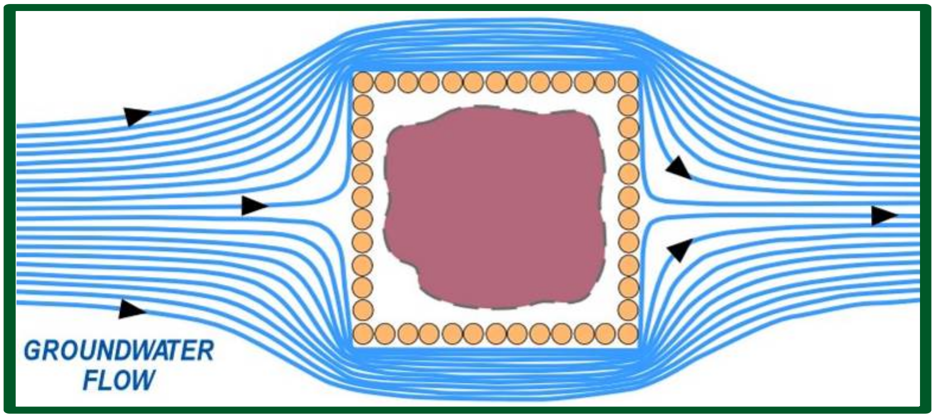
ESTCP
Cost and Performance Report

(ER-201328)



Contaminant Flux Reduction Barriers for Managing Difficult-to-Treat Source Zones in Unconsolidated Media

June 2017

This document has been cleared for public release;
Distribution Statement A

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Page Intentionally Left Blank

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)* 20/06/2017	**2. REPORT TYPE** Cost & Performance Report	**3. DATES COVERED** *(From - To)* Oct 2013 to June 2017

4. TITLE AND SUBTITLE

Contaminant Flux Reduction Barriers for Managing Difficult-to-Treat Source Zones in Unconsolidated Media

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Poonam R. Kulkarni, Elaine A. Higgins, Brian A. Strasters, Charles J. Newell

5d. PROJECT NUMBER
ER-201328

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
GSI Environmental Inc.
2211 Norfolk, Suite 1000
Houston, Texas 77098

8. PERFORMING ORGANIZATION REPORT NUMBER
ER-201328

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Environmental Security and Technology Certification Program
4800 Mark Center Drive, Suite 17D08
Alexandria, VA 22350-3600

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
ER-201328

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The overall objective of this project was to evaluate if inexpensive flow reduction agents delivered via permeation grouting technology could help manage difficult-to-treat chlorinated solvent source zones. This approach aims to provide two benefits for improving groundwater quality at chlorinated volatile organic carbon (CVOC) sites by: 1. physically reducing the mass flux of contaminants leaving the source zone by using permeation grouting, thereby reducing risk and making the downgradient plume more amenable for management by natural attenuation processes; and 2) increasing the Natural Source Zone Depletion (NSZD) rate within the source by diverting competing electron acceptors around the source zone to create an enhanced reductive dechlorination zone (ERDZ). This report describes the results of a Small-Scale Demonstration that achieved an average 64% reduction in flow through three small barriers. This was lower than the performance objective of a 90% reduction in flow and was likely caused by the low permeability of the silty sands in the test area. Finally, applications of one acre in area or more are significantly less costly than conventional in-situ remediation technologies ($996K per acre and $21 per cubic yard for a one acre site).

15. SUBJECT TERMS
Barrier, ERDZ, NSZD, Chlorinated Solvents, Grouting

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Charles J. Newell
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**		66	**19b. TELEPHONE NUMBER** *(include area code)* 713-522-6300

Page Intentionally Left Blank

COST & PERFORMANCE REPORT

Project: ER-201328

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

Page

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

bgs	Below ground surface
$CaCl_2$	Calcium chloride
cis-1,2-DCE	cis-1,2-dichloroethylene
cm/sec	centimeter per second
cP	centipoise
CVOC	chlorinated volatile organic carbon
DBE	dibasic ester
DNAPL	Dense Non-Aqueous Phase Liquid
DoD	Department of Defense
ERDZ	Enhanced Reductive Dechlorination Zone
ESTCP	Environmental Security Technology Certification Program
EVO	Emulsified vegetable oil
ft	Foot, feet
ft^2	Square foot, feet
gal	gallons
gpm	gallons per minute
in	inch
IDSS	Integrated DNAPL Site Strategy
kg	kilogram
L	Liter
m	meters
m^2	square meter
mg	milligram
MNA	Monitored Natural Attenuation
Msl	Mean sea level
NaSi	Sodium silicate
NSF	Naval Support Facility
NSZD	Natural Source Zone Depletion (NSZD)
OoM	Order of Magnitude
PFM	Passive Flux Meter
PVC	Polyvinyl chloride

SERDP	Strategic Environmental Research and Development Program
TCE	Trichloroethylene
V%	Percentage by volume
VC	Vinyl chloride
Wt-%	Percentage by weight
μg/L	micrograms per Liter
yd^3	cubic yard

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the financial and technical support provided by the Environmental Security Technology Certification Program (ESTCP) for this project. In particular, we would like to thank Andrea Leeson and the ESTCP Support Office staff for their valuable technical and operational assistance. The authors also wish to acknowledge Solution-IES for their contributions towards the treatability study and novel silica gel formulation.

Page Intentionally Left Blank

EXECUTIVE SUMMARY

Technology Description

The overall objective of this project was to evaluate if inexpensive flow reduction agents delivered via permeation grouting technology could help manage difficult-to-treat chlorinated solvent source zones. This approach aims to provide two benefits for improving groundwater quality at chlorinated volatile organic carbon (CVOC) sites by:

1. physically reducing the mass flux of contaminants leaving the source zone by using permeation grouting (Figure ES-1), thereby reducing risk and making the downgradient plume more amenable for management by natural attenuation processes; and

2. increasing the Natural Source Zone Depletion (NSZD) rate within the source by diverting competing electron acceptors (e.g., dissolved oxygen, nitrate, and sulfate) around the source zone to create an enhanced reductive dechlorination zone (ERDZ) (Figure ES-2).

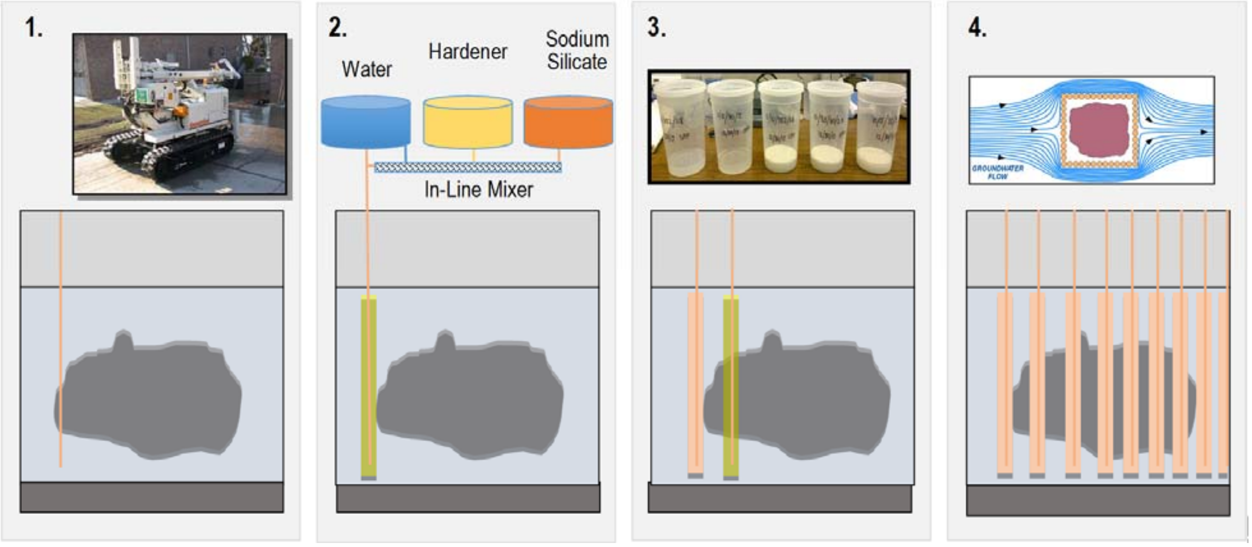


Figure ES-1: Permeation Grouting Sequence

1. A small injection point (either inexpensive single use multi-level well or direct push injection point that injects while pulling up) is driven into source zone. 2. Water, hardener, and silica gel are mixed on the surface and injected as a liquid into the injection point, filling up the pore space of the sands. 3. After 0.5 to 4 hours, the silica gel changes from liquid state to a gel state, greatly reducing the water flow through the sand/gel mix. 4. The process is repeated by drilling and injecting in adjacent injection points (spaced 0.8 to 2 m apart), forming a barrier surrounding the source.

