generally food-grade organic compounds and similar in nature to substrates used for enhanced bioremediation. Consequently, the regulatory issues associated with full-scale technology implementation are the same as those for enhanced bioremediation. Given the familiarity of enhanced bioremediation to most federal and state agencies, there are not expected to be significant regulatory impediments to using the technology.

In many cases, an underground injection control (UIC) permit may be necessary when using the shear-thinning technology, particularly if groundwater recirculation is used in the design. The technology does not result in discharge of wastewater or discharge to air. Waste generation is minimal and primarily related to the installation of injection and/or monitoring wells. As with most technologies involving injection of chemicals to the subsurface, every effort should be taken to inject the entire volume of the prepared fluid.

8.2 End-User Concerns

The shear-thinning technology is aimed at improving treatment within lower permeability zones of heterogeneous subsurface environments. These low-k zones represent a major challenge for remediation because they contribute to long-term mass storage yet are difficult to treat using injection-based technologies. The increasing use of high-resolution characterization methods has provided evidence of significant heterogeneity at sites that might otherwise have been considered relatively homogeneous. Therefore, the shear-thinning technology is expected to be applicable at a wide variety of sites where enhanced bioremediation is being used or considered, particularly those with low-k strata in contact with (or embedded in) the targeted groundwater bearing unit.

Acceptance of this technology requires that end-users can achieve distribution of amendment into lower-permeability zones using a remedial design that is safe and effective. It will not be effective is used to directly inject solutions into low-k materials (e.g., clays). Instead, the use of a shear-thinning fluid promotes cross-flow from high-k zones into zones (except near the injection well). Cross flow is less effective in moving fluid into the low-k layer as the distance from the low-high permeability interface increases. Thus, the effectiveness is dependent on the thickness of the low-k layer (or lens) that is being targeted. Amendments will be more difficult to distribute to the center of thicker layers. However, there may be applications where distributing the amendment along a thin interface of a thick low-k layer would be effective for reducing matrix diffusion. While site-specific conditions and treatment goals should always dictate remedial decision-making, a rule of thumb would be to target aquifers with permeability contrasts less than two orders of magnitude and/or for low-k layers thinner than about 0.5 m if distribution to the center of the layer is necessary to meet goals. This permeability contrast would be equivalent to silt layers present within a sand matrix, but not clay layers. A similar recommendation is reported by Crimi et al (2013) in their demonstration of shear-thinning polymers in combination with chemical oxidants.

In terms of delivery material to the subsurface, shear-thinning fluids are injected at a relatively high velocity compared to natural groundwater flow velocities, such that the shear-thinning nature of the solution allows it to flow readily. An estimate should be made of the injection pressure at the design injection flow rate, or for a range of possible injection flow rates, for water-only injection. A water-only injection test or from step-drawdown and constant rate extraction test can be used to obtain expected injection pressures. The injection pressure for the STF will be this baseline injection pressure multiplied by the viscosity of the STF under the injection conditions. There is typically high shear rate near the injection well, such that an upper bound for the viscosity is the measured viscosity at a shear rate of 150/s. In the field, observed initial pressure increases from STF have been only about 20% of this value, although the injection pressure increases with time. Thus, this range of injection pressures should be considered in the design. For the current demonstration, average injection pressures for the shear-thinning fluid over the course of the test was similar to those for water solutions, but there was an evident increase over time for the former case. For all applications of this technology, it is recommended to monitoring pressure continuously and use a pre-determined maximum pressure limit based on system constraints. If field pressures approach this limit, pressure can be decreased by decreasing the injection flow rate.

If injection pressure becomes a limiting factor, then the rheological properties (i.e., viscosity) of the STF can be modified. Viscosity is needed to induce distribution of amendment into low-k layers (e.g., through the cross flow phenomena), and in general, higher viscosity leads to more cross flow between layers. However, there are diminishing returns as the viscosity of the injection fluid increases. More detailed modeling approaches are available to support more thorough site-specific assessments (Silva et al., 2012; Oostrom et al., 2014), though it may be difficult to explicitly model some sites due to uncertainties in the actual layer permeability contrasts and the configuration of layering. Given this limitation, a rule of thumb is to use a static viscosity of near 100 cP for the STF when applying the technology.

Shear-thinning fluids increase in viscosity after the injection (shear force) is completed, and this property increases their persistence in the subsurface and promotes sustained treatment. In some cases, end-users may be concerned about long-lasting secondary effects on groundwater quality. However, these shear-thinning fluid mixtures are not infinitely stable and can be expected to decrease in viscosity over the course of weeks to months. The STF formulation used in this demonstration was persistent over 8 months, but there was no evidence of excessive deterioration of groundwater quality (e.g., acidification, biofouling).

As noted above, the inherent similarity of the technology to conventional in situ bioremediation should help to minimize potential end-user concerns. The primary difference is that the amendment formulation includes a polymer that must be mixed into the injection solution.

Injection designs already familiar to most site managers (e.g., injection wells configured in a grid or barrier pattern) are also applicable to this technology.

8.3 Procurement

There are no procurement issues related to the use of this technology. Materials, including shear-thinning polymers, are readily available and relatively similar to those already familiar to environmental remediation professionals. There are a number of technology specialists and other service providers that are experienced at designing and performing these types of injections.

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APPENDIX A:
POINTS OF CONTACT
Enhanced Amendment Delivery to Low Permeability Zones for Chlorinated Solvent Source Area Bioremediation

Environmental Security and Technology Certification Program (ESTCP)
Project ER-200913

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APPENDIX B

Groundwater Sampling Results and Characterization Data

TABLE B.1
RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PRE-TEST CHARACTERIZATION, AUGUST 2013
ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	MW1	MW2	C1A	C1A	C1B	C1C	C2A	C2B	C2C
SAMPLE ID:	T1	T2	T3	T4 (Dup of T3)	T5	T6	T7	T8	T9
SAMPLE DATE:	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound									
Chloroform	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	0.0052J	<0.005
Dichloroethane, -1,1	<0.001	<0.001	0.0007J	0.00068J	<0.001	<0.001	0.00078J	0.00035J	<0.001
Dichloroethene, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,2-cis	0.004	0.0041	0.027	0.028	0.0061	0.0068	0.045	0.012	0.0043
Dichloroethene, -1,2-trans	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.005	<0.005	0.0014J	0.0012J	<0.005	<0.005	<0.005	<0.005	0.001J
Trichloroethane, -1,1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Trichloroethene	0.011	0.0076	0.0019	0.0021	0.0079	0.013	0.0086	0.0075	0.0078
Vinyl chloride	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inorganic Ions									
Chloride (mg/L)	--	--	--	--	--	--	--	--	--
Bromide (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1	<1
Sulfate (mg/L)	13	12	34	43	95	72	78	120	26
Organic Carbon									
Total Organic Carbon (mg/L)	0.62	0.46	6.8	6.8	10	5.5	12	22	4.6
Dissolved Gases									
Methane (mg/L)	<0.01	<0.01	0.024	0.03	0.027	0.024	0.027	0.031	0.016
Ethene (mg/L)	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	0.018	<0.013	<0.013

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.1
RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PRE-TEST CHARACTERIZATION, AUGUST 2013
ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	C1D	C3A	C3B	C3C	C3D	C3D	MW3	DG1
SAMPLE ID:	T10	T11	T12	T13	T14	T15 (Dup of T14)	T16	T17
SAMPLE DATE:	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013	8/25/2013
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound								
Chloroform	<0.005	<0.005	<0.005	0.0003J	03.0004J	0.0004J	<0.005	<0.005
Dichloroethane, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,2-cis	0.0085	0.0044	0.0077	0.0089	0.0062	0.0051	0.0055	0.0013
Dichloroethene, -1,2-trans	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Trichloroethane, -1,1,1	<0.001	<0.001	<0.001	<0.001	0.0006J	0.0005J	<0.001	<0.001
Trichloroethene	0.0042	0.0009J	0.014	0.027	0.028	0.026	0.014	0.005
Vinyl chloride	<0.001	0.0023	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inorganic Ions								
Chloride (mg/L)	--	--	--	--	--	--	--	--
Bromide (mg/L)	<1	<1	<1	<1	<1	<1	<1	<1
Sulfate (mg/L)	61	24	200	74	52	62	16	8.4
Organic Carbon								
Total Organic Carbon (mg/L	5.1	6.1	21	13	7.9	10	0.63J	0.48J
Dissolved Gases								
Methane (mg/L)	0.015	0.04	0.021	0.021	0.02	0.015	<0.010	<0.010
Ethene (mg/L)	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.1

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PRE-TEST CHARACTERIZATION, AUGUST 2013

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	C2D	DA31	DG3	DG2	C2D
SAMPLE ID:	T18	T19	T20	T21	T22
SAMPLE DATE:	8/26/2013	8/26/2013	8/26/2013	8/26/2013	8/26/2013
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound					
Chloroform	<0.005	<0.005	<0.005	<0.005	0.007J
Dichloroethane, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,2-cis	0.0012	0.0004J	0.0045	<0.001	0.0013
Dichloroethene, -1,2-trans	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.005	<0.005	<0.005	<0.005	0.0009J
Trichloroethane, -1,1,1	<0.001	<0.001	<0.001	<0.001	<0.001
Trichloroethene	<0.001	0.0094	0.0011	0.0099	0.0006J
Vinyl chloride	<0.001	<0.001	<0.001	<0.001	<0.001
Inorganic Ions					
Chloride (mg/L)	--	--	--	--	--
Bromide (mg/L)	--	<1	<1	<1	<1
Sulfate (mg/L)	--	8.1	8.6	6.7	110
Organic Carbon					
Total Organic Carbon (mg/L)	--	0.46J	0.95J	0.49J	23
Dissolved Gases					
Methane (mg/L)	<0.01	<0.01	<0.01	<0.01	0.012
Ethene (mg/L)	<0.013	<0.013	<0.013	<0.013	<0.013

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.2

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - POST-TEST CHARACTERIZATION, SEPTEMBER 2013

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	DA-35	DA-34	DA-31	INJ	C2D	MW1	C1A	MW2	MW3
SAMPLE ID:	X138	X140	X139	X141	X142	X143	X144	X145	X146
SAMPLE DATE:	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound									
Chloroform	<0.005	<0.005	<0.005	0.0022	0.0017	0.0029	0.001	0.0008	0.0012J
Benzene	<0.001	<0.001	<0.001	<0.001	0.00038	<0.001	<0.001	<0.001	<0.001
Dichloroethane, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.00077	0.00031	0.00032J
Dichloroethene, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,2-cis	0.0023	0.0049	0.00071	<0.001	0.0011	0.0073	0.04	0.018	0.016
Dichloroethene, -1,2-trans	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.005	<0.005	<0.005	<0.005	0.0016	<0.005	0.0011	<0.005	0.00091J
Trichloroethane, -1,1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Trichloroethene	0.0023	0.017	0.013	0.00069	<0.001	0.004	0.001	0.019	0.015
Vinyl chloride	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inorganic Ions									
Chloride (mg/L)	--	--	--	--	--	--	--	--	--
Bromide (mg/L)	0.89	0.24	<1	<10	36	12	40	25	14
Sulfate (mg/L)	8.5	7.3	8	<50	320	18	5	9.8	8.7
Organic Carbon									
Total Organic Carbon (mg/L)	0.65	0.38	0.45	1100	450	780	380	22	230
Dissolved Gases									
Methane (mg/L)	<0.01	<0.01	<0.01	<0.01	0.036	<0.01	<0.01	<0.01	<0.01
Ethane (mg/L)	<0.013	<0.013	<0.013	<0.013	0.006	<0.013	<0.013	<0.013	<0.013
Ethene (mg/L)	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.2

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - POST-TEST CHARACTERIZATION, SEPTEMBER 2013

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	C1B	DG1	C2A	C1C	C2B	C2B	C1D	C2C
SAMPLE ID:	X147	X148	X149	X150	X151	152 (Dup of X15	X153	X154
SAMPLE DATE:	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013	9/25/2013
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound								
Chloroform	0.0024J	<0.005	0.0042J	0.0027	0.0036	0.0036	0.0025	0.0038
Benzene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethane, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,2-cis	0.0046	0.0074	0.011	0.00077	0.0012	0.0011	0.00043	0.0013
Dichloroethene, -1,2-trans	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	0.00079J	<0.005	<0.005	0.0009	<0.005	<0.005	<0.005	<0.005
Trichloroethane, -1,1,1	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Trichloroethene	0.0029	0.014	0.0076	0.0011	0.0018	0.0019	0.00064	0.0025
Vinyl chloride	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Inorganic Ions								
Chloride (mg/L)	--	--	--	--	--	--	--	--
Bromide (mg/L)	6.4	65	<10	2.1J	5.9J	3.9J	1.8J	8.9J
Sulfate (mg/L)	8.9	86	3.8J	3.9J	14J	5.9J	2.8J	56
Organic Carbon								
Total Organic Carbon (mg/L)	920	43	1600	1000	1000	1100	1200	980
Dissolved Gases								
Methane (mg/L)	<0.01	<0.01	0.021	<0.01	0.02	<0.01	<0.01	<0.01
Ethane (mg/L)	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013
Ethene (mg/L)	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013	<0.013

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.2

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - POST-TEST CHARACTERIZATION, SEPTEMBER 2013

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	C3A	C3B	C3C	C3D
SAMPLE ID:	X155	X156	X157	X158
SAMPLE DATE:	9/25/2013	9/25/2013	9/25/2013	9/25/2013
PARAMETER	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound				
Chloroform	0.00041	0.0023	0.0034	0.00049
Benzene	<0.001	<0.001	<0.001	<0.001
Dichloroethane, -1,1	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,1	<0.001	<0.001	<0.001	<0.001
Dichloroethene, -1,2-cis	0.003	0.0096	0.0046	0.0017
Dichloroethene, -1,2-trans	<0.001	<0.001	<0.001	<0.001
Toluene	<0.005	<0.005	<0.005	<0.005
Trichloroethane, -1,1,1	<0.001	<0.001	<0.001	0.00044
Trichloroethene	0.00048	0.012	0.011	0.0058
Vinyl chloride	0.0027	<0.001	<0.001	<0.001
Inorganic Ions				
Chloride (mg/L)	--	--	--	--
Bromide (mg/L)	45	38	14	17
Sulfate (mg/L)	2.2J	31J	23J	47
Organic Carbon				
Total Organic Carbon (mg/L)	23	360	710	12
Dissolved Gases				
Methane (mg/L)	<0.01	<0.01	<0.01	0.019
Ethane (mg/L)	<0.013	<0.013	<0.013	<0.013
Ethene (mg/L)	<0.013	<0.013	<0.013	<0.013

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.3

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PERFORMANCE MONITORING, FEBRUARY 2014

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	DG-3	DG-2	DG-2	DA-31	INJ	C2D	MW1	C1A	MW2
SAMPLE ID:	DA-35	DA-34	DUP-1	DA-31	INJ-1	C2D	MW-1	C1A	MW-2
SAMPLE DATE:	2/4/2014	2/3/2014	2/3/2014	2/3/2014	2/4/2014	2/3/2014	2/3/2014	2/3/2014	2/4/2014
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound									
Acetone	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Acrolein	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089
Chloroform	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Benzene	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033
Dichloroethane, -1,1	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	0.00038 J	0.00059 J	0.00035 J
Dichloroethene, -1,1	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Dichloroethene, -1,2-cis	0.0031	<0.00026	<0.00026	0.00048 J	0.0058	0.002	0.043	0.034	0.036
Dichloroethene, -1,2-trans	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
2-Butanone (MEK)	<0.0039	<0.0039	<0.0039	<0.0039	0.0097 J	0.028	<0.0039	<0.0039	0.014
Naphthalene	0.0014 J	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078
Trichloroethane, -1,1,1	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Trichloroethene	0.0013	0.018	0.018	0.016	<0.0004	0.00048 J	<0.0004	0.00086 J	0.0010
Vinyl chloride	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026
Inorganic Ions									
Chloride (mg/L)	3.8	3.9	3.5	3.7	19	56	28	16	36
Bromide (mg/L)	0.72 J	<0.079	<0.079	<0.079	1.7	22	28	52	24
Sulfate (mg/L)	7.3	6.2	6.0	7.4	<0.077	22	<0.077	0.65 J	0.094 J
Organic Carbon									
Total Organic Carbon (mg/L)	0.58 J	0.11 J	0.21 J	0.20 J	98	56	100	19	200
Dissolved Gases									
Methane (mg/L)	<0.0029	<0.0029	<0.0029	<0.0029	0.2	0.037	<0.0029	<0.0029	<0.0029
Ethane (mg/L)	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	0.0078 J	<0.0041	<0.0041	<0.0041
Ethene (mg/L)	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.3

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PERFORMANCE MONITORING, FEBRUARY 2014

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	C1B	C1B	DG1	C2A	C1C	C2B	C1D	C2C
SAMPLE ID:	C1B	DUP-2	DA-33	C2A	C1C	C2B	C1D	C2C
SAMPLE DATE:	2/3/2014	2/3/2014	2/4/2014	2/4/2014	2/3/2014	2/4/2014	2/3/2014	2/4/14
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound								
Acetone	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Acrolein	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089
Chloroform	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Benzene	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033
Dichloroethane, -1,1	0.00038 J	0.00038 J	<0.00026	<0.00026	0.00033 J	0.00036 J	<0.00026	<0.00026
Dichloroethene, -1,1	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Dichloroethene, -1,2-cis	0.036	0.037	0.0018	0.015	0.029	0.024	0.0054	0.012
Dichloroethene, -1,2-trans	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
2-Butanone (MEK)	<0.0039	<0.0039	<0.0039	0.0074 J	0.0062 J	0.067	0.014	0.0078 J
Naphthalene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078	0.00096 J
Trichloroethane, -1,1,1	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Trichloroethene	0.00060 J	0.00058 J	0.0042	0.00070 J	<0.0004	0.00051 J	<0.0004	<0.0004
Vinyl chloride	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026
Inorganic Ions								
Chloride (mg/L)	34	34	3.7	30	52	63	34	21
Bromide (mg/L)	31	31	0.96 J	8.0	22	17	5.3	4
Sulfate (mg/L)	<0.077	<0.077	7.3	<0.077	0.47 J	<0.077	0.80 J	<0.077
Organic Carbon								
Total Organic Carbon (mg/L)	170	160	3.3	120	240	380	210	120
Dissolved Gases								
Methane (mg/L)	0.048	0.053	<0.0026	0.23	0.070	0.13	0.17	0.21
Ethane (mg/L)	<0.0041	<0.0041	<0.0041	0.0090 J	<0.0041	<0.0041	<0.0041	<0.0041
Ethene (mg/L)	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.3

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PERFORMANCE MONITORING, FEBRUARY 2014

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	DA-32	C3A	C3B	C3C	C3D
SAMPLE ID:	DA-32	C3A	C3B	C3C	C3D
SAMPLE DATE:	2/4/2014	2/4/2014	2/4/2014	2/4/2014	2/4/2014
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound					
Acetone	0.047 J	<0.01	<0.01	<0.01	<0.01
Acrolein	0.06	<0.0089	<0.0089	<0.0089	<0.0089
Chloroform	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Benzene	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033
Dichloroethane, -1,1	<0.00026	<0.00026	0.00037 J	0.00035 J	0.00047 J
Dichloroethene, -1,1	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Dichloroethene, -1,2-cis	0.034	0.0081	0.047	0.026	0.02
Dichloroethene, -1,2-trans	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
2-Butanone (MEK)	0.12	<0.0039	0.046	<0.0039	<0.0039
Naphthalene	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.00078	<0.00078	<0.00078	<0.00078	<0.00078
Trichloroethane, -1,1,1	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Trichloroethene	0.00062 J	0.00096 J	<0.0004	0.011	0.011
Vinyl chloride	0.00089 J	0.003	<0.00026	<0.00026	<0.00026
Inorganic Ions					
Chloride (mg/L)	18	15	52	17	18
Bromide (mg/L)	16	51	35	52	66
Sulfate (mg/L)	6	6.7	0.71 J	0.22 J	0.14 J
Organic Carbon					
Total Organic Carbon (mg/L)	510	22	290	95	47
Dissolved Gases					
Methane (mg/L)	5.8	0.024	0.077	<0.0029	<0.0029
Ethane (mg/L)	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041
Ethene (mg/L)	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.