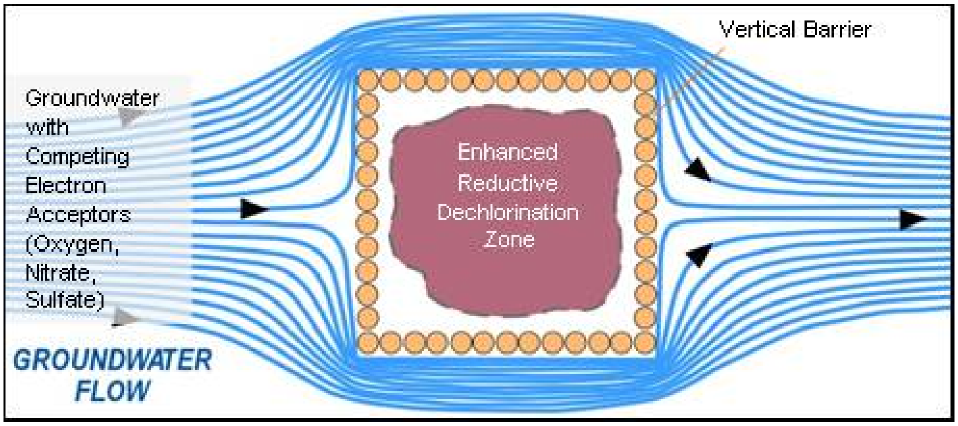


Figure ES-2: Enhanced Reductive Dechlorination Zone Concept

Electron acceptors that flow into a CVOC source zone can consume valuable electron donor. Diverting them can increase the NSZD rate.

Objectives of the Demonstration

In addition to the objectives highlighted above, the demonstration included the following tasks:

- <u>Task 1: Research Flux Reduction Materials</u>: Several novel silica gel/vegetable oil-formulations were developed and tested in lab-scale batch and column studies by project team member Solutions-IES. In a parallel effort, the technical literature regarding properties and field injection protocols of conventional silica gel was reviewed and supplemented with confirmation lab tests at GSI to select the most cost-effective silica gel material and the specific silica gel hardening reagent necessary for subsurface gelling. The results of this evaluation were used to select one type of silica gel and a vegetable-oil formulation for the Small-Scale field demonstration (Task 2).
- <u>Task 2: Perform a Small-Scale Field Demonstration:</u> Test cells were constructed in an unimpacted zone at the demonstration site. Two cells were constructed with the selected silica gel solution and two cells were constructed with the vegetable-oil formulation developed by Solutions IES. The main goal of the Small-Scale demonstration was show positive performance of a small barrier test cell, and to demonstrate how commonly used remediation equipment (direct push rigs, injection skids) can be adapted to make permeation grouting barriers.
- <u>Task 3: Expand to a Large-Scale Field Demonstration:</u> The results of Task 2 (Small-Scale Field Demonstration) were designed to make a go / no-go decision for a larger-scale technology demonstration. Key performance metrics involved the measurement of the change in mass flux, hydraulic gradient and geochemical parameters. Because the design work on Task 3 was conducted partly in parallel to the other Tasks, a site had been selected, a conceptual design completed, and some detailed design work was performed. However, the results of the Small-Scale Field Demonstration did not reach the pre-established performance goals and therefore the Large-Scale Field Demonstration was not performed.

Demonstration Results

The project demonstration had these results:

- Two grout mixtures were selected based on gel tests and a treatability study by Solutions-IES:
  - A *Silica Gel Grout:* 10 vol-% of sodium silicate (NaSi), 5 vol-% of dibasic ester (DBE) hardener, and 85 vol-% of water. This formulation had a gel time of approximately 4 hours and had an estimated viscosity of 3-4 centipoise (cP).
  - *Solutions-IES Novel Silica Gel/Veg-Oil Grout:* 5 percentage by weight (wt-%) of emulsified vegetable oil (EVO), 10 wt-% of NaSi, 1.8 wt-% of DBE, and 83 wt-% of water. This formulation provided a 3-4 orders of magnitude reduction in lab permeability tests, and a gel time of 18 hours.

- A description of a Small-Scale Demonstration that achieved **an average 64% reduction** in flow through three small barriers. This was lower than the performance objective of a 90% reduction in flow and was likely caused by the low permeability of the silty sands in the test area.
- A Large Scale Demonstration was not performed due to the low permeability of the planned test area. However, based on standard geotechnical practice, 90% groundwater flow reduction with silica gel permeation grouting is likely achievable at sites with the main transmissive units having hydraulic conductivity closer to the optimal range (from 5×10^{-4} to 10^{-2} centimeter per second [cm/sec]).

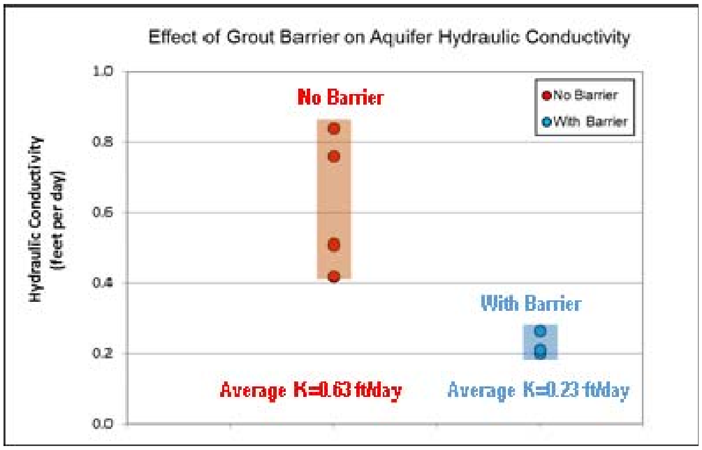


Figure ES-3: Results of Small-Scale Demonstration

- Performance of 90% groundwater flow reduction with silica gel grouting is likely achievable at sites with the main transmissive units having hydraulic conductivity closer to the optimal range (from 5×10^{-4} to 10^{-2} cm/sec).
- Applications of one acre in area or more are significantly less costly than conventional in-situ remediation technologies ($996K per acre and $21 per cubic yard for a one acre site).

Implementation Issues

- This Environmental Security Technology Certification Program (ESTCP) demonstration was able to use existing remediation technology (direct push rigs and injection skids) to build four small barriers for the Small-Scale Demonstration.
- The mixing process is generally more complex than standard injection-based remediation projects because the injection skid needs to mix three fluids, delivery multiple locations simultaneously, let operators see pressure, flowrate, and have contingency for grout set-up in the injection manifolds. The design described in the Final Technical Report worked well.
- It was difficult to assess performance of the barrier for the Small-Scale Demonstration at the chosen location. Contributing factors include:
  - The hydraulic conductivities were relatively low (0.63 feet [ft] per day [$2x10^{-4}$ cm/sec]) resulting in low pumping rates (< 0.1 gallons per minute [gpm]) and low volumes of extracted groundwater during the before- and after-tests (< 20 gallons [gal]);
  - Potential construction problems associated with the multi-level injection wells in a very fine-grained heterogeneous unit as one injection well had to be abandoned.
- The “donut” configuration (Section 5.1.2) may have not been efficient at testing the permeation grouting process; a larger demonstration area may have resulted to better test data. However, using constant head injection tests, **an average of 64% reduction in flow resulted**, which is significant but below the 90% reduction performance goal. This result, and relatively low hydraulic conductivities in the planned Northern Plume test area, led to the decision not to perform the Large-Scale Demonstration.
- Applications for the flux reduction technology are likely to have better performance at sites with higher permeability and higher groundwater velocity than at the site used for the demonstration, both for demonstrating the hydraulic effect of the barrier and the benefits from electron acceptor diversion.

1.0 INTRODUCTION

The overall objective of this project was to evaluate if inexpensive flow reduction agents delivered via permeation grouting technology could help manage difficult-to-treat chlorinated solvent source zones. This approach aims to provide two benefits for improving groundwater quality at chlorinated volatile organic carbon (CVOC) sites by:

1. physically reducing the mass flux of contaminants leaving the source zone, thereby reducing risk and making the downgradient plume more amenable for management by natural attenuation processes; and
2. increasing the Natural Source Zone Depletion (NSZD) rate within the source by diverting competing electron acceptors (e.g., dissolved oxygen, nitrate, and sulfate) around the source zone to create an enhanced reductive dechlorination zone (ERDZ). The influx of competing electron acceptors into treatment zones can consume a large fraction of the available electron donor supply at bioremediation sites, necessitating more frequent substrate reinjection.

Natural Source Zone Depletion (NSZD) and Enhanced Reductive Dechlorination Zones (ERDZs)

NSZD is the term for the attenuation of the source zone itself at a contaminated groundwater site from processes such as mass loss to moving groundwater and biodegradation in the source zone (Newell et al., 2014)

One way to increase NSZD rates at chlorinated solvent sites is to use a barrier to divert competing electron acceptors (oxygen, nitrate, and sulfate) around the source zone, thereby making the geochemistry inside the barrier more conducive for anaerobic biodegradation. This is called an ERDZ (Kamath et al., 2008)

1.1 BACKGROUND

The Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program (SERDP/ESTCP) recently identified *"Treatment of Contaminants in Low-K Zones"* as a "High" Research and Development need for the Department of Defense (DoD) remediation program (Leeson and Stroo, 2011). These types of sites represent an increasing fraction of the DoD's chlorinated site portfolio, as the easier and smaller source zones are successfully treated. For example, sites dominated by matrix diffusion-type sources from low permeability (Low-K) zones are increasing for two reasons: (1) untreated sites continue to age and transform from Middle Stage sites (sites where Dense Non-Aqueous Phase Liquid [DNAPL] sources are active) to Late Stage Sites (sites where matrix diffusion sources dominate) (Sale et al., 2008); and (2) more chlorinated solvent sources zones are treated and the bulk of the DNAPL is removed, but the low-permeability source zones are still too strong to close the site or rely on monitored natural attenuation (MNA) processes.

One of the likely side effects of matrix diffusion dominated sites is concentration rebound after in-situ treatment. This has been commonly observed at sites treated with chemical oxidation (e.g., McGuire et al, 2005; Krembs et al., 2010), and it has been speculated that rebound can occur at sites treated with in-situ bioremediation if monitoring is continued for longer periods. A key paper describing sustained treatment (Adamson et al., 2011) makes the case that even for apparent long-lasting technologies, some of the treatment effects will diminish over time, and that periodic reapplication of treatment chemicals may be needed over the lifetime of the site. If this is the case, then the DoD's remediation liability over the decades-long periods that these sources will be active may be much larger than currently estimated.

For these long-lived, difficult-to-treat sites, inexpensive (in units of dollars per cubic yard, or dollars per acre) technologies are needed that can: (1) immediately and reliably address the key problem associated with these recalcitrant source zones, specifically the mass flux of contaminants leaving the source zone; (2) increase the actual treatment of the contaminants leaving Low-K source zones, or DNAPL; and (3) last for decades or longer. To evaluate the impact of remediation at these sites, mass flux (or mass discharge) is the most useful measurement because it establishes the amount of mass per unit time leaving the source zone (Newell et al., 2011).

Contaminant flux reduction barriers can potentially prove to be an innovative application of existing technologies that can meet these objectives inexpensively and reliably. This technology provides long-term (decades) or permanent treatment of source zones where the mass flux is greatly reduced, back diffusion and DNAPL sources are reliably managed, and contaminant attenuation rates within the source zone are substantially increased. Unit costs for flux reduction treatment of an acre site are anticipated to be ~ $21 per cubic yard and < $1 million per acre. This is significantly less than reported unit cost for in-situ biodegradation ($30-180 per cubic yard), chemical oxidation (median $125 per cubic yard), and thermal remediation (median $161 per cubic yard) (McGuire et al., 2016); and lower than the analysis presented in Sale et. al. (2008) that showed that costs for chlorinated solvent source zone remediation “will range between $1 million and $5 million per acre.” For the performance criteria for this project, it was assumed a typical in-situ remediation cost of $**3 million per acre.**

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this ESTCP field demonstration was to: (1) evaluate different flux reduction agents, including novel materials; (2) conduct a Small-Scale field study to evaluate permeation grouting materials in terms of cost, ease of installation, and performance (i.e., flux reduction properties) and (3) conduct a Larger-Scale field demonstration with the best-performing material to evaluate the reduction in contaminant mass flux and hydraulic gradient and the creation of enhanced anaerobic conditions for contaminant biodegradation.

Permeation Grouting

Permeation grouting is the flow of grout into the pores of the soil, without displacing or changing the soil structure, resulting in modification of the characteristics of the ground with the hardening or gelling of the grout. One way permeation grouting is used is o decrease the permeability of the soil or provide "watertightening" (Powers et al., 2007)

Specific performance objectives and success criteria are described in Section 3.

1.3 REGULATORY DRIVERS

SERDP/ESTCP recently identified *“Treatment of Contaminants in Low-K Zones”* as a “High” Research and Development need for the DoD remediation program (Leeson and Stroo, 2011). These types of sites represent an increasing fraction of the DoD’s chlorinated site portfolio, as the easier and smaller source zones are successfully treated. For example, sites dominated by matrix diffusion-type sources from low permeability (Low-K) zones are increasing for two reasons: (1) untreated sites continue to age and transform from Middle Stage sites (sites where DNAPL sources are active) to Late Stage Sites (sites where matrix diffusion sources dominate) (Sale et al., 2008); and (2) more chlorinated solvent sources zones are treated and the bulk of the DNAPL is removed, but the low-permeability source zones are still too strong to close the site or rely on MNA processes.

The National Research Council (NRC) has recently advanced an important new concept about managing contaminated groundwater sites called a Transition Assessment. Despite years of effort and considerable investment, many sites “will require long-term management that could extend for decades or longer.” The NRC discusses the need for developments that can aid in “transition from active remediation to more passive strategies and provide more cost-effective and protective long-term management of complex sites,” including conducting formal Transition Assessments. This concept, which is an intrinsic part of the ITRC’s Integrated DNAPL Site Strategy (IDSS) framework, has now been validated by a key U.S. scientific body, the National Research Council.

The Contaminant Flux Reduction Barrier technology is targeted to address sites dominated by matrix diffusion and that are candidates for long-term passive management of a site. At these sites, further active remediation (such as chemical oxidation, bioremediation, chemical reduction, thermal treatment) will likely not change the long-term management of the site because of the residual contaminants in low permeability zones. If MNA will not be protective, there is a need for a technology that will reduce the mass flux from these zones and have the potential for some accelerated NSZD of the remaining chlorinated solvent mass.

Page Intentionally Left Blank

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The technology combines the concepts of source zone attenuation, high-resolution mass flux, and enhanced biodegradation. The original concept was to reduce groundwater flow by reducing the "mobile porosity" of the saturated zone, which carries most of the groundwater flow and typically ranges from 0.02 to 0.10 (e.g., 2% to 10% of the pore space carries most of the groundwater flow (Payne et al., 2008). By using permeation grouting for "water tightening," liquid injectable grouts are injected into the subsurface and naturally flow into the mobile porosity. The grouts contain a hardening agent that converts the liquid grout into a solid gel that blocks groundwater flow through the pore space. One key concept is that the technology is designed to reduce, but not totally eliminate groundwater flow through the barrier. Water tightening by geotechnical contractors inherently has some residual flow, which is important for this application to accommodate infiltration water that enters the enclosed source zone from the top. As described in Section 7, the concept of grouting just the mobile porosity was optimistic, and grouting the entire porosity (typical between 24% and 44%) in the volume of the barrier is required for a tight seal (90% reduction in groundwater flow or more).

A second benefit is that by creating a barrier around a treatment zone, groundwater flow carrying competing electron acceptors will be diverted, resulting in an engineered reaction zone similar to the ERDZ concept that was developed by Newell et al. (2003, 2004) and is part of the Biobalance Toolkit (Kamath et al., 2008). The reduction in competing electron acceptors in the treatment zone enables the appropriate geochemical environment for an ERDZ (Newell et al., 2004). A spreadsheet calculator for that lays out the calculations for estimating the benefits from a ERDZ is shown in Appendix A.

The specific tasks of the project are as follows:

1. <u>Task 1: Flux Reduction Material Formulation</u>: Several novel silica gel/vegetable oil-formulations were developed and tested in lab-scale batch and column studies by project team member Solutions-IES. Desired characteristics of the formulations were potential long-term restoration of permeability and the potential for enhanced biodegradation of contaminants in the small portion of groundwater passing through barrier (all groundwater barriers leak). In a parallel effort, the technical literature regarding properties and field injection protocols of conventional silica gel was reviewed and supplemented with confirmation lab tests at GSI to select the most cost-effective silica gel material and the specific silica gel hardening reagent necessary for subsurface gelling. The results of this evaluation were used to select one type of silica gel and a vegetable-oil formulation for the Small-Scale field demonstration (Task 2).

- <u>Task 2: Small-Scale Field Demonstration:</u> Test cells were constructed in a relatively unimpacted zone at the demonstration site. Two cells were constructed with the selected silica gel solution and two cells were constructed with the vegetable-oil formulation developed by Solutions IES. The main goal of the Small-Scale demonstration was show positive performance of a small barrier test cell, and to demonstrate how commonly used remediation equipment (direct push rigs, injection skids) can be adapted to make permeation grouting barriers.