TABLE B.4

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PERFORMANCE MONITORING, MAY 2014

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	DA-35	DA-34	DG1	DA-31	INJ	MW1	C1A	MW2
SAMPLE ID:	DA-35	DA-34	DA-33	DA-31	INJ-1	MW-1	C1A	MW-2
SAMPLE DATE:	5/22/2014	5/21/2014	5/22/2014	5/21/2014	5/21/2014	5/21/2014	5/21/2014	5/21/2014
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound								
Acetone	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Acrolein	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089
Chloroform	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Benzene	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033
Dichloroethane, -1,1	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026
Dichloroethene, -1,1	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Dichloroethene, -1,2-cis	0.001	<0.00026	<0.00026	0.0018	0.0079	0.042	0.027	0.026
Dichloroethene, -1,2-trans	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
2-Butanone (MEK)	<0.0039	<0.0039	<0.0039	<0.0039	<0.0039	<0.0039	<0.0039	0.028
Naphthalene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078
Trichloroethane, -1,1,1	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Trichloroethene	<0.0004	0.013	0.0039	0.014	<0.0004	<0.0004	<0.0004	<0.0004
Vinyl chloride	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026
Inorganic Ions								
Chloride (mg/L)	5.6	2.7	3.2	3.4	4	22	13	31
Bromide (mg/L)	<0.079	<0.079	0.74 J	<0.079	0.48 J	23	45	21
Sulfate (mg/L)	8.7	7.2	17	10	5.8	<0.077	1.5 J	0.26 J
Organic Carbon								
Total Organic Carbon (mg/L)	0.37 J	0.48 J	0.48 J	0.51 J	2.8	32	9.1	140
Dissolved Gases								
Methane (mg/L)	0.022	<0.0029	<0.0029	<0.0029	0.025	0.25	0.21	0.31
Ethane (mg/L)	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041
Ethene (mg/L)	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.
4. Wells DA-32 and MW-3 were not sampled during this event.

TABLE B.4

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PERFORMANCE MONITORING, MAY 2014

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	C2D	C1B	C2A	C1C	C2B	C2B	C1D	C2C
SAMPLE ID:	C2D	C1B	C2A	C1C	C2B	DUP-1	C1D	C2C
SAMPLE DATE:	5/21/2014	5/21/2014	5/21/2014	5/21/2014	5/21/2014	5/21/2014	5/21/2014	5/21/2014
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound								
Acetone	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Acrolein	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089
Chloroform	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Benzene	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033
Dichloroethane, -1,1	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026
Dichloroethene, -1,1	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Dichloroethene, -1,2-cis	0.0058	0.042	0.01	0.024	0.026	0.026	0.0069	0.01
Dichloroethene, -1,2-trans	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
2-Butanone (MEK)	0.046	<0.0039	<0.0039	<0.0039	0.05	0.045	0.012	<0.0039
Naphthalene	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078
Trichloroethane, -1,1,1	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Trichloroethene	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Vinyl chloride	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026
Inorganic Ions								
Chloride (mg/L)	59	35	18	33	48	47	18	12
Bromide (mg/L)	18	26	4.2	17	18	18	3.5	0.89 J
Sulfate (mg/L)	3.6 J	0.17 J	<0.077	0.48 J	<0.077	<0.077	0.41 J	<0.077
Organic Carbon								
Total Organic Carbon (mg/L)	230	97	43	100	160	160	69	40
Dissolved Gases								
Methane (mg/L)	1.3	0.64	1.8	1.7	5.1	6.1	1.7	2.8
Ethane (mg/L)	0.0067 J	<0.0041	0.011 J	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041
Ethene (mg/L)	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.
4. Wells DA-32 and MW-3 were not sampled during this event.

TABLE B.4

RESULTS OF GROUNDWATER ANALYSIS: SUMMARY OF DETECTED COMPOUNDS - PERFORMANCE MONITORING, MAY 2014

ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

LOCATION ID:	C3A	C3B	C3C	C3D	C3D
SAMPLE ID:	C3A	C3B	C3C	DUP-2	C3D
SAMPLE DATE:	5/22/2014	5/22/2014	5/22/2014	5/22/2014	5/22/2014
PARAMETER	mg/L	mg/L	mg/L	mg/L	mg/L
Volatile Organic Compound					
Acetone	<0.01	<0.01	<0.01	<0.01	<0.01
Acrolein	<0.0089	<0.0089	<0.0089	<0.0089	<0.0089
Chloroform	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Benzene	<0.00033	<0.00033	<0.00033	<0.00033	<0.00033
Dichloroethane, -1,1	<0.00026	<0.00026	<0.00026	<0.00026	<0.00026
Dichloroethene, -1,1	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
Dichloroethene, -1,2-cis	0.0095	0.034	0.017	0.021	0.02
Dichloroethene, -1,2-trans	<0.0004	<0.0004	<0.0004	<0.0004	<0.0004
2-Butanone (MEK)	<0.0039	0.13	<0.0039	<0.0039	<0.0039
Naphthalene	<0.001	<0.001	<0.001	<0.001	<0.001
Toluene	<0.0078	<0.0078	<0.0078	<0.0078	<0.0078
Trichloroethane, -1,1,1	<0.00032	<0.00032	<0.00032	<0.00032	<0.00032
Trichloroethene	<0.0004	<0.0004	0.0071	0.0017	0.0019
Vinyl chloride	0.0034	<0.00026	<0.00026	<0.00026	<0.00026
Inorganic Ions					
Chloride (mg/L)	9.4	56	6	11	10
Bromide (mg/L)	100	30	30	45	45
Sulfate (mg/L)	0.50 J	<0.077	2.2 J	0.64 J	0.35 J
Organic Carbon					
Total Organic Carbon (mg/L)	3.3	320	14	19	19
Dissolved Gases					
Methane (mg/L)	0.14	0.87	0.083	0.05	0.067
Ethane (mg/L)	<0.0041	<0.0041	<0.0041	<0.0041	<0.0041
Ethene (mg/L)	<0.0043	<0.0043	<0.0043	<0.0043	<0.0043

Notes:

1. Non-detect results reported as less than the sample detection limit (SDL).
2. J = Estimated value below the lowest calibration point. Confidence correlates with concentration.
3. Volatile Organic Compounds analyzed following EPA Method 8260B.
   Ethene and methane were analyzed by RSK 175, inorganic ions were analyzed by EPA 300.0, and volatile fatty acids by SM5560.
4. Wells DA-32 and MW-3 were not sampled during this event.

APPENDIX C

Soil Boring Logs and Well Construction Diagrams (field sketches)

TABLE C.1
CONSTRUCTION DETAILS FOR CONTINUOUS MULTICHANNEL TUBING (CMT) WELLS
ESTCP Project No. ER-0913 - Joint Base Lewis-McChord, Washington

Construction Material	Measurent Point	CMT-1 depths (ft bgs)	CMT-1 thickness (ft)	CMT-2 depths (ft bgs)	CMT-2 thickness (ft)	CMT-3 depths (ft bgs)	CMT-3 thickness (ft)
Cement Grout	Top	0	3	0	3	0	3
3/8" bentonite Chips	Top	3	37	3	36.5	3	34.3
3/8" coated bentonite Pellets	Top	40	5	39.5	5	37.3	6
20-40 Silica Sand	Center	45	1.1	44.5	1	43.3	2.3
Port #3	Center	45.6	NA	45	NA	45	NA
3/8" coated bentonite Pellets	Top	46.1	5.4	45.5	5	45.6	5.9
20-40 Silica Sand	Center	51.5	1.5	50.5	2	51.5	1
Ports # 1 and #4	Center	52.6	NA	52	NA	52	NA
3/8" coated bentonite Pellets	Top	53	7.6	52.5	7	52.5	6.9
20-40 Silica Sand	Center	60.6	1.5	59.5	1	59.4	1.1
Ports #2 and #5	Center	61.6	NA	60	NA	60	NA
3/8" coated bentonite Pellets	Top	62.1	3.4	60.5	3.1	60.5	3
20-40 Silica Sand	Top	65.5	1.5	63.6	1.8	63.5	1.5
Port #6	Center	66.1	NA	64.2	NA	64.2	NA
Port #7	Center	66.7	NA	64.7	NA	64.7	NA
3/8" coated bentonite Pellets	Top	67	2	65.4	4.6	65	4.5
Total Depth	Bottom	69	NA	70	NA	69.5	NA

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Field Boring Log and As-Built Diagram

Job No.: 6-3444
Date: 10-Aug-2013
Page: 1 of 4

Drilling Time

Rig - Up: 10:25
Drilling:
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-1
Total Depth: 69'
Client: E-STCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic 7/6
Depth to GW:
Depth after:

Project: Sheer Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.		Sand Grade	
Int. Casing		T/Sand Pack	
Screen Slot		T/Pellets	
Screen Depths		Qty. Water Added	
Sump		Centralizer(s)	

SOIL DESCRIPTION

Surface Conditions: Grassy / Golf Course Driving Range

Well Location: CMT-1

Depth ~~(ft)~~	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	Soil Description	USCS Symbol	As-Built
									0-1: Sand with cobbles, dark brown, no odor dry, topsoil w/ roots		
									1-3': sand with smaller cobbles, dark brown, no odor dry		
5									3'-4' larger cobbles w/ gravel, some dark sand, dry		
									4-6' larger cobbles w gravel and sand, dry		
									6-7' gravelly Sand and gravel, some (dark brown cobbles, dry		
10									7-10' no ~~re~~recovery		
									~~10-11.5'~~ : 10-11.5': sand w/ cobbles and gravel gray, dry, no odor (same as 6-7')		
									11.5-13': sand with cobbles and gravel, dark brown, ~~dry~~ moist, no odor		
15									13-14': sand with cobbles n gravel, dark brown		
									14-15' gravel with sand and cobbles dark gray, moist no odor		

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Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 10-Aug-2013
Page: 2 of 4

Drilling Time

Rig - Up: 10:25
Drilling:
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-1
Total Depth: 69'
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic 7/6
Depth to GW:
Depth after:

Project: Shear Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.
Int. Casing
Screen Slot
Screen Depths
Sump
Sand Grade
T/Sand Pack
T/Pellets
Qty. Water Added
Centralizer(s)

SOIL DESCRIPTION

Surface Conditions: Grassy, driving range

Well Location: CMT-1

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	Soil Description	USCS Symbol	As-Built
									15-16': cobbles w/ sand and gravel dark gray and light brown, moist		
									16-17.5': gravel with sand and cobbles wet, no odor, dark gray		
25									17.5-20': gravel with sand and cobbles (some large cobbles), wet		
									20-22.5': gravel with cobbles and sand (SG) as above, light gray and some dark gray at ~21.5', ~~moist~~ dry		
30									22.5-25': gravel with cobbles and ~~some~~ (SG) sand, smaller cobbles than ~~before~~ above		
									25-27.0: sand w/ cobbles, dark grey, dry		
35									27-30: cobbles w/ sand/clay, wet, dark grey, some large cobbles		
									30-31: cobbles and mud, light brown, liquid		
									31-33.5: cobbles with gravel and mud, wet		
									33.5-36: cobbles with gravel and mud, wet ~~dark~~ light brown		

36-38.5: cobbles with gravel and mud, wet, light brown

38.5-40: ~~cobbles with~~ gravel with cobbles, and mud light brown, no odor

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ENVIRONMENTAL

Field Boring Log and As-Built Diagram

Job No.: G3444
Date: 10-Aug-2013
Page: 3 of 4

Drilling Time

Rig - Up:	10:25
Drilling:	
Well Install.:	
Grouting:	
Standby:	
Downtime:	
Decon:	
Water:	

Boring/Well No.: CMT-1
Total Depth: 69'
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic 7"/6"
Depth to GW:
Depth after:

Project: Sheer Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.		Sand Grade	
Int. Casing		T/Sand Pack	
Screen Slot		T/Pellets	
Screen Depths		Qty. Water Added	
Sump		Centralizer(s)	

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built

SOIL DESCRIPTION

Surface Conditions: Grassy, Driving Range

Well Location: CMT-1

40-42: gravel with pebbles and cobbles and sand; dark gray, wet no odor

42-43: same as above

43-44: sand w/ some cobbles, dark brown/black, moist, no odor

44-47: same as above

47-48: gravel w/ cobbles and sand, moist dark gray, no odor

48-50: gravel w/ large cobbles, smaller cobbles at ~ 49-50', dark gray, moist, no odor

50-52': cobbles, w/ gravel and mud, dark gray moist, no odor

52-53': gravel with pebbles and sand, moist dark gray/brown, no odor

53-55': gravel with pebbles, cemented zone, unsolidated dark gray, moist, no odor

55-57: same as 52-53'

57-58': cobbles w/ gravel and mud, "soapy" liquid, light gray, no odor

58-60': gravel and sand with small cobbles moist, light gray, no odor

Depth (m): 40, 45, 50, 55, 60

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Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 10-Aug-2013
Page: 4 of 4

Drilling Time

Rig - Up: 10:25
Drilling: 13:45
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-1
Total Depth: 69'
Client: ESKP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic 7/6
Depth to GW:
Depth after:

Project: Sheer Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.		Sand Grade	
Int. Casing		T/Sand Pack	
Screen Slot		T/Pellets	
Screen Depths		Qty. Water Added	
Sump		Centralizer(s)	

Depth (m) | Sample | Moisture | Blows/ft/PP(TSF) | Dye Test | HC Odor | UV Light Resp. | Munsell Color Notation | OVA (ppm) | USCS Symbol | As-Built

SOIL DESCRIPTION

Surface Conditions: Grassy / Driving range

Well Location:

60

60-61.5': sand with gravel and rocks, dark brown moist, no odor

61.5-63 : sand with minor amount of gravel (insignificant) some occassional cobbles or rocks, dark brown moist, no odor

63-66' : sand (SG), dark brown, no odor moist

65

66-68' : gravel with sand, cobbles & mud dark brown, moist, no odor
– brown organic-matter looking like composition at 68'

68-70' : cobbles, with sand, light gray, moist, no odor

70

3

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Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 11-Aug-2013
Page: 1 of 4

Drilling Time

Rig - Up: 14:40
Drilling: 14:55
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-2
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic 7/6
Depth to GW:
Depth after:

Project: Shear Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.
Int. Casing
Screen Slot
Screen Depths
Sump
Sand Grade
T/Sand Pack
T/Pellets
Qty. Water Added
Centralizer(s)

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built
									Surface Conditions:		
									Well Location:		
									0-1: topsoil, roots, grass, sand, light brown, dry, no odor		
									1-3.5: sand, dark brown/black, some pebbles, dry no odor		
									4-7': gravel w/ cobbles and sand, dry, no odor, light gray with dark brown at ~6'		
5									7-8': sand with cobbles, dark brown, dry, no odor		
									8-10: fine sand, some pebbles, light gray, dry, no odor		
									10-10.5' - sand with cobbles, dark/black, dry, no odor		
10									11-13.5' - gravel w/ cobbles & sand, gray & brown moist, no odor		
									13.5-16' - cobbles w/ gravel & sand, dark brown/gray, moist, no odor, dark orange staining at ~15.5'		
									16-17' - cobbles w/ sand, brown, dry no odor		
15									17-18' - sand w/ cobbles, light gray & brown, dry no odor		
									18-19' - sand w/ cobbles, brown, moist, no odor		
									19-20' - gravel & sand w/ large cobbles, dark gray moist, no odor		
20											

GSI ENVIRONMENTAL

Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 11-Aug-2013
Page: 2 of 4

Drilling Time	
Rig - Up:	
Drilling:	
Well Install.:	
Grouting:	
Standby:	
Downtime:	
Decon:	
Water:	

Boring/Well No.: CMT-2
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic / 7/6
Depth to GW:
Depth after:

Project: Sheer Thinning
Location: JBLM, WA

Well Construction Specifications			
Casing Diam.		Sand Grade	
Int. Casing		T/Sand Pack	
Screen Slot		T/Pellets	
Screen Depths		Qty. Water Added	
Sump		Centralizer(s)	

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built
									Surface Conditions:		
									Well Location:		
20									20-22': cobbles with sand, light gray to dark brow, dry, no odor		
									22-24': sand (fine) with cobbles & pebbles, dark gray, dry, no odor		
									~~24-26~~': 24-25.5 - fine sand with cobbles & pebbles, dark gray to brown, dry, no odor		
25									25.5'-26: sandy clay, ~~black~~ with pebbles, black with organic matter, moist, no odor had fragments of marking tape used for locating the boring		
									26-27 - no recovery		
30									27-28'- cobbles with sand and gravel, dark/black, moist no odor		
									28-29'- gravel with pebbles, dark gray, moist, no odor		
									29-30': cobbles w/ some gravel and mud, soupy, light brown, no odor.		
35									30-32': sand coarse with pebbles, dark gray, moist no odor		
									32-34': cobbles with gravel, dark gray, wet, no odor, soupy at 33-34'		
40									34-38': cobbles with gravel and mud, gray, wet, soupy, no odor		

38-39': sand w/pebbles, dark gray/black, moist, no odor

39-40': gravel coarse w/ cobbles & pebbles, dark gray, moist, no odor

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Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 12-Aug-2013
Page: 3 of 4

Drilling Time

Rig - Up:
Drilling:
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-2
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic 7/6
Depth to GW:
Depth after:

Project: Shear Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.		Sand Grade	
Int. Casing		T/Sand Pack	
Screen Slot		T/Pellets	
Screen Depths		Qty. Water Added	
Sump		Centralizer(s)	

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built
									Surface Conditions: Grassy, Driving Range **Well Location:**		
40									40-41': cobbles w/ gravel and pebbles, dark gray, moist no odor, muddy 41-41.5': cobbles w/ pebbles, muddy, dark gray / light brown, wet, no odor 41.5-42': sand / gravel w/ pebbles, dark gray, moist/wet, no odor, unsolidated 42-43.0': cobbles w/ sand and gravel, dark gray, moist, no odor		
45									43-48': sand (fine) w/ some pebbles, dark gray w/ occasional cobble, moist, no odor unsolidated		
50									48-50': cobbles w/ sand & gravel, dark gray, moist no odor 50-54': gravel w/ pebbles, some cobbles, brown & dark gray, mud & sand, wet, no odor, increasing amount of sand at ~53-54'		
55									54-56': cobbles w/ sand, pebbles & gravel, light brown, wet, no odor, soupy/muddy at ~55.5' 56-60': gravel w/ cobbles & pebbles and sand, light gray to light brown, no odor, wet muddy/somewhat soupy at ~ 58-59'		
60											

GSI ENVIRONMENTAL

Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 12-Aug-2013
Page: 4 of 4

Boring/Well No.: CMT-2
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic / 7/6
Depth to GW:
Depth after:

Project:
Location:

Drilling Time

Rig - Up:
Drilling:
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Well Construction Specifications