- Task 3: Large-Scale Field Demonstration: The results of Task 2 (Small-Scale Field Demonstration) were designed to make a go / no-go decision for a larger-scale technology demonstration. Key performance metrics were to include the change in mass flux, hydraulic gradient and geochemical parameters will be measured. Because the design work on Task 3 was conducted partly in parallel to the other Tasks, a site had been selected, a conceptual design completed, and some detailed design work was performed. However, the results of the Small-Scale Field Demonstration did not reach the pre-established performance goals and therefore the Large-Scale Field Demonstration was not performed.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.2.1 Advantages of the Technology

The key advantage of this technology is that creating flow/mass flux reduction barriers around the perimeter of difficult-to-treat source zones is less expensive than treating the entire volume of the source zone. In addition, there are potential benefits of reducing the influx of competing electron acceptors, thereby establishing an Enhanced Reduction Dechlorination Zone at chlorinated solvent sites that already contain electron donors within the source zone.

Costing models show that this technology has the potential to be significantly cheaper (approximately $21 per cubic yard for large sites) (Section 6), provide better performance, and be more predictable and reliable than existing technologies for larger sites. Unlike most remediation systems in which costs are directly proportional to the size of treatment areas, this technology has decreasing costs per source zone area. If proven to be feasible, the proposed methods are also easy to implement and scale up, making them attractive options for closing large sites.

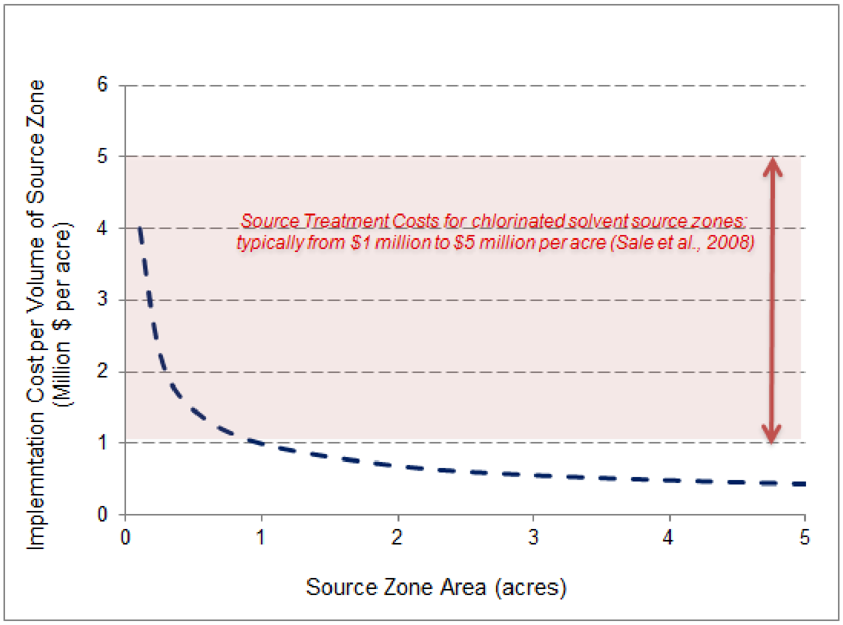


Figure 2.1: Approximate Cost Model for Application to Various Source Zone Areas

Additionally, little to no maintenance and operating costs are involved, making this a very cost-effective technology over the long term. The lifetime of most grouts is relatively long; for example cement grouts are expected last indefinitely unless in unusual groundwater conditions. One grouting reference (Karol, 2003) stated that silica gel grouts are expected to have a 50-year lifetime. The implementation of this technology also requires minimal subsurface disturbance and waste materials.

Finally, the technology provides an isolation of the source zone or plume, reduces mass discharge, and enhances biodegradation within the treatment zone.

2.2.2 Limitations of the Technology

Potential limitations of the technology include:

- No direct active treatment and reliance on NSZD alone for treatment may not be acceptable to site stakeholders. Even though the NSZD rate of the chlorinated solvents in the source zone is likely to be increased, longer remediation timeframes are expected compared to active treatment.
- The silica gel / injected materials are semi-permanent. As such, complete restoration of the treatment zone via natural groundwater flow to original conditions may be difficult;
- The technology does not control the vapor intrusion pathway, and other controls will be required if this pathway is active;
- At a small number of sites, the accumulation of water within the barriers and elevated water levels may occur if the barrier is too tight and does not have a method to release accumulated groundwater.
- Access may be a problem for construction of the barrier, but this is likely to be a much smaller problem compared to application of most in-situ treatment technologies.
- High mobilization costs may make the technology less cost effective for small sites.

Page Intentionally Left Blank

3.0 PERFORMANCE OBJECTIVES

Our overall objective was to demonstrate a treatment technology for difficult-to-treat chlorinated solvent source zones that focuses on *reducing the groundwater flow through a chlorinated solvent source zone*. There are two significant benefits associated with this approach: (1) it will reduce the mass flux of contaminants leaving the source zone; and (2) it will increase the biodegradation rate within the source as competing electron acceptors (dissolved oxygen, nitrate, and sulfate) are diverted around the source zone.

Specific performance objectives are summarized in Table 3.1.

Data from the Small-Scale demonstration was used to assess changes in flow reduction, which is generally proportional to mass flux reduction at most contaminated sites. As the Large-Scale Task 3 demonstration was not conducted, some performance objectives could not be evaluated.

Table 3.1: Performance Objectives of the Small-Scale and Large-Scale Demonstrations

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Evaluate flow-reduction materials in terms of cost and reduction in aquifer transmissivity	1. Unit cost for installing barrier for two injection materials (Small-Scale Demo); 2. Transmissivity of treatment zone before and after barrier installation (Small-Scale Demo); 3. Groundwater flow before and after barrier installation (Large-Scale Demo); 4. Change in hydraulic gradient (Large-Scale Demo)	Reduction in groundwater flow of at least 1 order of magnitude (OoM) (90% reduction)	NOT ACHIEVED: A 64% reduction in groundwater flow was estimated for the Small-Scale Demonstration; thereby the performance metric was not achieved.
Determine cost factors of technology relative to conventional remediation strategies	Project costs ($ per cubic yard and $ per acre); estimates for applying more conventional in-situ technologies at similar scale using literature values (e.g., McDade et al., 2005) (Large-Scale Demo)	Life-cycle cost (20 year time frame) for flux reduction material application < 50% of current in-situ treatment technologies for a 1-acre site.	ACHIEVED: Application of a revised cost model based on data from this study show 33% cost of typical in-situ remediation project of $3 million per acre (Sale et al.,2008) .
Evaluate reduction of mass flux at chlorinated solvent site	Mass flux of contaminants before and after barrier installation, determined through the use of Passive Flux Meters (PFMs) (Large-Scale Demo)	Mass flux reduction of similar OoM as reduction in groundwater flow: at least one OoM (90% reduction)	NOT APPLICABLE: The Large-Scale Demonstration was not performed so the performance metric was not evaluated.

Table 3.1: Performance Objectives of the Small-Scale and Large-Scale Demonstrations

Performance Objective	Data Requirements	Success Criteria	Results
Determine enhancement of anaerobic conditions within treatment zone once groundwater flow is diverted	Geochemical parameters such as dissolved oxygen, sulfate, nitrate, and oxygen-reduction potential (Large-Scale Demo)	Calculated 90% reduction in soluble electron acceptor flux using ESTCP Mass Flux Toolkit; calculated reduction in electron acceptor concentrations in treatment zone; evaluation of benefits using BIOBALANCE Tool.	NOT APPLICABLE: The Large-Scale Demonstration was not performed so the performance metric was not evaluated.
Qualitative Performance Objectives			
Ease of installation	Feedback from field personnel on material preparation and injection process, including pressures and rates	Material preparation and injection is predictable.	ACHIEVED: Based on the experience of the Small-Scale Demonstration, the process is moderately complex to implement in the field but with no major problems. This metric is considered to be achieved.

4.0 SITE DESCRIPTION

Site 17 at the Naval Support Facility (NSF), Indian Head in Indian Head, Maryland was selected for the field demonstration (Tasks 2 and 3), based on the following site criteria:

- Shallow depth to groundwater (<20 feet [ft])
- Transmissive zone preferably with an underlying clay layer
- Good accessibility to source zone
- Availability of detailed hydrogeological information
- Uncontaminated zone to perform the Small-Scale demonstration

Site 17 of the NSF is located on a stretch of shoreline along the Mattawoman Creek in Indian Head, Maryland. From the 1960s until the early 1980s, metals parts were discarded here, including shipping containers, empty drums, motor casings, and other various metals parts (CH2M-Hill, 2008). Two chlorinated solvent plumes have been characterized, namely the North Plume and South Plume. The South Plume was remediated using soil mixing, and the North Plume was selected as the location of the Large-Scale demonstration for this project (Figure 4.1).

One difficult aspect of this site was the relatively low groundwater flow rate at the site. This made conducting the Small-Scale demonstration and measuring flow reduction due to the barriers more challenging.