Casing Diam.		Sand Grade	
Int. Casing		T/Sand Pack	
Screen Slot		T/Pellets	
Screen Depths		Qty. Water Added	
Sump		Centralizer(s)	

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built
									Surface Conditions:		
									Well Location:		
60									59.5-60': gravel with pebbles & some cobbles, ~~dark~~ light brown, wet, some [illegible] no odor		
									60-62': gravelly sand with some pebbles & cobbles, brown/dark gray, wet, no odor		
65									62-65': sand with occasional cobbles, brown to dark gray, moist, no odor, unconsolidated transitions to clayey sand at ~64-65'		
									65-67' - clayey sand with occasional cobbles, dark gray, wet, no odor, unconsolidated,		
									67-67.5' - gravelly sand with cobbles and pebbles, dark gray, no odor unconsolidated		
70									67.5-68.5' - sand, no cobbles or pebbles, dark gray no odor, moist		
									68.5-70' - sand, no cobbles or pebbles, dark/blue dark gray, moist, no odor		
3											

GSI
ENVIRONMENTAL

Field Boring Log and As-Built Diagram

Job No.: G-3444
Date: 13-Aug-2013
Page: 1 of 4

Drilling Time

Rig - Up: 7:50 AM
Drilling: 8:05 AM
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-3
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic / 7/6"
Depth to GW:
Depth after:

Project: Shear Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.
Int. Casing
Screen Slot
Screen Depths
Sump
Sand Grade
T/Sand Pack
T/Pellets
Qty. Water Added
Centralizer(s)

Depth (~~m~~) ft	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built

SOIL DESCRIPTION

Surface Conditions: Grassy / Golf Course Driving Range

Well Location:

0-2.5': fill w/ small cobbles & grass/roots brown, dry, no odor

2.5-6': sand with cobbles & pebbles, brown to light gray, dry, no odor

6-8': same as above, increasing amount of cobbles at ~6-7' with large cobbles

8-10': sand, dusty, light gray, some cobbles and pebbles, no odor

10-11' - same as above w/some brown sand

11-14': cobbles and pebbles with sand, brown with some light gray, moist, no odor, increasing amount of sand at 13-14'

14-16: same as above, except more sand and less cobbles & pebbles; brown

16-18.5': cobbles and pebbles with sand, increased amount of sand from above depths dark gray / light brown, moist, no odor

18.5-20: cobbles & gravel with sand, dark brown/gray wet, no odor

5
10
15
20

GSI ENVIRONMENTAL

Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 13-Aug-2013
Page: 2 of 4

Drilling Time	
Rig - Up:	
Drilling:	
Well Install.:	
Grouting:	
Standby:	
Downtime:	
Decon:	
Water:	

Boring/Well No.: CMT-3
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic - 7/6"
Depth to GW:
Depth after:

Project: Shear Thinning
Location: JBLM WA

Well Construction Specifications			
Casing Diam.		Sand Grade	
Int. Casing		T/Sand Pack	
Screen Slot		T/Pellets	
Screen Depths		Qty. Water Added	
Sump		Centralizer(s)	

SOIL DESCRIPTION

Surface Conditions: Grassy

Well Location:

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built
20									20-21.5': sand with cobbles & pebbles, brown, moist no odor		
									21.5-24': sand with decreasing amount of cobbles & pebbles, dark brown, moist, no odor		
									24-26.0': same as above		
25									26-27': sand with embeded cobbles and pebbles, light gray, wet, no odor, semi unconsolidated		
									27-28.5': cobbles with sand, light gray/gray, wet no odor, some consolidation at ~28'		
30									28.5-30': cobbles with gravel and sand, light brown, wet (soupy), no odor		
									30-31': cobbles at ~29' with decreasing amount of sand, dark gray, wet no odor		
35									31-39': cobbles with gravel and mud; smaller cobbles/pebbles at ~37-39', brown and dark gray, wet (soupy mud) no odor		
									39-40': gravel with pebbles & some cobbles light brown, wet (soupy), mud, no odor		
40											

GSI ENVIRONMENTAL

Field Boring Log and As-Built Diagram

Job No.: G3444
Date: 13-Aug-2013
Page: 3 of 4

Drilling Time

Rig - Up:
Drilling:
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-3
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic - 7/6"
Depth to GW:
Depth after:

Project: Shear Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.
Int. Casing
Screen Slot
Screen Depths
Sump
Sand Grade
T/Sand Pack
T/Pellets
Qty. Water Added
Centralizer(s)

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built

Surface Conditions:

Well Location:

40

40-45.0': gravel with cobbles, pebbles and sand, large cobbles at ~ 41-42'; increasing amounts of gravel + sand 42-44.5'; brown wet (some [illegible]), no odor

45-50': sand, very dark gray/black, moist no odor consolidated at ~48-49', some large cobbles at ~ 49.5' and occassional cobble throughout the interval

45

50-51': cobbles ~~and~~ with gravel/pebbles and some sand, dark gray, wet, no odor

51-55': gravel with cobbles and sand, dark gray to brown, moist, no odor, amount of sand increases at ~52.5-54'

50

55-57': cobbles w/gravel and sand and pebbles, brown to dark gray, wet, no odor

57-58.5': sand with some cobbles, dark gray, wet, no odor

55

58.5-60': sand with some cobbles at ~59', some pebbles dark brown, wet, no odor

60

GSI
ENVIRONMENTAL

Field Boring Log and As-Built Diagram

Job No.: 63444
Date: 13-Aug-2013
Page: 4 of 4

Drilling Time

Rig - Up:
Drilling:
Well Install.:
Grouting:
Standby:
Downtime:
Decon:
Water:

Boring/Well No.: CMT-3
Total Depth:
Client: ESTCP
Geologist: MR
Driller: Cascade
Method/Dia.: Sonic - 7/6"
Depth to GW:
Depth after:

Project: Shear Thinning
Location: JBLM, WA

Well Construction Specifications

Casing Diam.
Int. Casing
Screen Slot
Screen Depths
Sump
Sand Grade
T/Sand Pack
T/Pellets
Qty. Water Added
Centralizer(s)

Depth (m)	Sample	Moisture	Blows/ft/PP(TSF)	Dye Test	HC Odor	UV Light Resp.	Munsell Color Notation	OVA (ppm)	SOIL DESCRIPTION	USCS Symbol	As-Built
60 65 70 3											

Surface Conditions: Grassy, Golf course

Well Location:

60-62.5': sand with some cobbles, brown to dark gray, wet no odor, unsolidated at ~62'

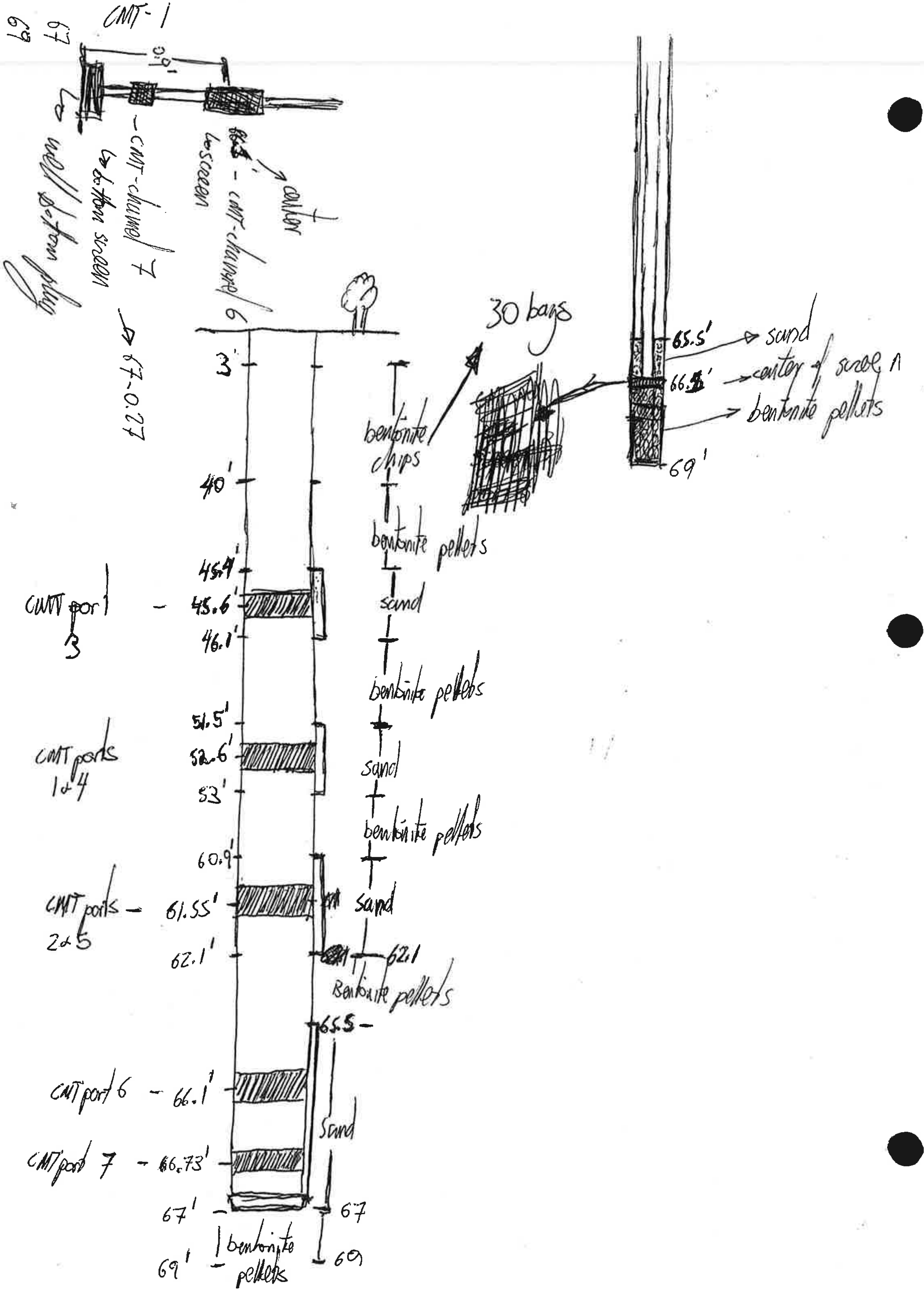
62.5-64.5': sand w/ occasional cobble, brown to dark gray, wet, no odor, unsolidated at ~63.5'

64.5-66.5' - cobbles w/ sand and gravel, dark gray, wet, no odor

66.5-68': cobbles and pebbles with sand, dark gray, wet w/ some mud ~67', no odor some consolidation at ~67.5'

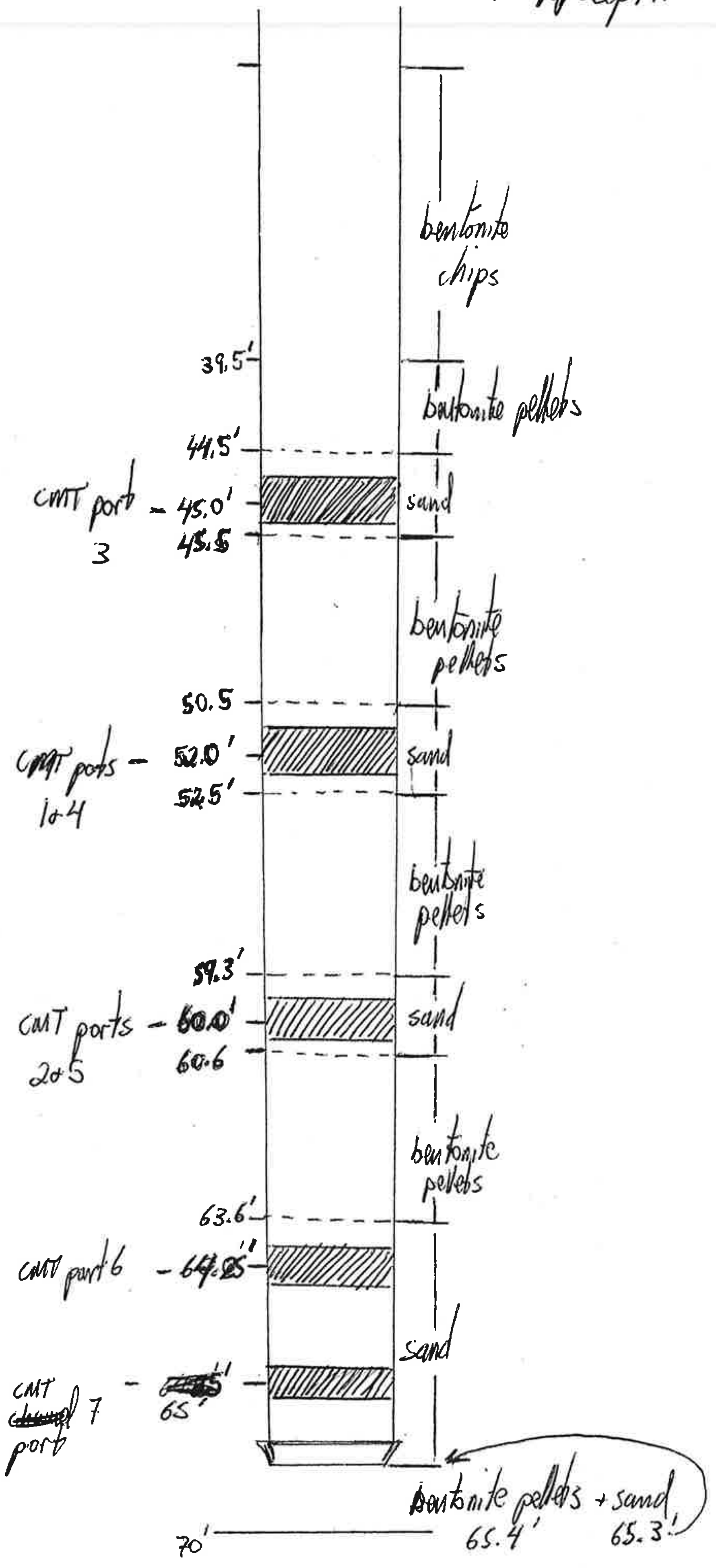
69-69: cobbles w/ clayey sand, light gray, moist no odor, consolidated, → outside of core

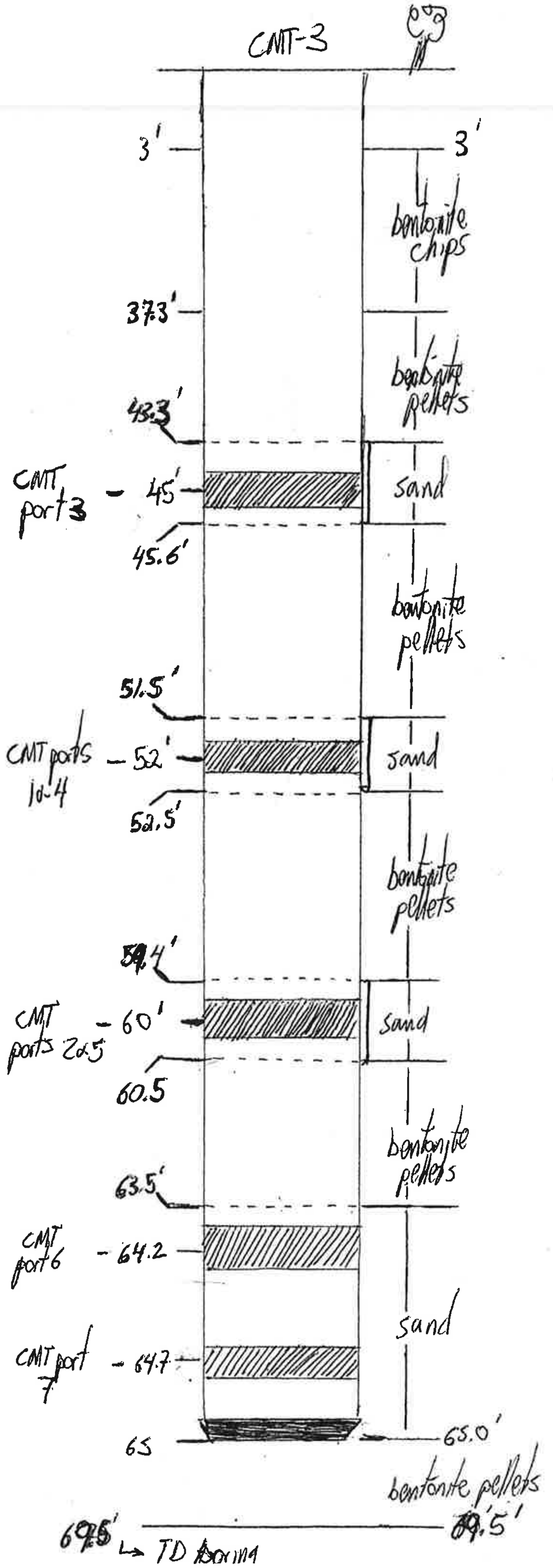
69-70': cobbles consolydated with clay/sand very hard, dark gray, no odor, → inside core inside sand bluish color; purple color deposits at ~68.5'; large cobble at 70'



CMT-1
69
67
0.61'
center
66.3 - CMT-channel 6
bo screen
- CMT-channel 7
bottom screen
well bottom plug
→ 67-0.27
30 bags
3'
40'
45.4'
CMT port 3 - 45.6'
46.1'
51.5'
CMT ports 1 & 4 52.6'
53'
60.9'
CMT ports 2 & 5 - 61.55'
62.1'
62.1
65.5
CMT port 6 - 66.1'
CMT port 7 - 66.73'
67'
69'
67
69
bentonite chips
bentonite pellets
sand
bentonite pellets
sand
bentonite pellets
sand
Bentonite pellets
Sand
bentonite pellets
65.5'
66.5'
69'
sand
center of scree n
bentonite pellets

CMT-2 → 8" casing to 40-ft
7" ~~to~~ depth



CMT-3
3'
3'
bentonite chips
37.3'
bentonite pellets
43.3'
CMT port 3 - 45'
sand
45.6'
bentonite pellets
51.5'
CMT ports 1 & 4 - 52'
sand
52.5'
bentonite pellets
59.4'
CMT ports 2 & 5 - 60'
sand
60.5
bentonite pellets
63.5'
CMT port 6 - 64.2
sand
CMT port 7 - 64.7
65
65.0'
bentonite pellets
69.5'
69.5'
↳ TD boring

APPENDIX D

Variances from Washington Department of Ecology

1. Variance Request from Washington Administrative Code (WAC) for decommissioning of a product not meeting various requirements **(August 5, 2013)**
2. Variance Request from Washington Administrative Code (WAC) for decommissioning of a product not meeting various requirements **(June 20, 2014)**

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
PO Box 47775 • Olympia, Washington 98504-7775 • (360) 407-6300

August 5, 2013

Vince R. Vermeul
Pacific Northwest National Laboratory
902 Battelle Boulevard
P.O. Box 999, MSIN K6-96
Richland, WA99352

Re: Variance request from Washington Administrative Code (WAC) for installation of a product not meeting various requirements. The property is located the U.S. Army, Join Base Lewis-McCord, Whispering Pine Golf Course, Area D disposal site, in the NE ¼ NE ¼ of Section 23, Township 19 North, Range 2 East, W.M. in Pierce County

Dear Mr. Vermeul:

You requested a waiver from various construction codes for installation of four Solinst-brand Continuous Multi-channel Tubing (CMT) monitoring well. CMT by this manufacturer and the proposed construction does not meet the following WAC for the reasons given:

- WAC 173-160-430, the casing standards for material composition are not met, and structural integrity is suspect
- WAC 173-160-444, polymers and additives are not NSF/ANSI approved, namely the plasticizer used to decrease the viscosity of the slurry used to pre-grout the unused channel space in the CMT
- WAC 173-160-450, the multiple screened areas do not provide casing stability as well as the minimum standard, a continuous seal to land surface
- WAC 173-160-451, Direct push wells shall not be greater than thirty feet in depth unless a variance is obtained.
- WAC 173-160-460, decommissioning standards will be impossible to meet due to the configuration of open area (screened interval) in each continuous channel at the point of sampling, preventing grouting to the bottom of the well Further, the manufacturer recommends against pulling the CMT, and perforating is impossible due to the honeycomb interior structure of the CMT. Based on agreement with Pacific Northwest National Laboratory and Cascade Drilling, the CMT wells will be overdrilled as a part of the decommissioning (see below for further requirements).

Department of Ecology (Ecology) received your variance request via email July 31, 2013. The request was submitted with the following:

- Decommissioning process overview published by the Solinst Canada LTD. manufacturer construction plan
- Scaled site map showing existing monitoring well network and current extent of contamination plumes, and proposed location of CMT well site.
- Letter of request describing, conceptually, groundwater occurrence and movement, geologic conditions, and presence of low-permeability layers.

The well site is within the same water table aquifer extending to about 70 feet below ground surface (bgs). Installation of these wells poses no risk of interconnecting aquifers due to target depths of installation and the areal hydrogeology. Installation shall include pre-grouting of unused channel space so decommissioning leaves no void space in any well or channel at the limits of their useful lives. Installation shall not penetrate the aquitards, or confining layer, at the base of the water table aquifer approximately 70 feet bgs. Chemical analysis suggests the superplasticizer additive does not contain constituents promoting bacteriological growth, or potential to contaminate groundwater. Use of CMT in other states (California) have shown apparent structural integrity to depths greater than 250 feet.

After an investigation, interview, and review of information available, a variance is hereby **granted** in accordance with WAC 173-160-106 to allow installation of the four (4) CMT wells at the site identified by the site map submitted with the variance request. This decision is based upon, but not limited to, the following:

1. Installation/construction of the CMT wells shall occur at site identified by the site map in the variance request.

2. The CMT wells must be installed according to the procedures outlined in the variance request. The 1.7-in OD CMT well casing must be installed within a 6-inch borehole. In order to ensure the annular space and surface seal is equidistant around the casing, the driller must install a temporary 2-inch Schedule 40 PVC well casing within the borehole and install the CMT casing within the PVC to keep it rigid, centralized, and plumb. Centralizers are required to be used outside temporary PCV casing and inside the drill string to ensure the CMT well is plumb. The temporary PVC casing must be retracted as the annular spaced is filled with sealing material.

3. It is required to use time-delayed bentonite pellets to seal between all screened intervals of the CMT wells. Any other sealing material must be approved by Ecology before using. Filter packing and additional sealing procedures shall follow the plan submitted with the variance request.

4. The unused channel spaces in each CMT well shall be pre-grouted to seal the wells during their useful life. If at any time during the useful life of the well where grout is withdrawn during sampling or the grout fails to seal any of the 7 channels ports of the CMT well, all wells must be immediately decommissioned as required in condition 7 below. Provide additional information to Ecology if a plasticizer is to be mixed with the pre-grout. Pre-grouting of all CMT ports must conform to sealing requirements specified in WAC 173-160-450.

5. Installation shall be completed for the CMT wells before the pre-grout is allowed to set, to prevent cracking of hardened seal material during installation.

6. Installation of CMT wells shall be constructed to approximately 70 feet deep below ground surface (bgs) and not extend into the aquitards/confining layer at the base of the water table aquifer.

7. Within 1 year of the completion of the CMT wells, all 4 wells must be decommissioned by a licensed resource protection well driller. Appropriate notice must be submitted to Ecology prior to decommissioning. The CMT wells must be decommissioned by overdrilling the entire CMT well and the entire borehole is properly sealed per WAC 173-160-460. The drill bit for overdrilling must be a minimum of 8 inches in diameter. All overdrilled materials (including

broken CMT material) must be removed before sealing the borehole. Enough seal material shall fill any voids from the bottom of the borehole to land surface.

8. Inform Ecology (John Pearch, 360-407-0297 or Bill Lum, 360-407-6648) or another Ecology staff, two business days before any of the following work begins. The site must be accessible to Ecology to inspect all construction work, sampling of the wells and decommissioning of the wells.

9. Well construction notice of intent for each well must be submitted and the appropriate fees paid at least 72-hours before any construction begins.

10. All well construction work must be performed by a licensed resource protection well driller.

11. All other minimum construction standards found in WAC 173-160 shall be followed to protect further degradation of the groundwater resource.

12. The driller must submit *Resource Protection Well Reports* describing the construction of the wells to Ecology (Southwest Regional office) within 30 days after completion of the work, one report per well constructed. **Attach a copy of this variance to each well report.**

13. With the exception of the specific provisions set forth (above) in this variance, all federal, state, and local requirements shall apply.

14. This variance expires **October 31, 2013.** After this date, approval of a new request for variance must be obtained for the work proposed.

YOUR RIGHT TO APPEAL

You have a right to appeal this variance to the Pollution Control Hearing Board (PCHB) within 30 days of the date of receipt of this variance. The appeal process is governed by Chapter 43.21B RCW and Chapter 371-08 WAC. "Date of receipt" is defined in RCW 43.21B.001(2).

To appeal you must do the following within 30 days of the date of receipt of this variance:

- File your appeal and a copy of variance with the PCHB (see addresses below). Filing means actual receipt by the PCHB during regular business hours.
- Serve a copy of your appeal and this variance on Ecology in paper form - by mail or in person. (See addresses below.) E-mail is not accepted.

You must also comply with other applicable requirements in Chapter 43.21B RCW and Chapter 371-08 WAC.

ADDRESS AND LOCATION INFORMATION

Street Addresses	Mailing Addresses
Department of Ecology Attn: Appeals Processing Desk 300 Desmond Drive SE Lacey, WA 98503	**Department of Ecology** Attn: Appeals Processing Desk PO Box 47608 Olympia, WA 98504-7608
Pollution Control Hearings Board 1111 Israel RD SW STE 301 Tumwater, WA 98501	**Pollution Control Hearings Board** PO Box 40903 Olympia, WA 98504-0903

For additional information visit the Environmental Hearings Office Website: http://www.eho.wa.gov . To find laws and agency rules visit the Washington State Legislature Website: http://www1.leg.wa.gov/CodeReviser.

SIGNATURE

Michael J. Gallagher (LHG # 1209)

Michael J. Gallagher
Section Manager
Water Resources Program

8/5/13
Date

Michael J. Gallagher for

John Pearch
Licensed Hydrogeologist (#1410)
Well Construction Coordinator
jope461@ecy.wa.gov

Date 8/5/13

Enclosure: Your Right to be Heard

cc: William E. Lum, II, Ecology-WR
David T. Adamson, GSI Environmental, Inc.
Trent Castner, Cascade Drilling, tcastner@boartlongyear.com
Greg Caron, HWTR, CRO

CERTIFIED MAIL: 7011 2970 0000 0555 3326

STATE OF WASHINGTON
DEPARTMENT OF ECOLOGY
PO Box 47775 • Olympia, Washington 98504-7775 • (360) 407-6300

June 20, 2014

Mike Truex
Pacific Northwest National Laboratory
902 Battelle Boulevard
PO Box 999, MSIN K6-96
Richland, WA 99352

RE: Variance request from Washington Administrative Code (WAC) for decommissioning of a product not meeting various requirements. The property is located on the U.S. Army, Joint Base Lewis-McCord, Whispering Pine Golf Course, Area D disposal site, in the NE ¼ NE ¼ of Section 23, Township 19 North, Range 2 East, W.M. in Pierce County.

Dear Mr. Truex:

You requested a waiver for decommissioning three Solinst-brand Continuous Multi-channel Tubing (CMT) monitoring wells (construction completed on August 14, 2013). CMT by this manufacturer and the proposed decommissioning does not meet the August 5, 2013, variance for the reasons given:

"It is unnecessary to comply with overdrilling requirement from August 5, 2013 variance for the three installed Continuous Multichannel Tube (CMT) wells because the CMT ports are completed within a single aquifer (see attached cross section and well construction details) and decommissioning by the Solinst method will appropriately seal the well (see attached Solinst Method)."

Also, attached is the MSDS for the polymer we plan to use, if needed, for decommissioning the channels of the CMT wells. If there is a need to use a different brand, we will ensure that it also "does not contain any components considered or known to be health hazards under the OSHA Hazard Communications Standard 29 CFR 1910.1200".

According to the 3 Well Reports with Ecology Well Tag ID BHN963, BHN964, and BHN965 each CMT well annular space was sealed with bentonite chips from 38 feet to 3 feet and cement grout from 3 feet to land surface. Bentonite pellets (swelling time delayed) were also used to seal below all four ports within each CMT well annular space (see attached well reports and As-built diagrams).

Department of Ecology (Ecology) received your variance request via email on May 15, 2014. The request was submitted with the following alternative methods:

"The CMT wells will be decommissioned per vendor recommendations (see Solinst CMT Decommissioning Procedure) by pumping cement grout into each channel from the bottom up using a tremie tube. Each channel will be completely filled from the monitoring interval to ground surface. PNNL, GSI, and the drilling contractor have experience with formulating and pumping grout for these types of decommissioning activities. The grout will be formulated per vendor recommendations and will meet the requirements of WAC 173-160-221(2). The grout will be pressure injected and forced, to the extent possible, out into the filter pack material. If problems are encountered with grout loss that results in the inability to retain grout within the CMT channels, additional solids (i.e., ultrafine cement) will be added to the mixture until the desired seal characteristics are achieved. In addition to grouting all CMT tubes, all CMT wells will be terminated 3 to 6 inches below ground surface and encased in cement within the current cement monument completed flush to ground surface for improved wellhead protection."

After an investigation, interview, and review of information available, a variance is hereby **granted** in accordance with WAC 173-160-106 to allow decommissioning of the three (3) CMT wells at the site identified by the site map submitted with the variance. This decision is based upon, but not limited to, the following:

1. All CMT wells must be decommissioned by a licensed resource protection well driller. Appropriate notice and fees must be received by Ecology 72 hours prior to decommissioning.

2. The CMT wells must be decommissioned according to your variance proposal. Enough seal material shall fill any voids from the top of pre-grout to land surface. Any channel spaces that were not already pre-grouted in each CMT well shall be grouted to land surface. Grouting of all CMT ports must conform to sealing requirements specified in WAC 173-160-450.

3. Before finishing decommissioning work, the driller must wait 12 hours until grout has set up or stopped settling in all the channels of the CMT well. If grout has settled, additional grout must be filled to the top of the CMT well and wait an additional 12 hours until the well is completely full of grout.

4. The top 6-inches of the CMT wells must be removed and the remaining borehole or any other voids or drains within the cement monument must be sealed with approved sealing material.

5. Inform Ecology (John Pearch, 360-407-0297), two business days before any of the following work begins. The site must be accessible to Ecology to inspect decommissioning of the wells.

6. All other minimum construction standards found in WAC 173-160 shall be followed to protect further degradation of the groundwater resource.

7. The driller must submit *Resource Protection Well Reports* describing the construction of the wells to Ecology (Southwest Regional office) within 30 days after completion of the work, one report per well constructed. **Attach a copy of this variance to each well report.**

8. With the exception of the specific provisions set forth (above) in this variance, all federal, state, and local requirements shall apply.

9. This variance expires **October 31, 2014.** After this date, approval of a new request for variance must be obtained for the work proposed.

YOUR RIGHT TO APPEAL

You have a right to appeal this variance to the Pollution Control Hearing Board (PCHB) within 30 days of the date of receipt of this variance. The appeal process is governed by Chapter 43.21B RCW and Chapter 371-08 WAC. "Date of receipt" is defined in RCW 43.21B.001(2).

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Pollution Control Hearings Board 1111 Israel RD SW STE 301 Tumwater, WA 98501	**Pollution Control Hearings Board** PO Box 40903 Olympia, WA 98504-0903

For additional information visit the Environmental Hearings Office Website: http://www.eho.wa.gov . To find laws and agency rules visit the Washington State Legislature Website: http://www1.leg.wa.gov/CodeReviser.

SIGNATURE

Michael J. Gallagher
Section Manager
Water Resources Program

6/20/14
Date

John Pearch
Licensed Hydrogeologist (#1410)
Well Construction Coordinator
jope461@ecy.wa.gov

6-20-14

Enclosure: Your Right to be Heard

By Certified Mail 7012 2920 0000 1182 4995

cc: Vince Vermeul, PNNL, vince.vermeul@pnnl.gov
Jake Horner, PNNL, jake.horner@pnnl.gov
David T. Adamson , GSI Environmental, Inc.
Greg Caron, Ecology, HWTR, CRO

DEPARTMENT OF
ECOLOGY
State of Washington

Water Resources Program

Variance Request- Minimum Standards for Well Construction

WAC173-160-106(1) allows you to request a variance from the Department of Ecology when strict compliance with state well construction standards is impractical. The variance request must propose comparable alternative specifications that will provide equal or greater human health and resource protection than the minimum standards. You must apply for a variance in writing and receive approval before constructing or decommissioning the well. (All fields must be completed.)

Requested by: David T. Adamson

Mailing Address: 2211 Norfolk, Suite 1000 City: Houston State: TX Zip: 77098

Daytime Phone: 713-522-6300 Date: 5/15/2014

Property Owner (if different): U.S. Army, Joint Base Lewis-McChord

Site Location: NE¼ NE ¼ Section: 23 Township: T19N Range:R2E ☐E or ☐WWM

Tax Parcel Number: NA

Well Address: Whispering Firs Golf Course

Well Driller/Company (if known): Cascade Drilling Inc.

Check one: ☐ Water Well ☒ Resource Protection Well ☐ Dewatering Well

What construction standard cannot be met?

Decommissioning approach listed in 8/5/2013 variance.

Describe the reason why standard cannot be met. Include site map and distances from all known potential sources of contamination if setback variance is being requested.

It is unnecessary to comply with overdrilling requirement from 8/5/2013 variance for the three installed Continuous Multichannel Tube (CMT) wells because the CMT ports are completed within a single aquifer (see attached cross section and well construction details) and decommissioning by the Solinst method will appropriately seal the well (see attached Solinst Method).

Describe the alternative construction method that will provide equal or greater protections than those provided by the minimum standard.

The CMT wells will be decommissioned per vendor recommendations (see Solinst CMT Decommissioning Procedure) by pumping cement grout into each channel from the bottom up using a tremie tube. Each channel will be completely filled from the monitoring interval to ground surface. PNNL, GSI, and the drilling contractor have experience with formulating and pumping grout for these types of decommissioning activities. The grout will be formulated per vendor recommendations and will meet the requirements of WAC 173-160-221(2). The grout will be pressure injected and forced, to the extent possible, out into the filter pack material. If problems are encountered with grout loss that results in the inability to retain grout within the

CMT channels, additional solids (i.e., ultrafine cement) will be added to the mixture until the desired seal characteristics are achieved. In addition to grouting all CMT tubes, all CMT wells will be terminated 3 to 6 inches below ground surface and encased in cement within the current cement monument completed flush to ground surface for improved wellhead protection.

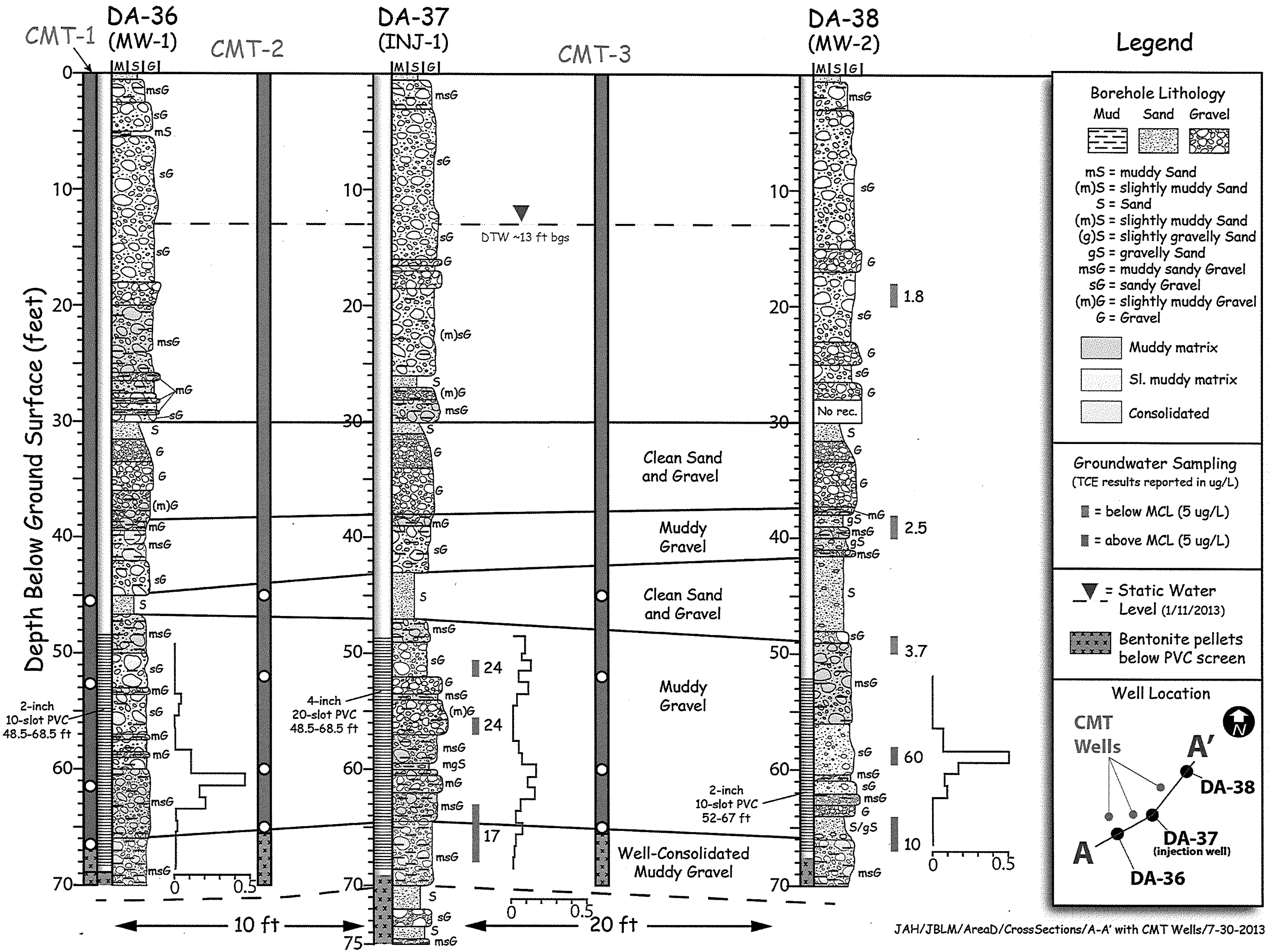
(Attach additional pages if necessary.) Complete and return with your site map to the appropriate regional office:

Northwest Regional Office
ATTN: Noel Philip
3190 160th Avenue SE
Bellevue, WA 98008
425-649-7044
Fax: 425-649-7098
nphi461@ecy.wa.gov

Southwest Regional Office
ATTN: John Pearch
PO Box 47775
Olympia, WA 98504
360-407-0297
Fax: 360-407-6305
jope461@ecy.wa.gov

Eastern Regional Office
ATTN: Mark Ader
N 4601 Monroe
Spokane, WA 99205
509-329-3544
Fax: 509-329-3529
made461@ecy.wa.gov

Central Regional Office
ATTN: Avery Richardson
15 W Yakima Ave #200
Yakima, WA 98902
509-575-2639
Fax: 509-454-7830
aric461@ecy.wa.gov



JAH/JBLM/AreaD/CrossSections/A-A' with CMT Wells/7-30-2013

Material Safety Data Sheet

May be used to comply with OSHA's Hazard Communication Standard, 29 CFR 1910 1200. Standard must be consulted for specific requirements.