4.1 SITE LOCATION AND HISTORY

The Small-Scale demonstration was conducted in a non-impacted area near the existing building north of South Plume and east of North Plume (Figure 4.1). This area was clear of trees and offered suitable access for installation of the test cells. The area was also close to existing monitoring well IS17MW03, which was used to assess the geology and degree of contamination, as described below. Because the Small-Scale demonstration was performed in a clean zone, no mass flux or electron acceptors measurements were made; the field test focused on reduction in groundwater flow with the presence of the barriers.

The Large-Scale demonstration was to be applied within the North Plume area, near the shore of Mattawoman Creek. A number of monitoring wells are present in the area (i.e., IS17MW04, IS17MW11, IS17MW12, IS17MW13, and IS17MW04) as part of ongoing delineation work by the Navy.

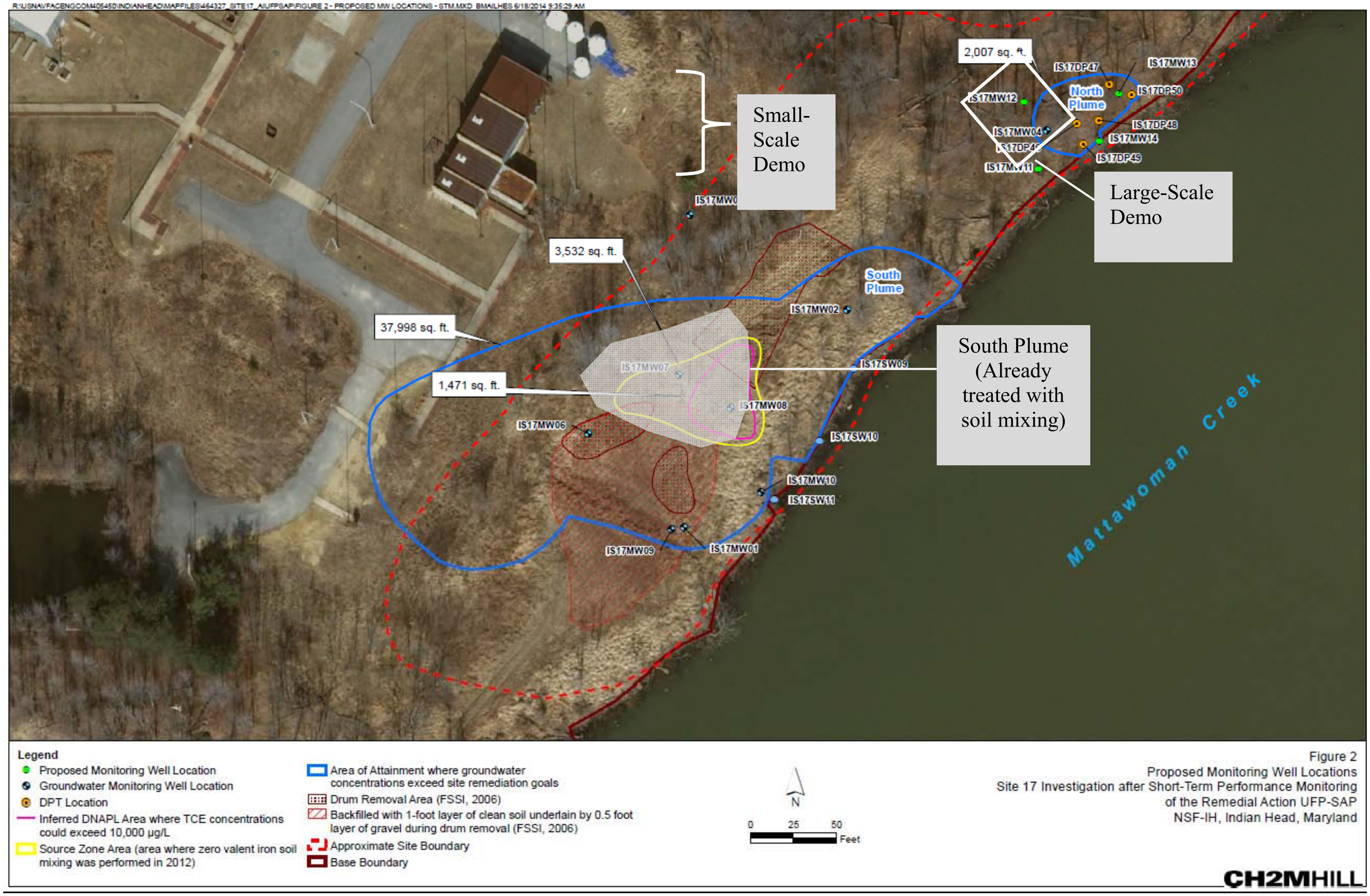


Figure 4.1: Locations of Small-Scale and Large-Scale Demonstration Areas

(basemap from CH2MHill, 2014, annotated by GSI)

4.2 SITE GEOLOGY / HYDROGEOLOGY

The geology in the region near IS17MW03 consists of an orange to gray clay to about 12 ft below ground surface (bgs), followed by a fine orange sand to 16 ft bgs (see Final Technical Report, Appendix B). The **fine orange sand** is the uppermost water bearing unit beneath the silt and was the focus of the demonstration. Evaluation of the cross-sections at the site provide further vertical and lateral information of the site geology and are also included in Appendix B. As such, the area in the vicinity of well IS17MW03 is expected to contain an underlying clay layer at approximately 30 ft bgs.

Groundwater seepage velocities estimated for the South Plume ranged from 43 to 400 ft/yr (CH2M-Hill, 2008, Table 4.3).

Slug tests conducted in the Task 2 **Small-Scale Demonstration** location, a relatively unimpacted zone at well IS17MW03 (Figure 4.01) yielded hydraulic conductivity estimates ranging from 0.5 ft/day to 1.2 ft/day (1.6×10^{-4} cm/sec to 3.2×10^{-4} cm/sec) with an average of 0.9 ft/day **(3×10^{-4} cm/sec)** (CH2M-Hill, 2008). The depth to groundwater at this well is approximately 11 ft bgs (6.72 ft mean sea level [msl]) and groundwater generally flows from northwest to southeast, discharging to the Mattawoman Creek (CH2M-Hill, 2004).

The geology in the region near the **Task 3 Large-Scale Demonstration** location, the North Plume, generally consists of red-brown silt and silty sand from 0-9 ft bgs, followed by a clay layer to at least 20 ft bgs (see Final Technical Report). Depth to groundwater is approximately 5 ft bgs and groundwater generally flows from northwest to southeast, discharging to the Mattawoman Creek (CH2M-Hill, 2004). Hydraulic conductivity measurements were collected in the North Plume and showed much lower hydraulic conductivity in this area range from 0.1 ft/day to 0.2 ft/day **(4 to 7×10^{-5} cm/sec)** (CH2MHill, 2012). A Passive Flux Meter was installed at well MW-04 and showed groundwater Darcy velocities of 0.12 cm/day (top measurement) and 0.17 cm/day (bottom measurements). Using a porosity of 0.20, this yields seepage velocities of 7.2 and 10 ft per year and with a hydraulic gradient of 0.04 ft/ft and hydraulic conductivity in the 4×10^{-5} to 5×10^{-5} cm/sec range.

Overall the geologic description (silty sands) and the hydraulic conductivity of the Northern Plume (**4 to 7×10^{-5} cm/sec)** were within, but at the far range of the silica gel grouting "rule of thumb" (minimum hydraulic conductivity of 1×10^{-5} cm/sec; see Section 5.1.1). In addition, the low groundwater flowrate in this area would have complicated the demonstration of the electron diversion performance metric as it would have taken several years to get a condition where a groundwater exchange would have taken place without the barrier.

4.3 CONTAMINANT DISTRIBUTION

The Small-Scale demonstration was conducted in a clean area of the site in the vicinity of well IS17MW03 (Figure 4.1) to minimize the cost of disposing water during the pumping tests. Recent analytical results at well IS17MW03 reported very concentrations of Trichloroethylene (TCE) of 0.81 micrograms per Liter (µg/L), and cis-1,2-dichloroethene (cis-1,2-DCE) and vinyl chloride (VC) below detection limits of 0.5 µg/L. As a precaution, groundwater extracted during the pumping tests was stored and tested prior to disposal in consultation with the Navy project manager.

The main contaminants in the North Plume are TCE, cis-1,2-DCE, and VC. Groundwater concentrations from July 2014 for these contaminants had the following ranges:

- TCE: ND μg/L (MW11) to 400,000 ug/L (MW04)
- cis-1,2 DCE: 0.91 ug/L (MW11) to 130,000 μg/L (MW04)
- VC: 0.9 μg/L (MW11) to 1,600 μg/L (MW04)

Preliminary mass flux measurements in MW04 using passive flux meters indicated TCE flux of 155 – 759 milligram per square meter (mg/m^2)/day (Figure 4.2). Soil concentrations from July 2014 indicate maximum TCE concentrations of 300 milligram per kilogram (mg/kg) at a depth interval of 12-16 ft bgs (near IS17MW12).