U.S. Department of Labor

Occupational Safety and Health Administration
(Non-Mandatory Form)
Form Approved
OMB No. 1218-0072

Product Name: **EVO-2500** (Proprietary Admixture)	Note: Blank spaces are not permitted. If any item is not applicable or no information is available, the space must be marked to indicate that.

Section I

Manufacturer: GENERAL RESOURCE TECHNOLOGY	Emergency Telephone Num: 1-800-324-8154 or 612-741-3041
Address: 2978 Center Court	Telephone Number for Info: 1-800-324-8154
Eagan , MN 55121	Date Prepared: 2/2011

Section II—Hazardous Ingredients/Identity Information

Hazardous Components (Specific Chemical Identity, Common Name(s))	OSHA PEL	ACGIH TLV	Other Limits (recommended)	% optional
Polycarboxylate Co-Polymer Blend (Proprietary formulation)				

(This product does not contain any components considered or known to be health hazards under the OSHA Hazard Communication Standard 29 CFR 1910.1200

Section III—Physical/Chemical Characteristics

Boiling Point: **215°F**		Specific Gravity (H_20 = 1): **1.00-1.18**	**pH @ 20°C** **5.0-8.0**
Vapor Pressure (mm Hg): **Not Available**		Melting Point: **N/A**	**Solids: (ASTM)** **25.0-32.0%**
Vapor Density (AIR = 1) : **Is heavier than air**		Evaporation Rate: **Not Available**	

Solubility in Water: **100% (Totally soluble in water.)**

Appearance and Odor: **Light brown liquid (characteristic odor)**

Section IV—Fire and Explosion Hazard Data

Flash Point (Method Used): **Not determined**	Flammable Limits: **Not determined**	LEL: **Not determined**	UEL: **Not determined**

Extinguishing Media: **Use water spray or fog, foam, dry chemical, or CO^2.**

Special Fire Fighting Procedures: **Self contained breathing apparatus, or full protective gear.**

Unusual Fire and Explosion Hazards: **Burning will produce hazardous compounds includes oxides of: Carbon**

N/D – Not Determined N/A – Not Applicable N/E – None Established

Section V—Reactivity Data

Stability: (Under Normal Conditions)	Unstable		Conditions to Avoid: High Temperatures
	Stable:	X	

Incompatibility(Materials to avoid) : **Strong Oxidizers**

Hazardous Decomposition or Byproducts: **N/A – No information available**

Hazardous Polymerization (under normal conditions)	May Occur		Conditions to Avoid: High Temperatures
	Will Not Occur:	X	

Section VI—Health Hazard Data

Route(s) of entry	Inhalation? **Not Established**	Skin? **Not Established**	Ingestion? **Not Established**

Health Hazards (Acute and Chronic)

Carcinogenicity	NTP? **NO data found**	IARC Monographs? **NO data found**	OSHA Regulated? **NO data found**

Signs and symptoms of exposure **Irritation of skin, eyes, and mucous membranes**

Medical conditions Generally aggravated by exposure **Any general medical condition that results in the weakening of the skin and eye tissue**

Emergency and First Aid Procedures **Skin: Wash with soap and copious amounts of water.**

Eyes: Irrigate eyes with copious amounts of water. If pain or irritation arises, call a Physician or Poison Control Center

Inhalation: Move to fresh air. If illness or irritation occurs, call a Physician or Poison Control Center.

Steps to Be Taken in Case Material Is Released or Spilled: **Ventilate area. Absorb with inert material and place in chemical waste containers for disposal. Obey relevant local, state, and federal regulations. Do not discard into lakes, streams, or ponds. Use personal protective equipment as described below.**

Waste Disposal Method: **Landfill in accordance with applicable local and federal regulations. Incineration is the preferred method of disposal.**

Precautions to Be Taken in Handling and Storing: **Normal care to avoid skin and eye contact.**

Other precautions: **None**

Section VIII—Control Measures

Respiratory Protection: **None required.**

Ventilation	Local Exhaust: **Fresh Air**	Special: **Eye wash solution or fountain should be readily available**
	Mechanical: **Fans or exhaust ventilation**	Other: **Always use caution when using construction chemicals.**
Protective Gloves: **Chemical resistant gloves suggested**		Eye Protection: **Chemical worker goggles**

Other Protective Clothing or Equipment: **Long sleeves or clothing that does not expose skin.**

Work/Hygienic Practices: **Wash thoroughly with soap and water……..Do not rub eyes!**

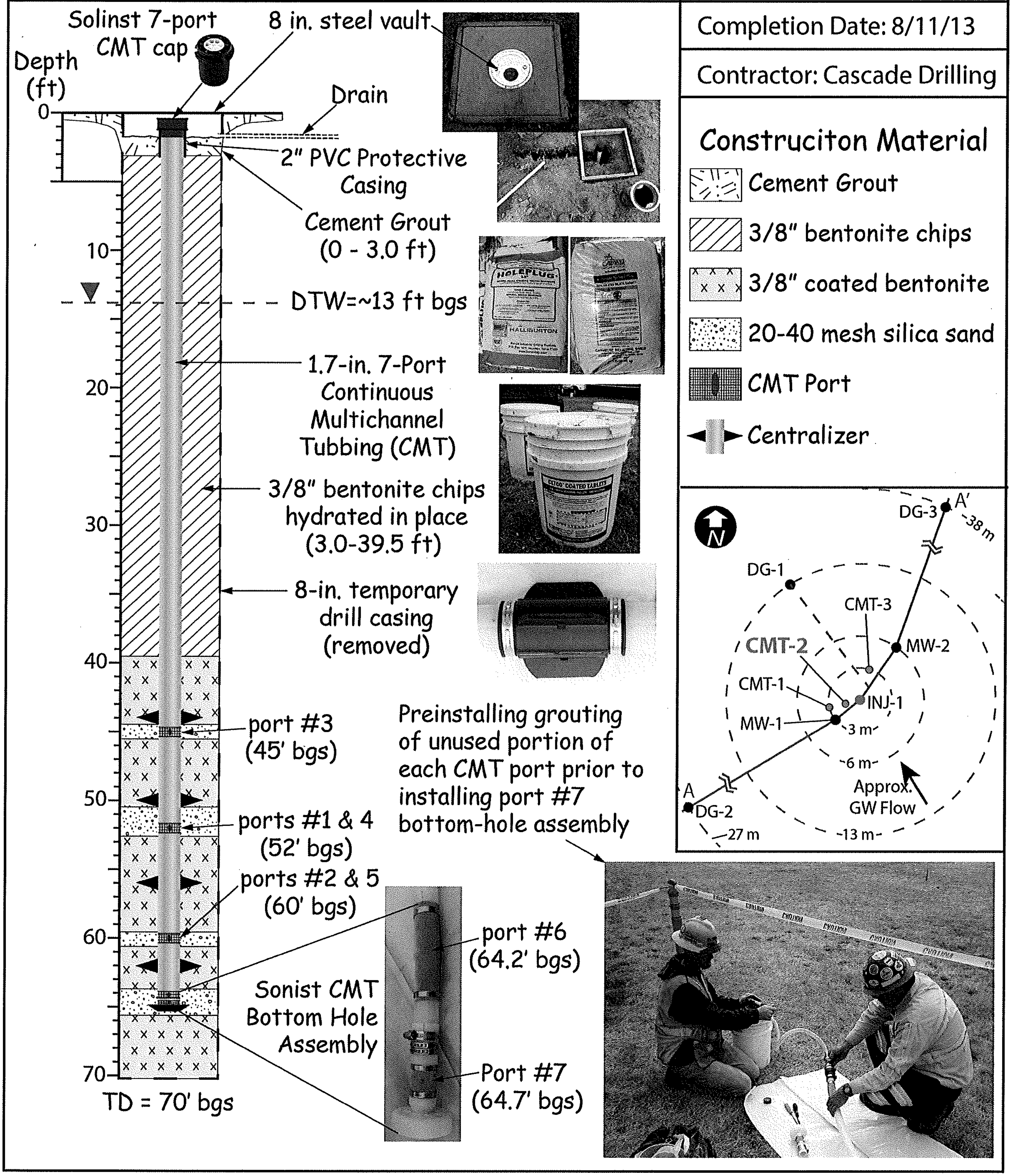
As-Built Diagram: CMT-2
Joint Base Lewis-McChord (Area D)

Drilling Date: 8/11/13

Drilling Method: Sonic

Completion Date: 8/11/13

Contractor: Cascade Drilling



APPENDIX E

Quality Assurance Project Plan

E.1. Quality Assurance Sampling Program

Laboratory analyses will be completed using the methods and protocols outlined in **Table 5.4**. In all cases, method-specific containers will be obtained from the respective laboratories prior to sampling. This includes containers requiring special preservatives (e.g., acids), all of which will be added to containers by labs and not in the field. Labs will be consulted on the necessary lab QA/QC samples to ensure that appropriate sample containers for these samples are provided to field personnel as well. A summary of the QA/QC sampling program is provided in **Table E.1**.

Table E.1. Summary of QA/QC Sampling Program

QA/QC Sample Category	Sampling Frequency	Analytes
Equipment Rinsate	Not required	--
Trip Blanks	One per sample shipment per sample matrix	CVOCs
Field Duplicates	Approximately one for every ten samples (soils and groundwater)	All requested analytes for each lab
Matrix Spike/ Matrix Spike Duplicates	Approximately one for every twenty samples (soils and groundwater)	Lab and method-specific
Laboratory Control Samples	One per method, batch, and matrix	Lab and method-specific
Laboratory Method Blank	One per method, batch, and matrix	Lab and method-specific

E.1.1 Field Quality Assurance Procedures

Field QA/QC samples will be collected and analyzed in order to i) evaluate field precision and accuracy, and ii) facilitate validation of sample results. Field sampling precision and accuracy will be assessed through the collection and laboratory analysis of field replicates and field blanks. Samples will be collected per applicable procedures provided in the sampling and analysis programs outlined in **Table 5.3** and **Table 5.4**.

Data from field QC samples will be examined to determine if any problems are evident for specific media or with laboratory procedures. The Project Manager will be responsible for reviewing the QA/QC data and to develop appropriate corrective actions should any problems be encountered.

- ***Equipment Rinsate Blanks:*** Dedicated disposable sampling equipment will be used in this field demonstration, therefore no equipment rinsate blanks are required.

- ***Trip Blanks:*** The effectiveness of sample handling techniques will be evaluated by submitting preserved trip blank samples for laboratory analysis. Trip blanks will consist of a pair of 40-mL VOA vials with Teflon^{TM} lined septa, filled in the laboratory (or organization*)* providing the sample containers) with laboratory-grade (organic-free/de-ionized or distilled) water. The unopened trip blanks will accompany the VOC sample bottles to the sampling site and back to the laboratory in the same shipping cooler. Proper labeling and documentation will be completed for trip blanks. Trip blanks will be prepared and analyzed with other samples being analyzed for VOCs at a minimum frequency of one per day when sampling water only (i.e., no trip blanks will be required if vapor is the only medium sampled on a particular day).
- ***Field Duplicate Samples:*** The precision of field sample collection techniques will be evaluated by collecting and analyzing field duplicates. Duplicate samples will be defined as those samples collected simultaneously from the same source under identical conditions into separate but identical containers, and preserved, stored, transported and analyzed in the same manner. Thus, to prepare a duplicate, an aliquot will be collected from a sample source and divided equally into two separate but identical sample containers. Each duplicate will be identically preserved, stored, transported and analyzed. Field duplicates will be given a different identification number to disguise the source of the sample from the laboratory. Field replicates will be analyzed by the same laboratory analyzing investigative samples. During the course of the demonstration, duplicates will be collected at a frequency of one duplicate for every 10 samples (10%).

E.1.2. Laboratory Quality Assurance Procedures

The selected off-site commercial laboratories will implement a QA/QC program to ensure the reliability and validity of analyses performed in the laboratory. Analytical procedures will be documented in writing as SOPs, each including a section addressing minimum QC requirements for the procedure. Internal quality control checks differ slightly for individual procedures, but in general QC requirements will include the following:

- Method blanks
- Instrument blanks
- Matrix spikes/matrix spike duplicates
- Surrogate spikes
- Laboratory duplicates
- Laboratory control standards
- Surrogate spikes
- Internal standard spikes
- Mass spectral tuning

Laboratories will be provided with extra sample volume for preparation and analysis of matrix spike and matrix spike duplicates. Field personnel will label all samples intended for MS/MSD analysis. All matrix spikes will be completed by lab personnel.

QC sample results will be properly recorded and included in the analytical data package. The data package will contain sufficient QC information to allow reconstruction and evaluation of the laboratory QC process by an independent data reviewer. Data generated in the laboratory will be properly recorded and compiled into a deliverable package containing sufficient QC information for comparison to relevant criteria. Samples analyzed in non-conformance with the QC criteria will be re-analyzed by the laboratory if sufficient volume is available.

E.2. Calibration of Analytical Equipment

The majority of analyses will be completed at commercial analytical laboratories. The exceptions are static water levels, organic vapor screening, and groundwater quality parameters, all of which will be measured in the field using analyte-specific equipment. This includes a Solinst Model 101 water level meter, a YSI 600 series (or equivalent) for monitoring groundwater, and a ppbRAE 3000 photoionizaton detector (or equivalent) for monitoring vapors in soil cores and in the workspace. All instruments will be calibrated at a minimum frequency of once daily following manufacturer specifications, using appropriate calibration solutions and/or gases.

E.3. Decontamination Procedures

Standard decontamination measures will be employed during sampling activities and all other investigations associated with the project. This includes the one-time use of sample and method-appropriate containers (see **Table 5.4**), decontamination of all sampling equipment (pump tubing, trowels) prior to sampling and between collecting each sample. Gloves will be worn by all sampling personnel and changed out between each sample to minimize cross-contamination. During soil sampling, drill rods and all other downhole equipment will be decontaminated (using pressure washing) prior to the start of drilling activities, and only decontaminated drilling equipment will be used when moving to a new drilling location. All investigation-derived waste will be collected and disposed of per site regulations.

E.4. Sample Documentation

Sample containers provided by the laboratory for this project will be shipped by common carrier or other suitable method in sealed coolers to a location designated by the project team. The laboratory will include a shipping form/laboratory chain-of-custody listing containers shipped and the purpose of each container. Containers will be considered in the custody of the laboratory until received by GSI or a designated representative. Upon receipt, the shipment will be checked to verify that all containers are intact. The containers will be maintained in the custody of the receiver in a clean, secure area until used for sample collection.

Procedures described below address custody during field sample collection, laboratory analysis, and file storage for the data collected as part of the project.

1) Field sampling personnel will be personally responsible for the care and custody of the samples until transferred or properly dispatched.

2) Sample bottles and vessels will be labeled with sample numbers and locations at the time of sample collection.

3) Sample labels will be completed with permanent ink.

4) The sample label affixed to the container will be inspected to confirm that all of the required information has been provided.

5) If appropriate, the sample container will be sealed in a zip-lock plastic bag, wrapped in bubble pack, and packed in a wet-ice or dry-ice cooler in a manner to minimize shifting or movement.

6) For each set of samples sent to the laboratory, a triplicate chain-of-custody form will be completed. Information on the chain-of-custody form and the sample container labels will be checked against the field logbook entries and the samples will be recounted. The information contained on the chain-of-custody form will include the following:
    - Site name and address or location;
    - Project number;
    - Date of sample collection;
    - Name of sampler responsible for sample submittal;
    - Identification of samples that accompany the form including
    - Field ID number,
    - Number of samples,
    - Date/time collected,
    - Sample container type, volume, preservative,
    - Parameters/methods of interest,
    - Data level requirement (e.g., Level II),
    - Comments about sample conditions;
    - Signature of person relinquishing custody and signature of person accepting custody, plus date and time; and
    - Identification of common carrier.

7) If a commercial courier service (e.g., Federal Express) transports the samples to the laboratory, the chain-of-custody form will be signed by a member of the field team, and a copy retained by the field team. The remaining two copies of the form will be sealed in a zip-type plastic bag and placed in the cooler with the samples. The cooler will be sealed with packaging tape and two custody seals signed and dated by a member of the field team. Custody seals will be placed on the exterior of the cooler over the lid and sides. Package routing documentation maintained by the courier service will serve as chain-of custody documentation during shipment, because commercial couriers do not sign chain-of-custody forms.

8) If samples are picked up by a laboratory representative, a member of the field team will sign the chain-of-custody record indicating that the samples have been transferred to the lab courier. The lab courier will also sign the form, indicating that the samples have been transferred to his or her custody. One copy of the chain-of-custody form will be retained by the field team and the remaining two copies will be sealed in a zip-type plastic bag and placed in the cooler chest with the samples.
   - Data validation reports
   - Data assessment reports
   - Project reports

9) All documentation will be stored in a cabinet at the GSI office and access limited to concerned project personnel. The Final Evidence File will be maintained at this location until the conclusion of the project. The GSI Project Manager will serve as the file custodian.

APPENDIX F

Tracer Data and Breakthrough Curves

The chloride and bromide data collected during the two injection tests are tabulated and plotted in this appendix. Data is plotted as normalized concentration versus volume injected (in gallons). Chloride concentrations are normalized to 100% = 231 mg/L and bromide is normalized to Bromide normalized to 100% = 248 mg/L, both based on the concentration of the injected solution.

The data are fit to a curve to determine the volume at the half-way point in the breakthrough. A sigmoidal curve (Equation 1) was used where possible. The coefficients for the best fit of the sigmoidal curve to the data were determined using TableCurve 2D (Jandel Scientific, San Rafael, California). For some data sets, a sigmoidal curve could not be fit to the data. Three issues made fitting a sigmoidal curve problematic: 1) insufficient data (i.e., less than 4 data points; for example, the C1D chloride data), 2) data with little or no detection of the analyte of interest over time (e.g., chloride data for C3A), and 3) data sets with only high and low, but no mid-range values (e.g., chloride data for C3C). For the cases where a sigmoidal curve fit was not possible, a linear fit was used between two selected points.

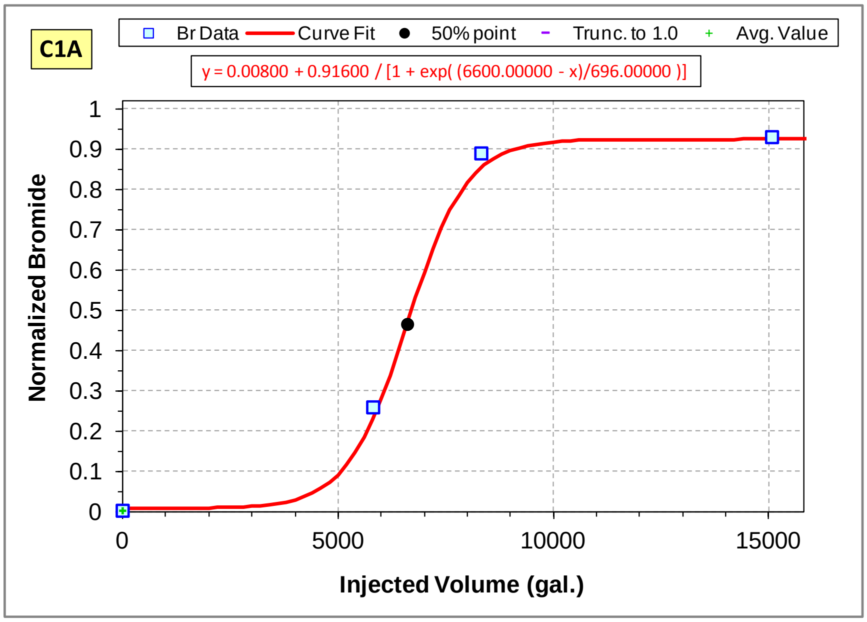
$$y = a + b / [1 + \exp((c - x)/d)] \qquad (1)$$

The half-way point in the breakthrough was determined as the volume at nominally half way between the range of minimum and maximum concentrations. For the sigmoidal curves, this equates to the transition point on the curve. For the linear fits, half-way between the approximate range or a normalized concentration of 50% was used to select the volume at the half-way point.

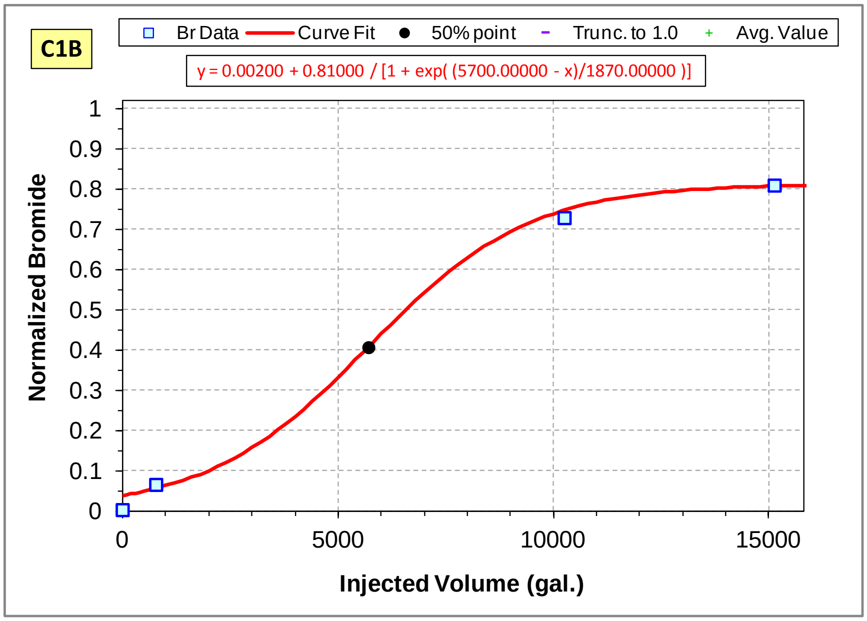
Note that when more than one data value was available at time zero, the values were averaged and the average values are presented in the tables and plots. Also, when concentration data exceeded the input concentrations, the normalized concentration was truncated to a maximum of 1.0 (i.e., 100%).

BROMIDE TRACER DATA FROM BASELINE INJECTION TEST

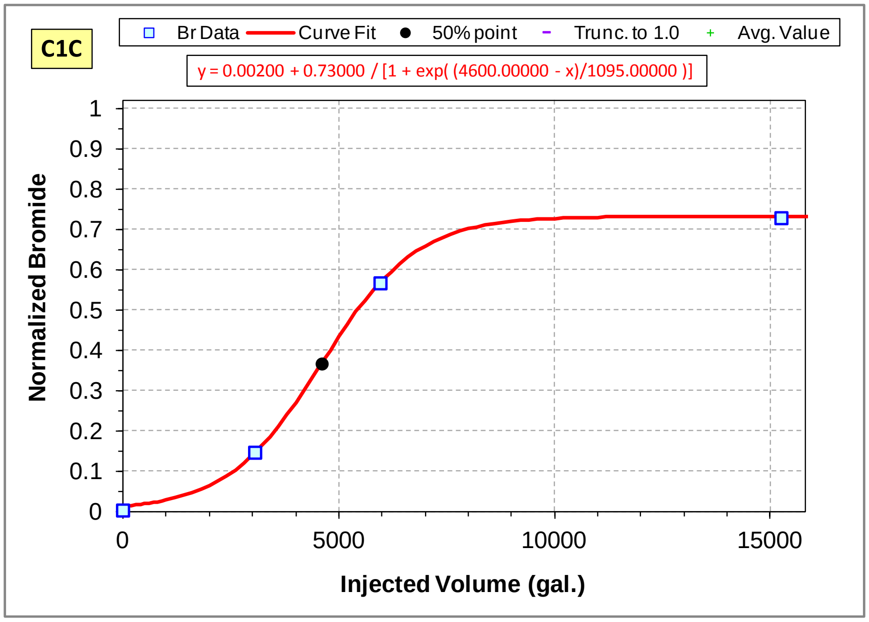
C1A	
Injected Volume (gal.)	Normalized Bromide Concentration
0	0.0020
5815	0.2586
8325	0.8889
15075	0.9293



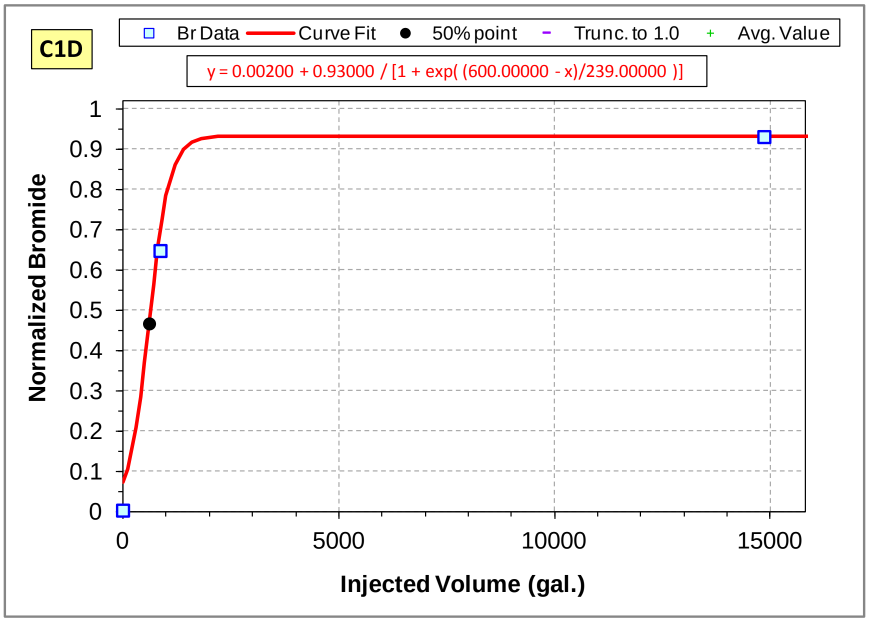
C1B	
Injected Volume (gal.)	Normalized Bromide Concentration
0	0.0020
778	0.0646
10259	0.7273
15136	0.8081



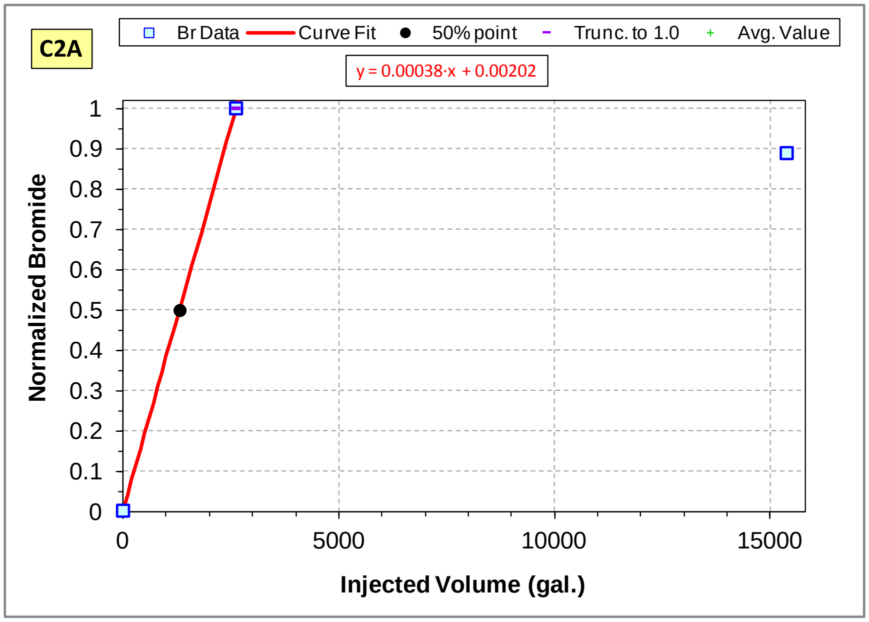
C1C	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
3062	0.1455
5966	0.5657
15257	0.7273



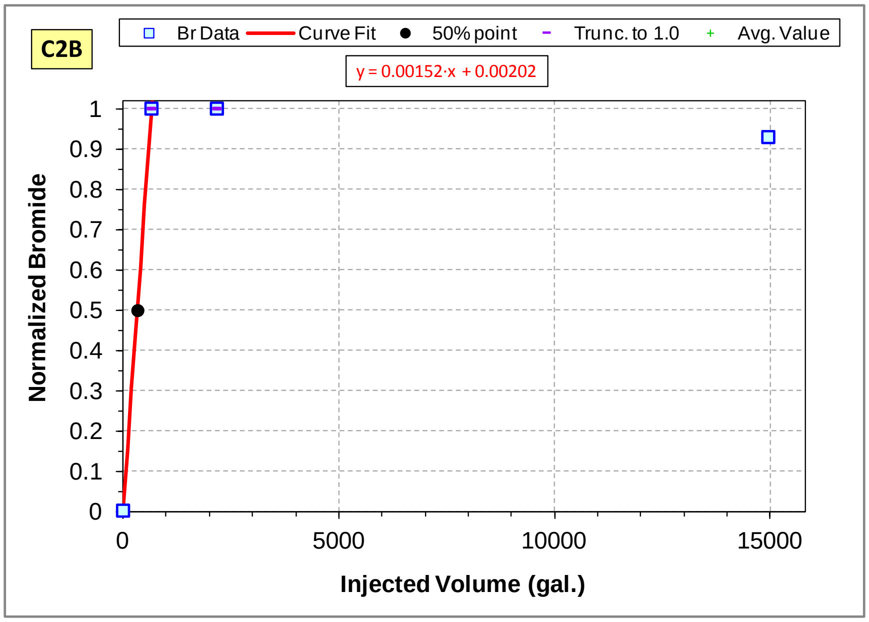
C1D	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
868	0.6465
14862	0.9293



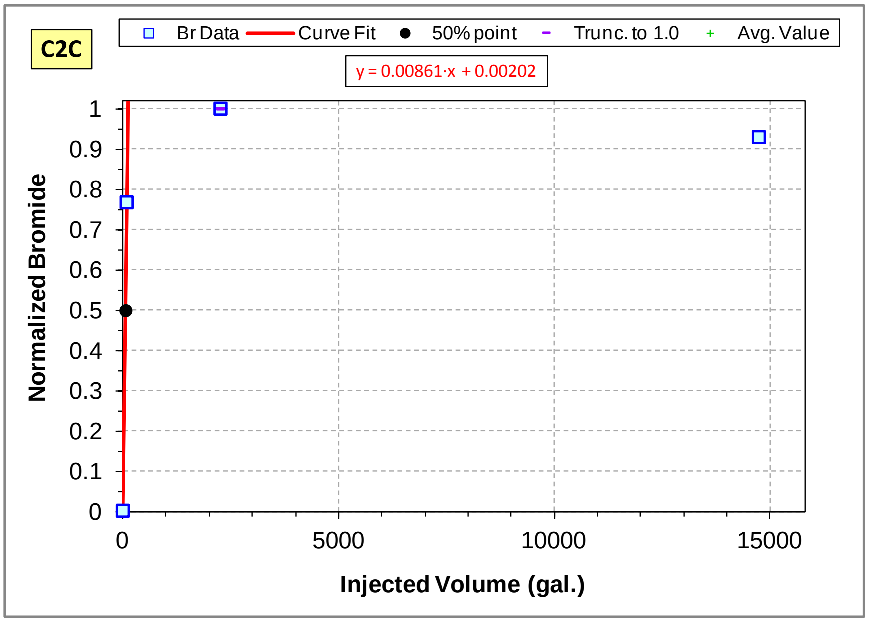
C2A	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
2618	1.0000
15379	0.8889



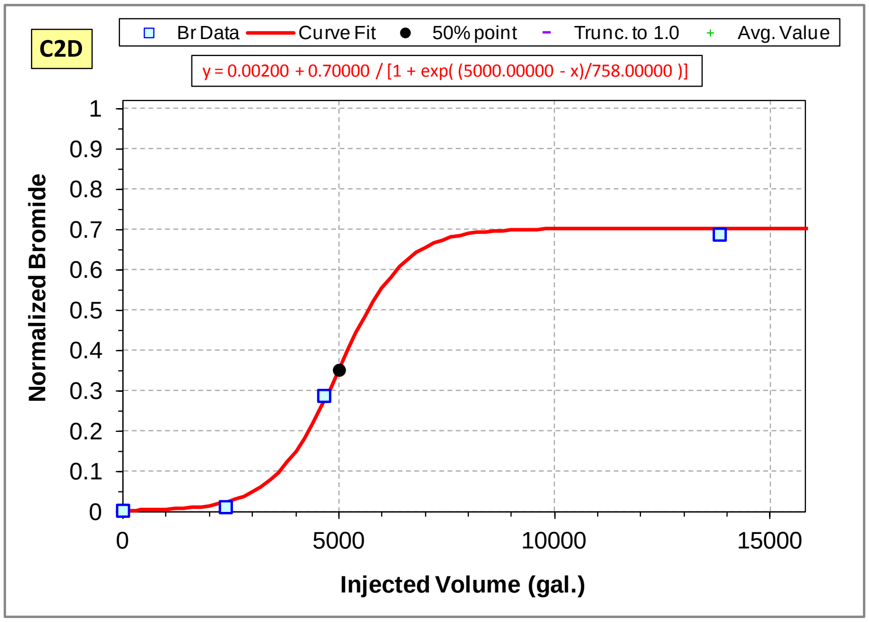
C2B	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
659	1.0000
2175	1.0000
14953	0.9293



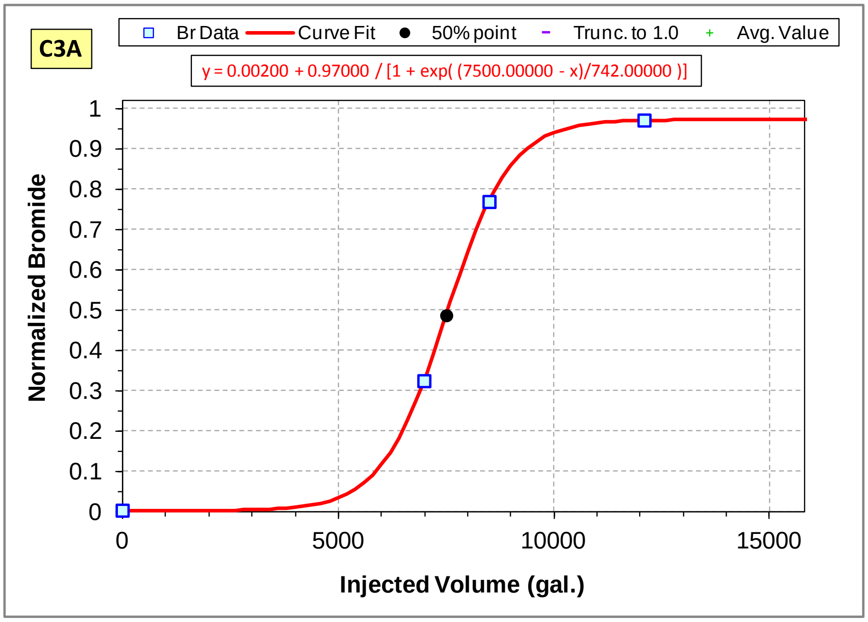
C2C	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
89	0.7677
2264	1.0000
14740	0.9293



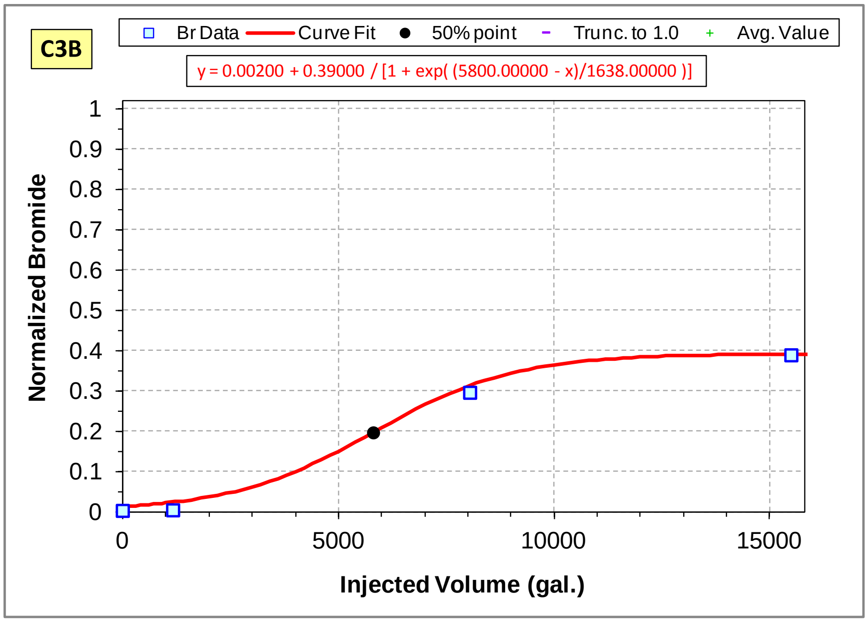
C2D	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
2382	0.0109
4661	0.2869
13828	0.6869



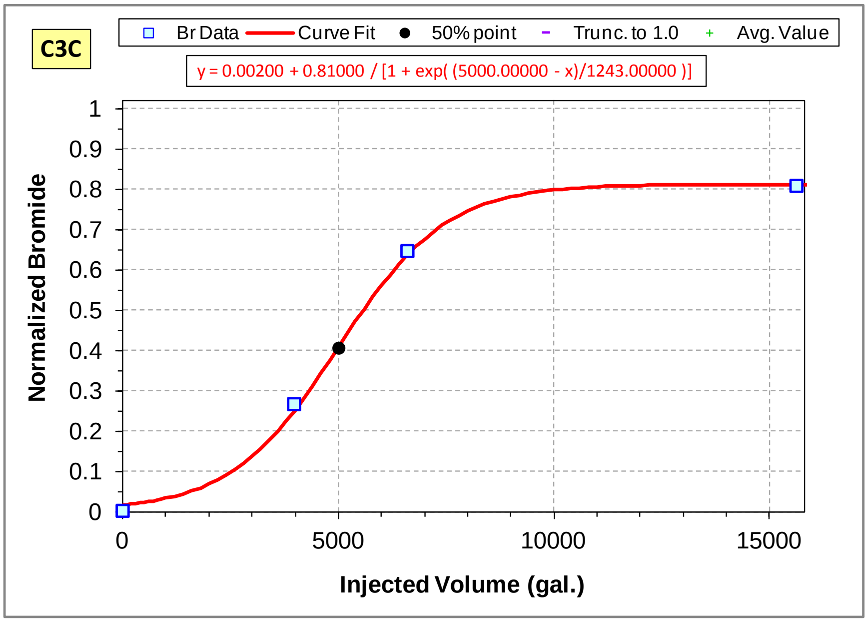
C3A	
Injected Volume (gal.)	Normalized Bromide Concentration
0	0.0020
6996	0.3232
8506	0.7677
12100	0.9697