These contaminant characteristics were good for the demonstration of the flux reduction barriers and the ERDZ concept:

- the high concentrations suggest that in-situ remediation technologies would be difficult to implement in this area, leading to a barrier-approach to manage the site;
- the high concentrations of cis-1,2-DCE show that electron acceptors and reductive dechlorination are present in the source zone, and therefore diverting electron acceptors would have a beneficial effect.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

5.1.1 Description of Flux Reduction Materials/Formulations

The Small-Scale demonstration consisted of two types of cells, or barriers, each constructed with a different flux reduction material. Cell type 1 consisted of a silica gel grout mix (sodium silicate [NaSi] solution) similar to that commonly used for permeation grouting in construction projects. Cell type 2 consisted of a silica gel/vegetable-oil formulation produced by project team member Solutions-IES. The silica gel/veg oil material was selected after research and lab work performed by Solutions-IES.

<u>Silica Gel Grout – (Small-Scale Demo Cell Type 1)</u>

GSI performed a detailed literature review of conventional permeation grouting techniques. Key findings are provided in the Final Technical Report as well as the Technical Guidance Manual.

In the most common type of permeation grouting performed by geotechnical contractors, NaSi grout, a low-viscosity fluid containing SiO_2, is mixed with a hardening agent prior to being injected in the subsurface. The electrolyte/reagent enables the process of gelation (solidification) in the soil, forming an impermeable barrier in the subsurface (Moridis et al., 1997, Truex, 2011). Gelling times can be controlled based on the volumetric ratio of silica gel to reagent / electrolyte solution and can also be influenced by pH, salinity of water, and temperature (Powers et al., 2007).

Key properties of NaSi for this type of application include the following:

i) This material has been used for decades, and the handling and application properties are well known.
ii) It is chemically benign, thereby posing no environmental hazard;
iii) It has a controllable gel time (one hour or less) that is compatible with subsurface injection processes and can be adjusted based on site-specific considerations;
iv) It is easy to inject with standard equipment, with typical spacing of 0.8 to 2 m (2.5 to 6.5 ft) in sandy soils (Powers et al., 2007).
v) It forms durable barriers after gelation is complete in the subsurface (Kim and Corapcioglu, 2002).
vi) It is resistant to both chemical and biological degradation (Moridis et al., 1999).

In order to ensure that the NaSi grout mix applied in the field demonstration will be effective, a number of preliminary lab tests were conducted at GSI Environmental's field office in Houston. These lab tests included the selection of a NaSi grout mix, as well as the testing of field equipment for the installation and monitoring of injection fluids. Powers et. al, 2007, suggest that lower concentrations of NaSi as compared to standard permeation grouting applications can achieve lower viscosities while providing the water tightening that is required for this barrier application.

As such, the gel times of 12 grout mixes consisting of a mixture of 10-30 percentage by volume (v%) of NaSi with two different hardening reagents: (i) 1-3 v% of calcium chloride ($CaCl_2$) and (ii) 2-5 v% of dibasic ester (DBE) were tested. Both of these reagents are commonly used in geotechnical practice for hardening silica gel for "geotechnical water tightening" projects. The selection criteria for the grout mix that was selected for the Small-Scale demonstration is as follows:

i) viscosity of approximately 2-5 centipoise (cP) to allow for penetration in lower-permeability silty soils (Karol, 2003);

ii) gel time of 3-5 hours.

The final selected formulation consisted of: 10 vol-% of NaSi, 5 vol-% of DBE hardener, and 85 vol-% of water. This formulation had a gel time of approximately 4 hours and had an estimated viscosity of 3-4 cP.

__Novel Silica Gel/Veg-Oil Grout – (Small-Scale Demo Cell Type 2)__

Solutions-IES tested several amendments to create a vegetable-oil formulation. Selection criteria for the formulation were as follows:

- low cost;
- easy to inject;
- reduces K of sand by at least a factor of 10, preferably a factor of 100;
- persistence in the subsurface greater than typical vegetable oils; and
- slowly ferments enhancing reductive dechlorination.

Mixtures of emulsified vegetable oil (EVO), NaSi, and DBE were identified as having the best potential for field application based on ease of injection, ability to reduce formation permeability, and cost. Based on this screening, several different combinations of EVO, NaSi and DBE were selected for further evaluation.

The final selected formulation consisted of: 5 percentage by weight (wt-%) of EVO, 10 wt-% of NaSi, 1.8 wt-% of DBE, and 83 wt-% of water (Borden et al., 2014).

This formulation provided a 3-4 orders of magnitude reduction in lab permeability tests, had a gel time of 18 hours, and the addition of EVO is expected to enhance long-term biodegradation of anaerobically biodegradable contaminants (Borden et al., 2014). Further details of the Treatability Study are provided in the Final Technical Report.

5.1.2 Task 2: Small-Scale Demonstration

For the Small-Scale Demonstration four circular treatment cells (two each for the silica gel and two for the silica gel/veg oil material) were constructed in four separate injection points consisting of multi-depth injection wells (Section 5.3.2);

Figure 5.1A below shows the conceptual layout of the Small-Scale demonstration, while Figure 5.1B and Section 5.2 shows the conceptual field design where grouting material was injected into each of the four injection points followed by clean chase water to construct a round donut shaped barrier. A pumping extraction test was conducted at each of the four injection points before the barrier installation in order to determine baseline aquifer characteristics. After injection of grout and establishment of treatment barriers, groundwater flow into the treatment cell was reduced. Post-barrier pumping tests were used to determine the reduction in aquifer transmissivity in each cell, and ultimately, the effectiveness of the groundwater flow barrier.

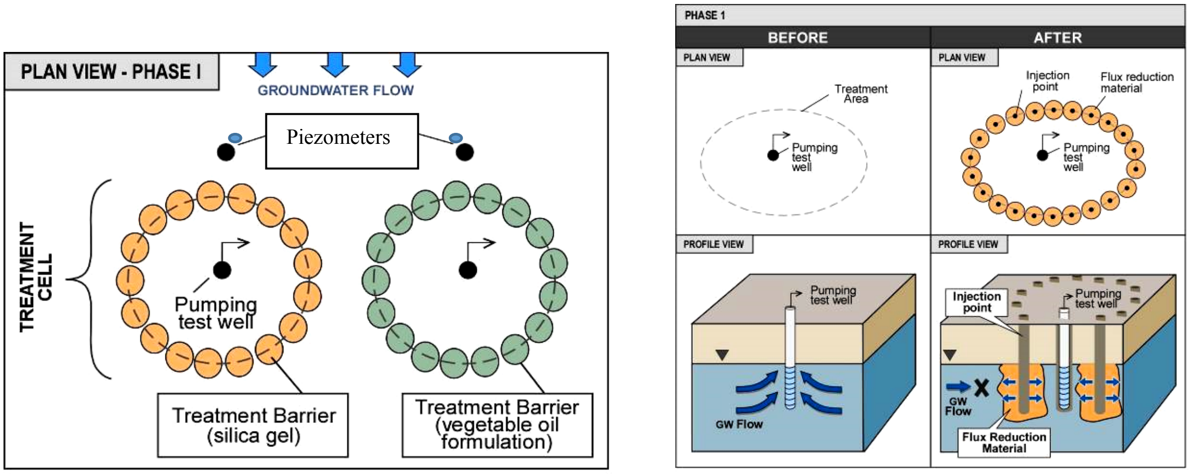


Figure 5.1A: Conceptual Layout of Small-Scale Field Demonstration, Plan View (left) and Flux Reduction (right)

See Section 5.2 for Final Design

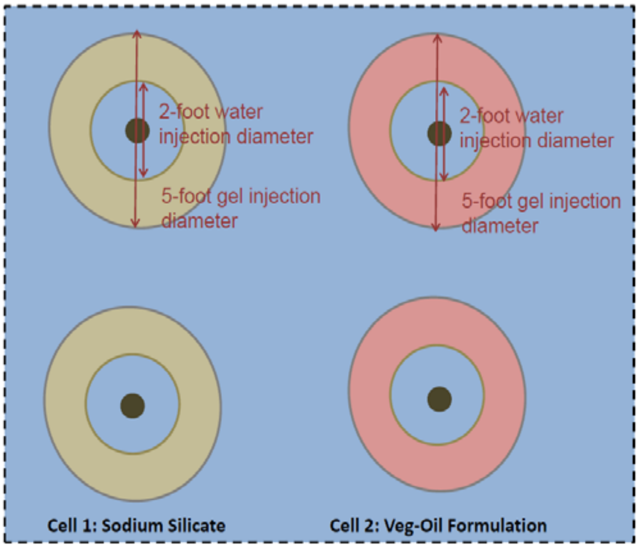


Figure 5.1B: Actual Field Design Configuration

5.1.3 Task 3: Large-Scale Demonstration

If the performance objectives for the Small-Scale Demonstration were achieved, the Large-Scale Demonstration was to be performed. Figure 5.2 shows a conceptual figure of the Large-Scale Demonstration, groundwater flow carrying competing electron acceptors will be diverted from the treatment area, creating an anaerobic, enhanced biodegradation treatment zone.