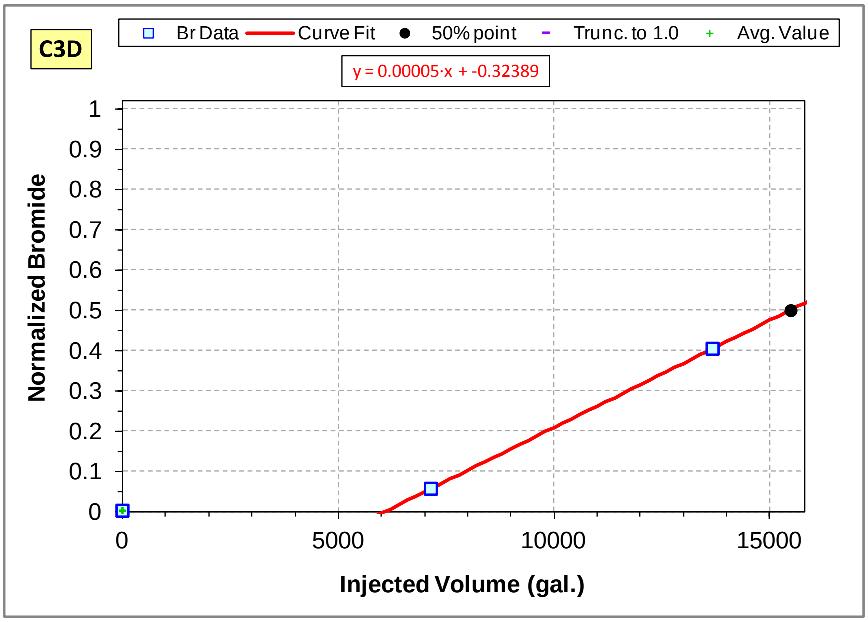
C3B	
Injected Volume (gal.)	Normalized Bromide Concentration
0	0.0020
1166	0.0034
8054	0.2949
15502	0.3879



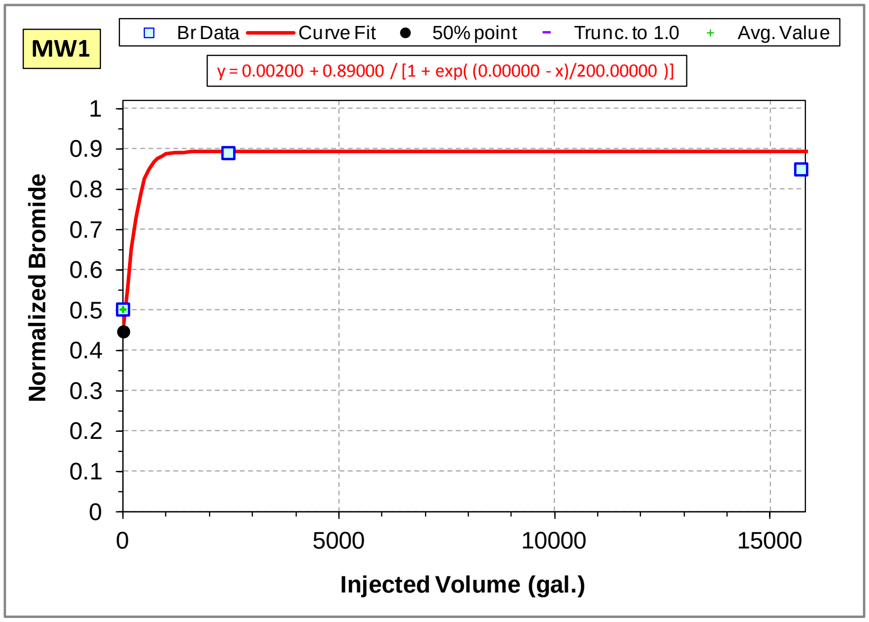
C3C	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
3977	0.2667
6603	0.6465
15624	0.8081



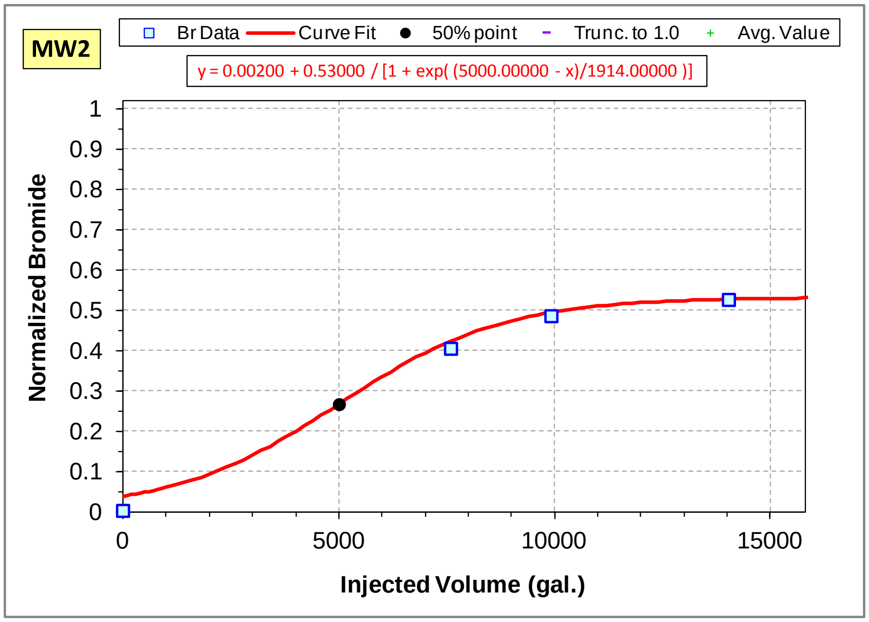
C3D	
Injected Volume (gal.)	**Normalized Bromide Concentration**
0	0.0020
7148	0.0566
13676	0.4040



MW1	
Injected Volume (gal.)	Normalized Bromide Concentration
0	0.5010
2441	0.8889
15715	0.8485



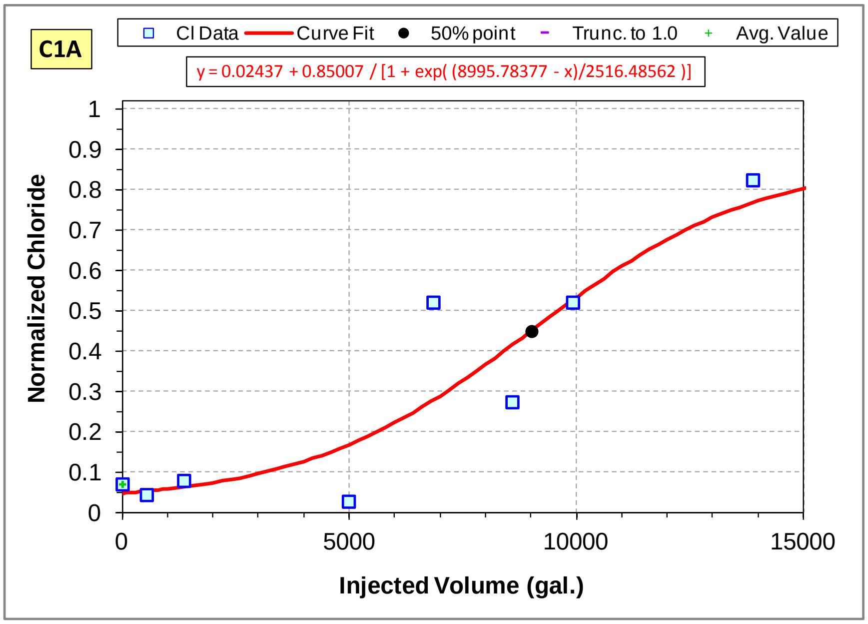
MW2	
Injected Volume (gal.)	Normalized Bromide Concentration
0	0.0020
7601	0.4040
9927	0.4848
14040	0.5253



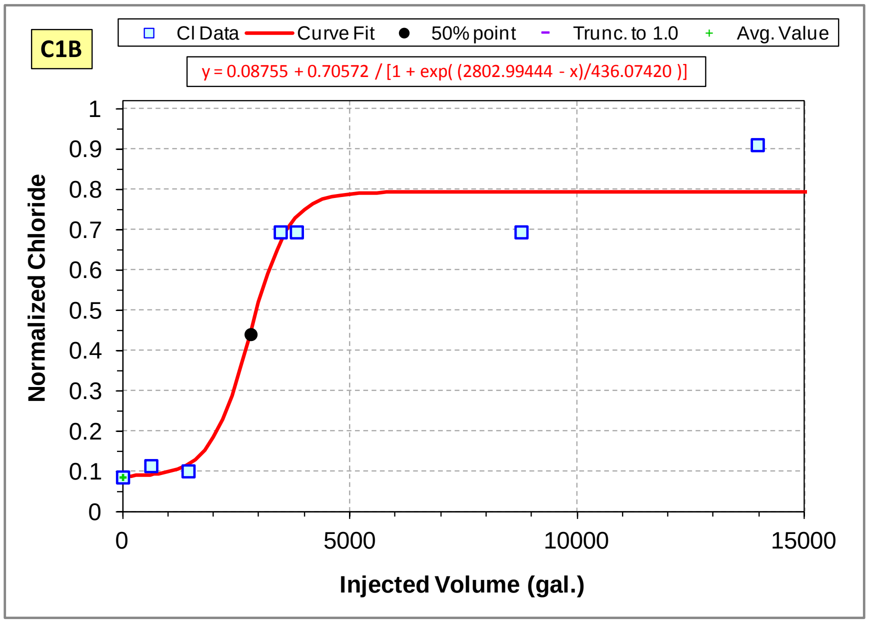
CHLORIDE TRACER DATA FROM STF INJECTION TEST

C1A	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0649
533	0.0429
1353	0.0779
4980	0.0264
6843	0.5195
8581	0.2727
9915	0.5195
13878	0.8225
18000 [a]	0.8225 [a]

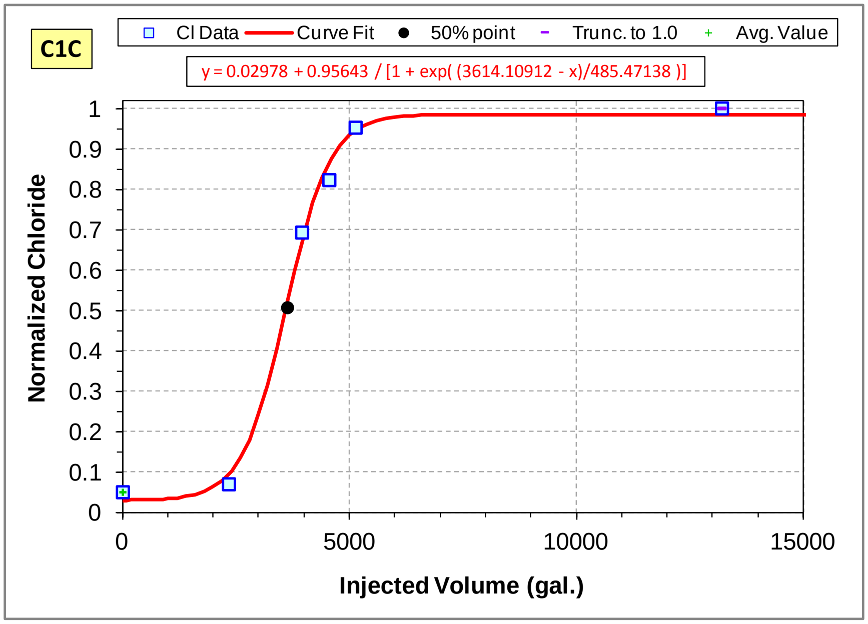
[a] Because of the nature of the data, a control point was added at a volume of 18,000 gallons so that the data could be fit to a sigmoidal curve.



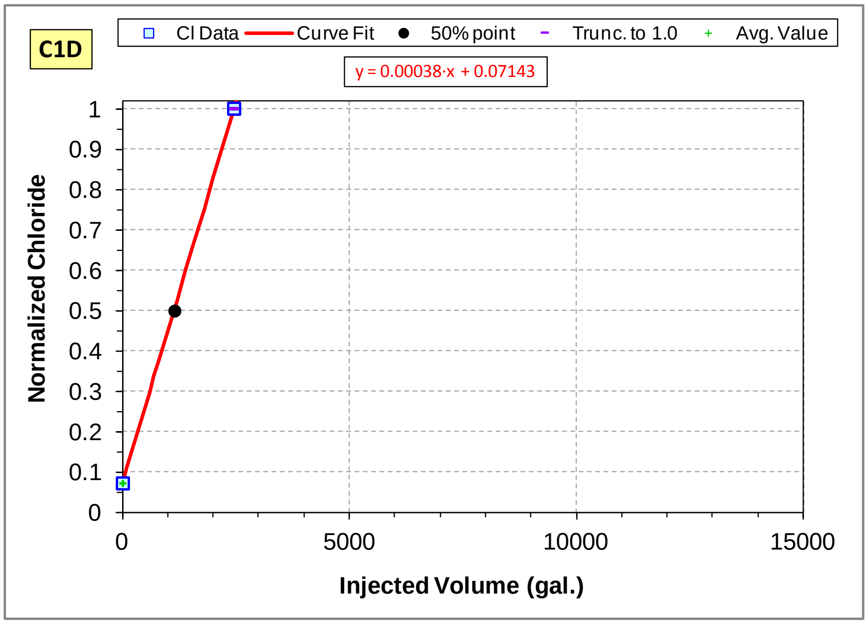
C1B	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0844
622	0.1126
1441	0.0996
3469	0.6926
3824	0.6926
8767	0.6926
13964	0.9091



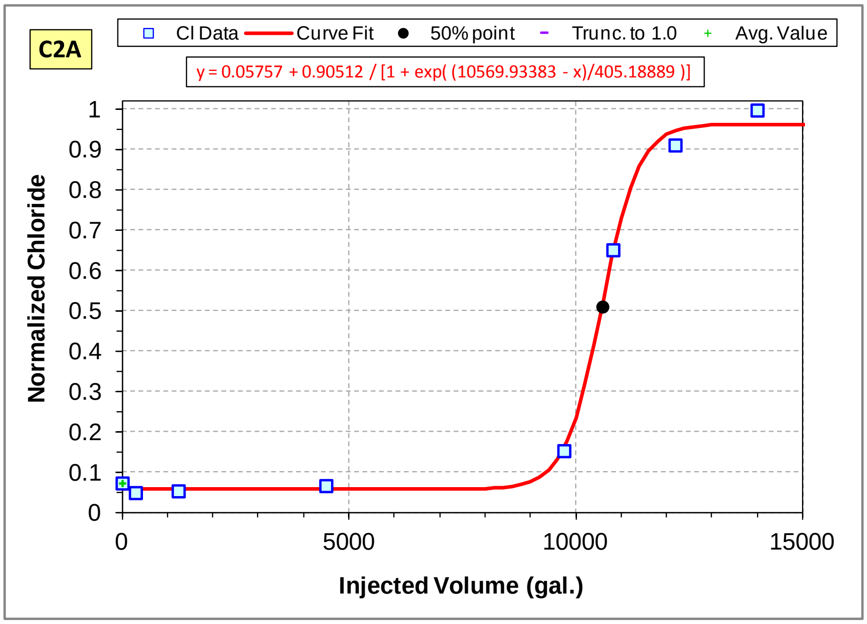
C1C	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0496
2336	0.0693
3948	0.6926
4547	0.8225
5126	0.9524
13196	1.0000



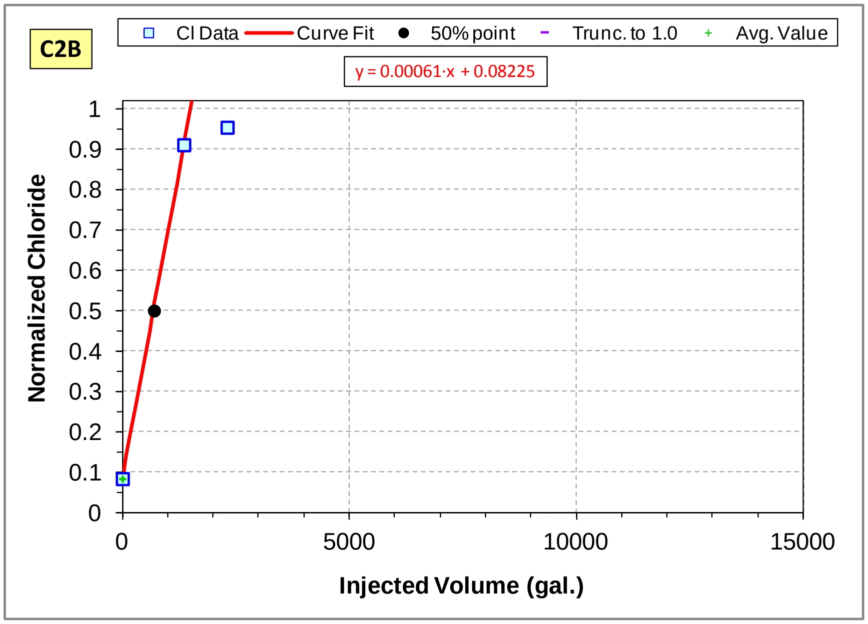
C1D	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0714
2451	1.0000



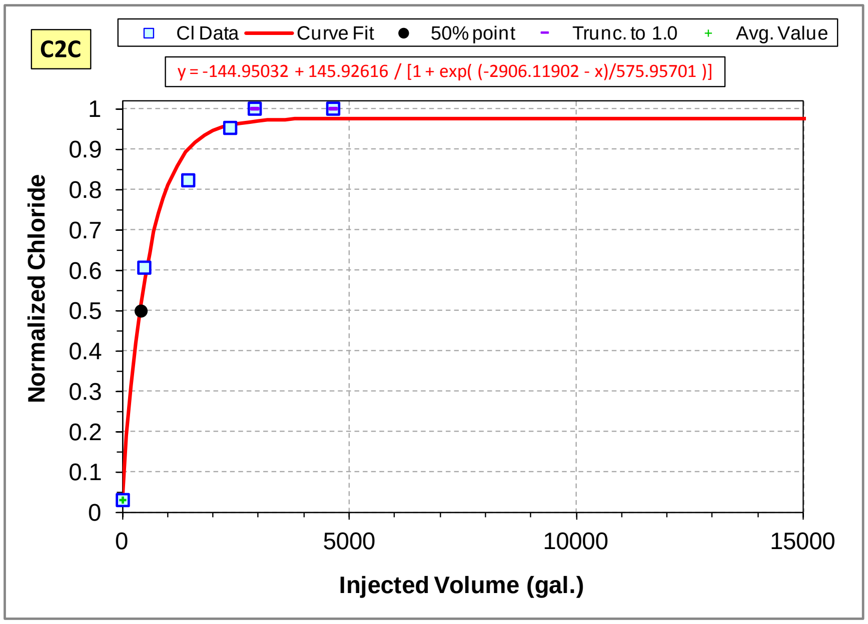
C2A	
Injected Volume (gal.)	**Normalized Chloride Concentration**
0	0.0714
292	0.0476
1236	0.0519
4489	0.0649
9734	0.1515
10815	0.6494
12185	0.9091
13993	0.9957