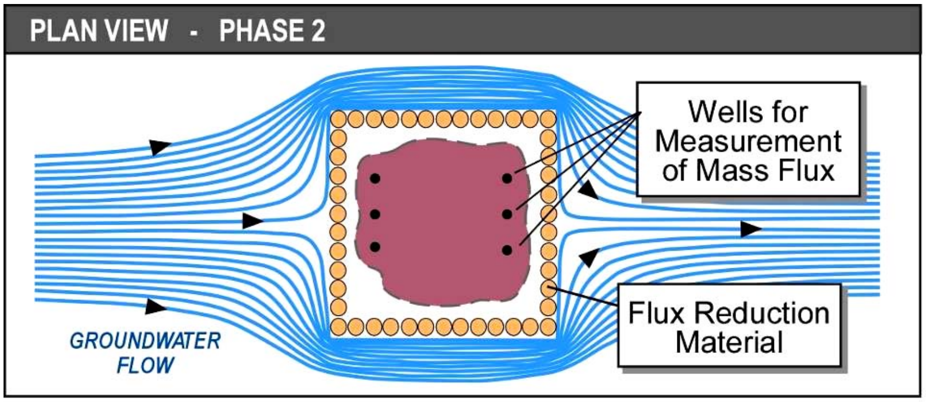


Figure 5.2: Large-Scale Field Demonstration, Plan View

The conceptual design for the Large-Scale Demonstration included six monitoring wells in order to:

i) measure change mass flux using Passive Flux Meters in three wells before and after barrier construction, and

ii) measure change in hydraulic gradient before and after the barrier in 3-pairs of wells.

In addition, a limited groundwater flow modeling study of the performance of different barrier configurations was performed using MODFLOW. The model runs assumed:

- Hydraulic conductivity of the formation: $1x10^{-2}$ cm/sec
- Hydraulic conductivity of the barrier wall itself ($1x10^{-5}$ cm/sec) (a conservative value; see right hand column of Table 5.1)
- Wall thickness: ~3 ft
- Hydraulic Gradient: 0.006 ft/ft

The base case, a four sided barrier, was predicted to achieve a 97% reduction in groundwater flow through the barrier based on counting the groundwater streamlines (Figure 5.3a, top panel). Three sided barriers showed a significant reduction in performance: a barrier aligned with groundwater flow with the opening facing downgradient showed only an 80% flow reduction (Figure 5.3a, bottom panel). A side-open barrier and diagonal barrier showed similar performance as the downgradient barrier: 83% and 74% respectively although there was some subjectivity in which streamlines to count. Overall the modeling study suggested that four sided barriers are likely required for good flow reduction, and three-sided barriers are much less effective.

Site experience also indicates that "hanging walls" (barriers that are not keyed into a low permeability zone on the bottom), will have much poorer performance than walls that do have a low permeability bottom.

5.2 BASELINE CHARACTERIZATION ACTIVITIES

5.2.1 Small-Scale Demonstration

The goal of the Small-Scale demonstration was to assess the reduction in transmissivity across a barrier created using two different flux reduction materials. As such, the baseline characterization activities included baseline aquifer transmissivity assessment using extracted groundwater volume.

Baseline Aquifer Transmissivity

The low transmissivity of the formation at the test site made evaluating the change in transmissivity more challenging. Conventional constant rate pump tests are difficult to implement in low permeability formations because wells can go dry and complicate the analysis of the data. Because it will be difficult to anticipate a constant pump rate test will succeed at the site, the relative change in before-and-after transmissivity was evaluated by two methods: (1) comparing the total volume of groundwater pumped from the formation at each location before and after the barrier installation; and (2) performing constant head injection tests (with injection rather than groundwater extraction).

For the extracted volume test, peristaltic pumps were operated in each injection depth of each multi-well injection point for a total of four hours. The pump intake tubing was placed in the middle of the screened interval and pumped at a flowrate where it was expected to draw down the water in the well to the pump intake. For the constant head injection tests, three injection depths at each multi-level well in the saturated zone were equipped with injection well heads and connected to the water storage vessels with garden hoses. The constant head injection tests were operated for a total of five hours at each well.

The groundwater recovered during the pumping tests was stored and tested, and disposed of in a manner amenable to the Navy project manager.

5.2.2 Large-Scale Demonstration

The Large-Scale demonstration was not performed because the performance metrics established for the Small-Scale Demonstration were not achieved. The general site characterization strategy to measure the performance of the Large-Scale Demonstration is provided in the Final Technical Report.

5.3 TREATABILITY OR LABORATORY STUDY RESULTS

Silica Gel Grout

Gel tests were conducted at GSI Environmental in order to ensure: (i) the proper selection of flux reduction material with an appropriate gel time, and (ii) effective flow measurement methods. The selection criterion for this grout mix was as follows:

i) viscosity of approximately 2-5 cP to allow for penetration in lower-permeability silty soils (Karol, 2003);

ii) gel time of 3-5 hours.

Results of these lab tests were applied to the implementation of the field program at the site. Gel Tests included:

i) Measurements of gel times and viscosities of various grout mixes composed of sodium silicate and two different hardeners CaCl2 and DBE;

ii) Multiple methods of measuring flow rate;

iii) Testing the feasibility of cleaning out different pieces of equipment once grout has gelled inside them.

As such, the gel times of 12 grout mixes consisting of a mixture of 10-30 v% of NaSi with two different hardening reagents: (i) 1-3 v% of $CaCl_2$, and (ii) 2-5 v% of DBE were tested. Both of these reagents are commonly used in geotechnical practice for hardening silica gel for "geotechnical water tightening" projects. Details of the testing procedures are summarized in the Final Technical Report.

The final phase of testing involved a combination of NaSi (10-30%) and DBE (1-5%). The final selected formulation consisted of: 10 vol-% of NaSi, 5 vol-% of DBE, and 85 vol-% of water. This formulation had a gel time of approximately 3-4 hours and had an estimated viscosity of 3-4 cP.

Novel Silica Gel/Veg-Oil Grout

Solutions IES designed and tested a novel silica gel/vegetable oil grout as described in the Final Technical Report.

The final selected formulation consisted of: 5 wt-% of EVO, 10 wt-% of NaSi, 1.8 wt-% of DBE, and 83 wt-% of water (Borden et al., 2014). This formulation provided a 3-4 orders of magnitude reduction in lab permeability tests, had a gel time of 18 hours, and the addition of EVO is expected to enhance long-term biodegradation of anaerobically biodegradable contaminants (Borden et al., 2014).

5.4 FIELD TESTING

5.4.1 Injection Skid Design

A skid-based delivery system was designed and was constructed to inject chemical grout to the subsurface. The skid included pumps, tanks, mixers, controls, and piping to facilitate mixing of the selected grout components prior to injection into the subsurface via injection points. The Injection Skid Design Manual and additional details are provided in the Final Technical Report.

Process Flow

A simplified process flow diagram (PFD) for the overall injection system is shown in Figure 5.3.