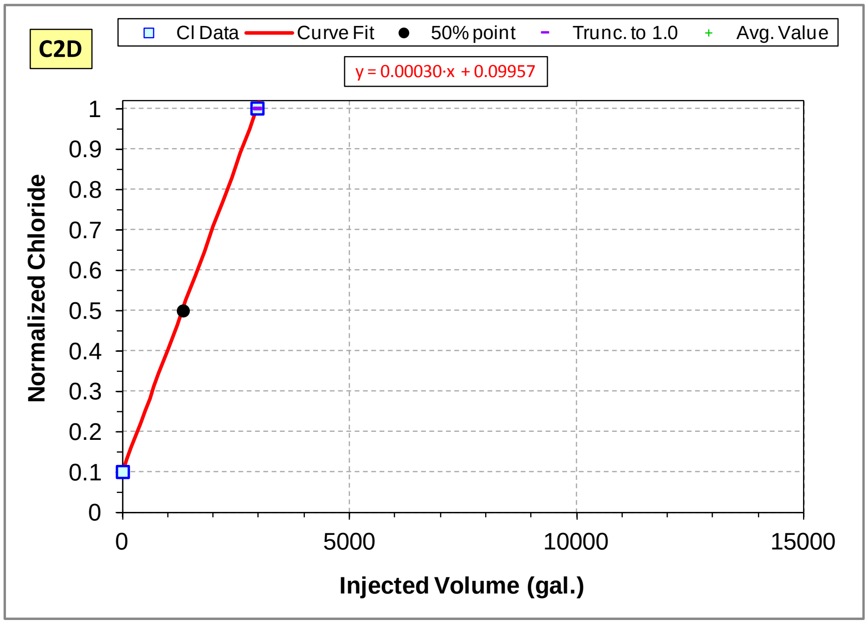
C2B	
Injected Volume (gal.)	**Normalized Chloride Concentration**
0	0.0823
1353	0.9091
2308	0.9524



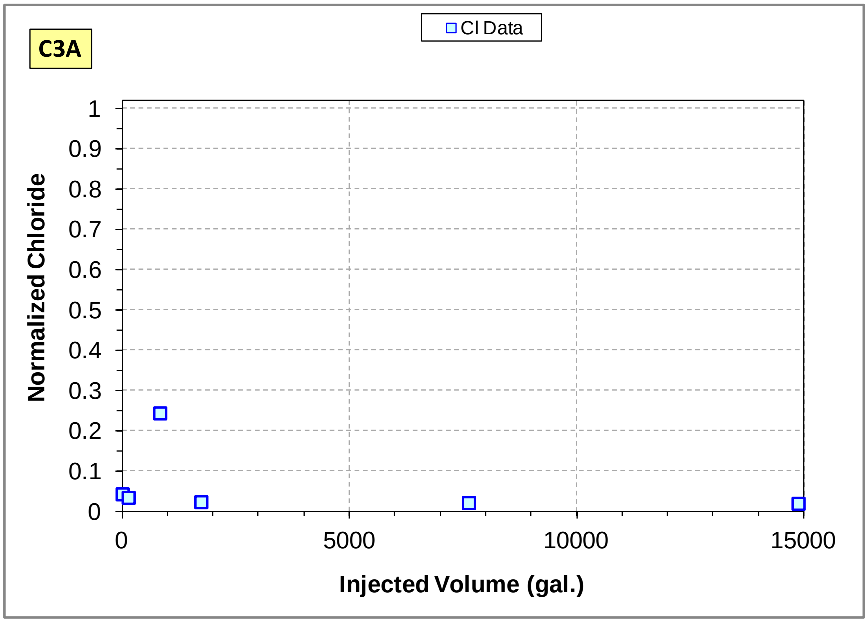
C2C	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0301
473	0.6061
1441	0.8225
2365	0.9524
2906	1.0000
4634	1.0000



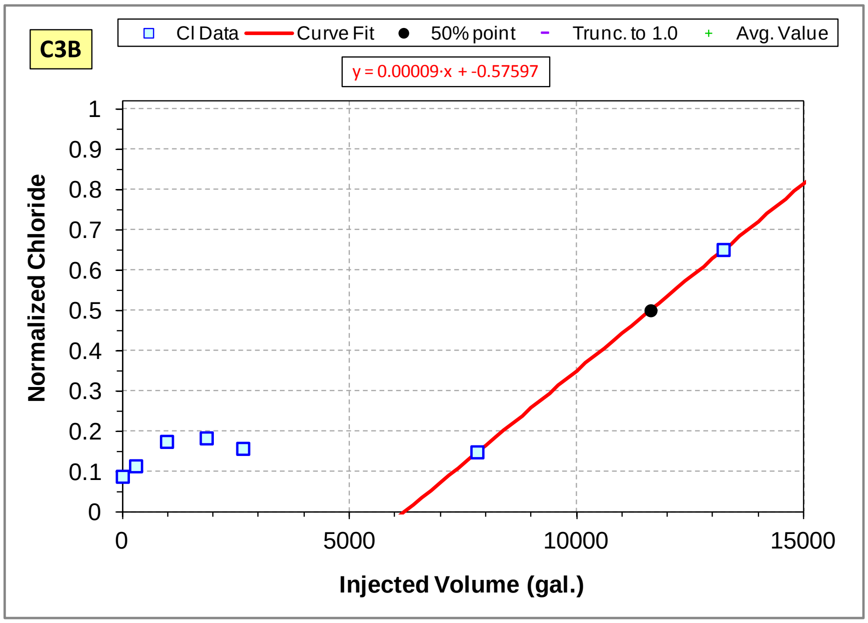
C2D	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0996
2963	1.0000



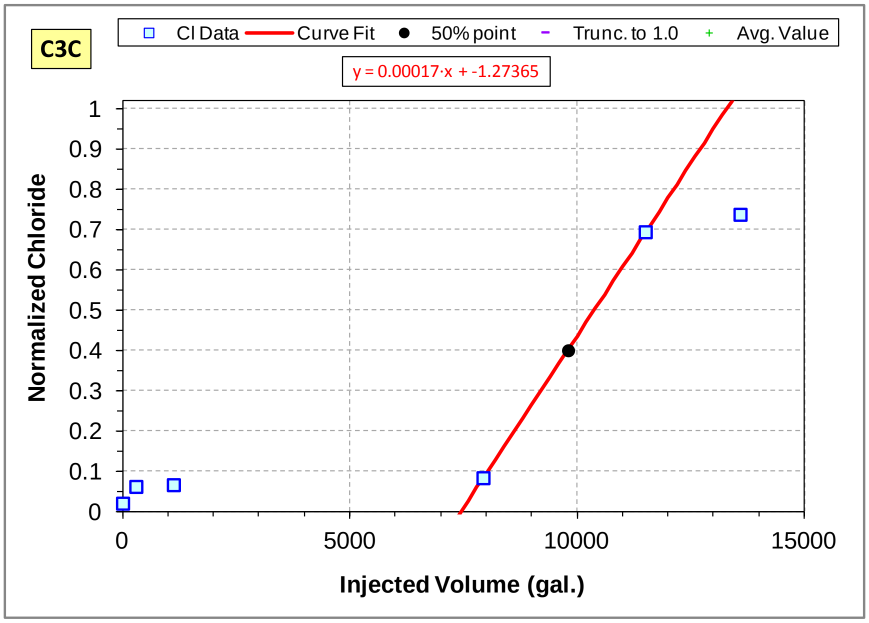
C3A	
Injected Volume (gal.)	**Normalized Chloride Concentration**
0	0.0416
132	0.0329
827	0.2424
1732	0.0221
7620	0.0199
14871	0.0182



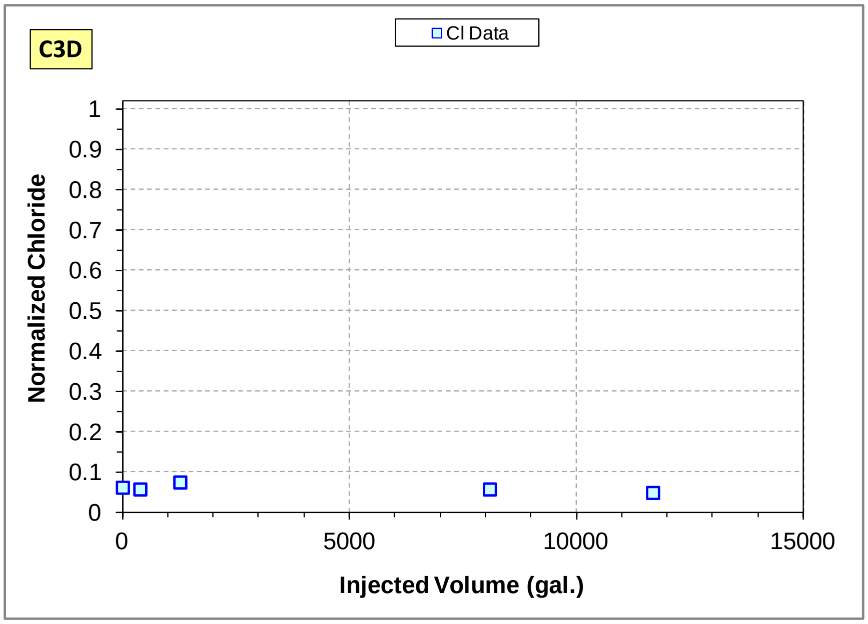
C3B	
Injected Volume (gal.)	**Normalized Chloride Concentration**
0	0.0866
292	0.1126
973	0.1732
1847	0.1818
2650	0.1558
7806	0.1472
13226	0.6494



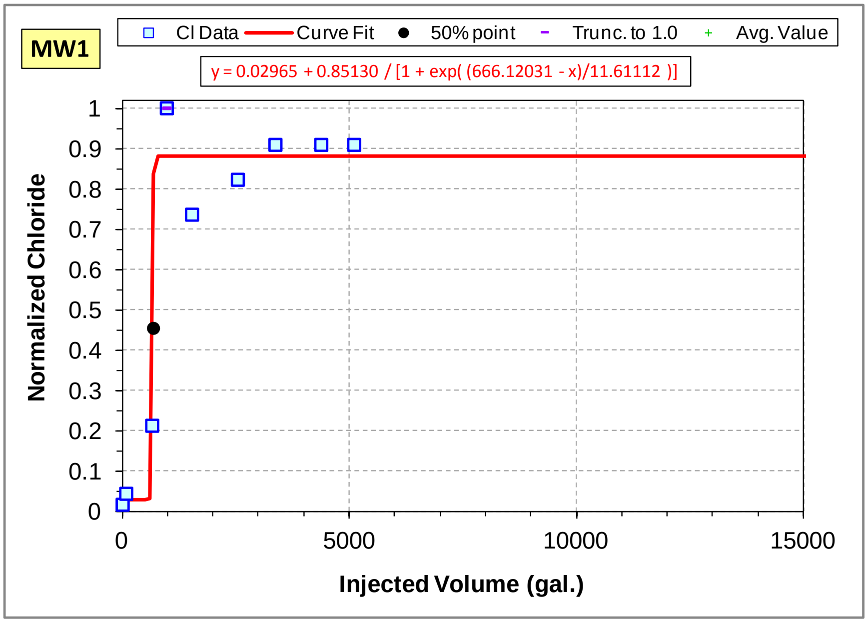
C3C	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0190
292	0.0606
1118	0.0649
7930	0.0823
11500	0.6926
13585	0.7359



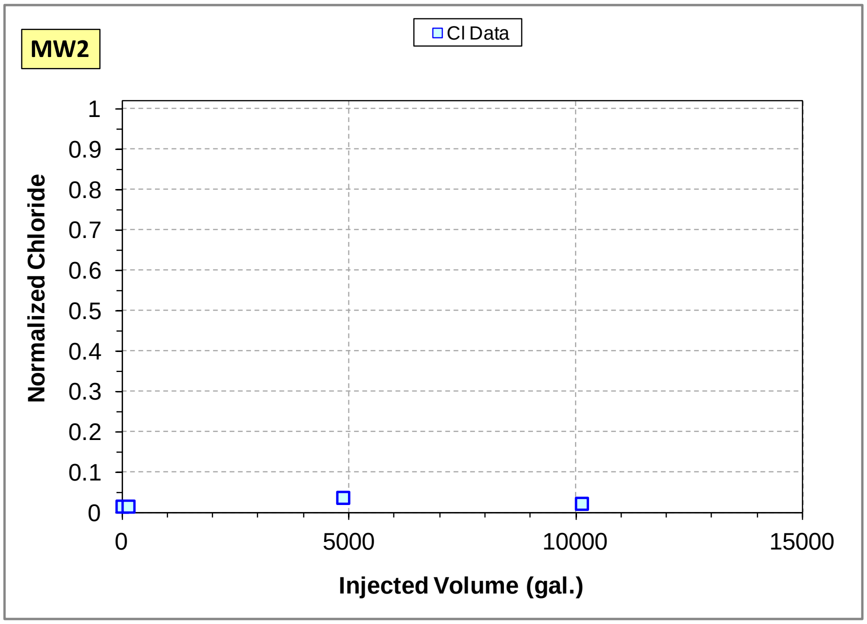
C3D	
Injected Volume (gal.)	Normalized Chloride Concentration
0	0.0606
385	0.0563
1265	0.0736
8085	0.0563
11678	0.0476



MW1	
Injected Volume (gal.)	**Normalized Chloride Concentration**
0	0.0160
79	0.0433
651	0.2121
973	1.0000
1528	0.7359
2537	0.8225
3363	0.9091
4372	0.9091
5097	0.9091



MW2	
Injected Volume (gal.)	**Normalized Chloride Concentration**
0	0.0143
132	0.0143
4864	0.0359
10125	0.0212



APPENDIX G

Cost Model

GSI Job Number: G-3444/G-3916
Issued: July 2014
Page 1 of 1

TABLE G.1
COST MODEL WITH BASELINE RESULTS

Enhanced Amendment Delivery to Low-Permeability Zones for Chlorinated Solvent Source Area Bioremediation
ESTCP ER-200913

		SCENARIO 1		SCENARIO 2			
COST ELEMENT	**DATA TRACKED OR ESTIMATED**	**Value**	**Single Injection of STF (Duration = 3 days)**	**Value**	**STF Injections Followed by Site Closure (Duration = 5 years)**	**Value**	**Conventional Amendment Injections Followed by MNA (Duration = 30 years)**
TASK 1. Laboratory Study and Amendment Selection							
Materials	Xanthan, carbon substrate, glassware		$500		$500		
Testing							
ESGH III	Labor (ESGH III) (hr)	40	$5,200	40	$5,200		
Analytical costs	Assumed rheometer available for use		$500		$500		
Task 1 Total			**$6,200**		**$6,200**		**$0**
TASK 2. Conventional In Situ Bioremediation							
Injection of conventional substrate	Treatment Volume (ft3)	6,280	$17,444	6,280	$23,259	6,280	$34,889
based on unit cost of $100 per cubic yd	Unit Cost (adjusted based on injection frequency) ($	75		100		150	
for 2 full-scale injection events with	Number of Injection Wells	1		1		1	
25% cost difference for each additional event	Idealized Radius of Influence per well (ft)	10		10		10	
	Treatment Area (ft2)	**314**		**314**		**314**	
	Thickness of Treatment Interval (ft)	20		20		20	
	Porosity	0.2		0.2		0.2	
	Idealized Pore Volume (gallons)	9,395		9,395		9,395	
	Number of Pore Volumes per Well	2		2		2	
	Number of Pore Volumes for Entire Site	2		2		2	
	Injection rate for comparison to STF injection (gpm)	30		30		30	
	Injection frequency	1		2		4	
	Total time required for injection (hr)	10		21		42	
TASK 2 Total			**$17,444**		**$23,259**		**$34,889**
TASK 3. Shear-Thinning Fluid Preparation and Injection (costs beyond conventional in situ bioremediation							
Project management	Labor (Sr ESGH), 10 hr per event (hr)	10	$1,900	10	$3,800		
Equipment	Rental of extra tank, mixer, pump		$5,000		$10,000		
Injection Rate	Injection rate used as basis for comparison to conventional injection (gpm)	30		30			
Extra time required for STF injection	Prep + difference in injection rates between STF and conventional (hr)	8		16			
Field Labor							
ESGH III	Labor - ESGH III (hr)	8	$1,040	16	$2,080		
Tech	Labor - Tech (hr)	8	$800	16	$1,600		
Tech	Labor - Tech (hr)	8	$800	16	$1,600		
Material	Estimated based on pore volumes injected and concentration		$496		$992		
Xanthan Gum	Concentration (mg/L)	800		800			
	Number of Pore Volumes	2		2			
	Number of Injection Wells	1		1			
	Injection Frequency	1		2			
	Total Mass (lb)	33		33			
	Xanthan gum unit cost ($/lb)	15		15			
Analytical	Subcontracted; confirmatory measurements following injection						
TOC	Number of samples at $20/sample	10	$200	10	$400		
Shipping and miscellaneous costs			$500		$1,000		
TASK 3 Total			**$10,736**		**$21,472**		**$0**
TASK 4. Modeling							
Not Included							
Task 4 Total			**$0**		**$0**		**$0**
TASK 5. Other Characterization/Reporting in Support of Remedy Selection/Design							
Not included							
Task 5 Total			**$0**		**$0**		**$0**
TASK 6. Well Installation (monitoring wells, injection wells, extraction wells)							
Not included (no unique costs)							
TASK 6 Total			**$0**		**$0**		**$0**
TASK 7. Treatment System Design and Installation							
Not included (no unique costs)							
TASK 7 Total			**$0**		**$0**		**$0**
TASK 8. Treatment System Operations and Maintenance							
Not included (no unique costs)							
TASK 8 Total			**$0**		**$0**		**$0**
TASK 9. Long-Term Monitoring							
Project management	Labor (Sr ESGH), 4 hr per event (hr)				$7,600		$45,600
Number of Events over project lifetime				10		60	
	Number of Events per year			2		2	
	Number of Years (yr)			5		30	
Number of Wells sampled over project lifetime				30		180	
	Number of Wells sampled per event			3		3	
Field Labor	Total over project lifetime						
ESGH I	Labor, 10 hr per 8 wells + 2 hr prep/wrap-up (hr)			58	$5,750	345	$34,500
Analytical	Subcontracted						
VOCs	Number of samples at $100/sample (including 10% duplicates)			33	$3,300	198	$19,800
TOC	Number of samples at $20/sample (including 10% duplicates)			33	$660	198	$3,960
Consumables, shipping, and misc. costs	$500 per event				$5,000		$30,000
Data review and reporting	Total over project lifetime						
ESGH I	Labor, 10 hr per event			100	$10,000	600	$0
TASK 9 Total			**$0**		**$32,310**		**$133,860**
TASK 10. Closeout and Decomissioning							
Not included (no unique costs)							
TASK 10 Total			**$0**		**$0**		**$0**
TASK 11. Final Reporting							
Not included (no unique costs)							
TASK 11 Total			**$0**		**$0**		**$0**
CONTINGENCY (15%)			$5,157		$12,486		$25,312
TOTAL COST			**$39,538**		**$95,728**		**$194,061**
COST PER INJECTION LOCATION			**$39,538**		**$95,728**		**$194,061**
COST PER FT			**$1,977**		**$4,786**		**$9,703**
LIFE-CYCLE COST PER CUBIC YD TREATED			NA		**$412**		**$834**