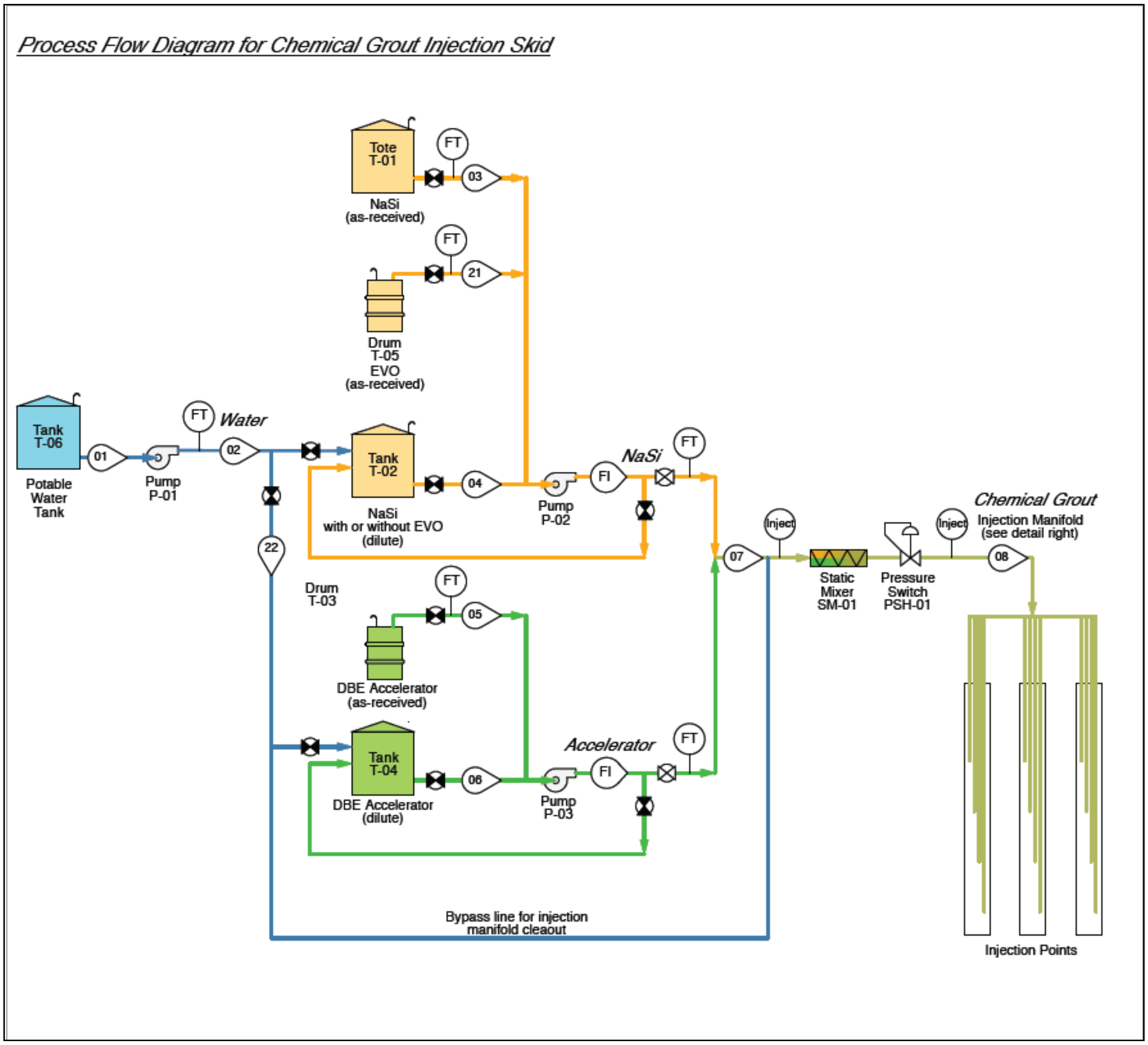


Figure 5.3: Process Flow Diagram for Chemical Grout Injection Skid

Description and Process Flow through Injection Manifold

Details of the injection manifold are depicted on the PFD shown on Figures 5.4 and 5.5. As noted above, the grout mixture flowed under constant pressure to the manifold, then into 12 branches of the manifold, and then to the injection points. The manifold and branches were constructed of polyvinyl chloride (PVC), and the individual lines were constructed of 0.5-in diameter, clear, flexible tubing. Each branch was equipped with a pinch valve, an injection point for water, a pressure gauge, flow totalizer, and a sight flow indicator. Flow rate of the grout in each branch was measured quantitatively using a flow totalizer, which was placed on the outside of the piping and moved from branch to branch of the manifold.

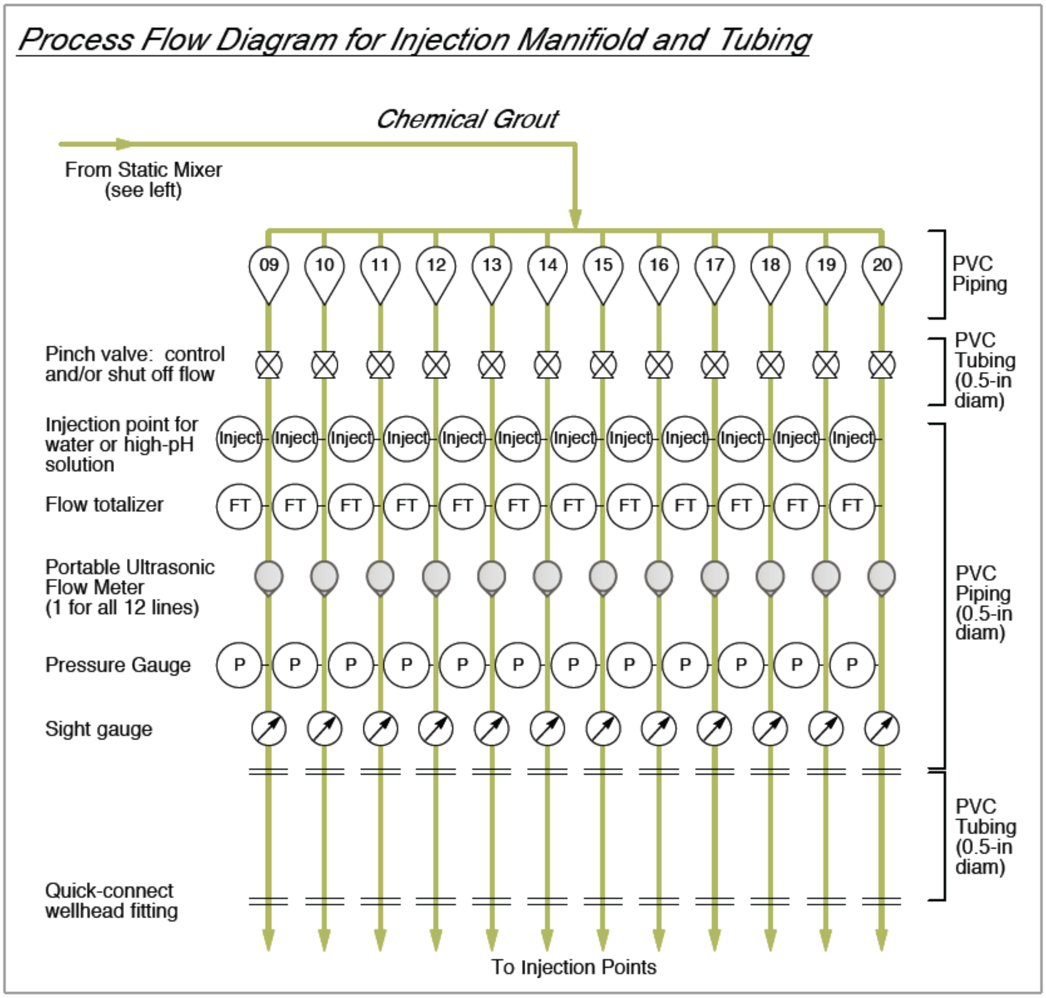


Figure 5.4: Process Flow Diagram for Injection Manifold and Tubing

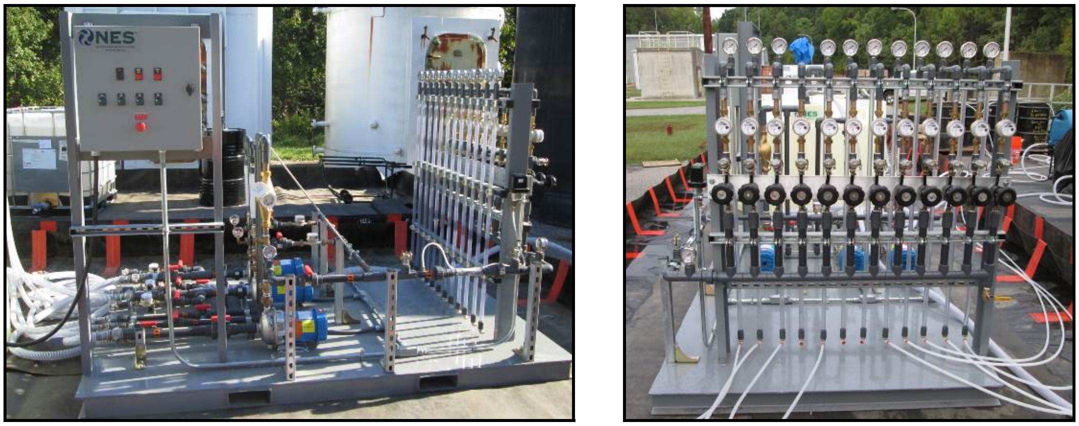


Figure 5.5: Injection Skid (Left) and Injection Manifold (Right)

Measures to Address Potential Clogging of Manifold and Tubing

Clogging could potentially occur within the static mixer, manifold, branches, and tubing downstream of the tee where the NaSi (with or without EVO) and accelerator come together if the residence time within the piping exceeds the planned set time of 3-4 hours. Design considerations implemented are provided in the Final Technical Report.

5.4.2 Small-Scale Demonstration

Injection Points

To ensure a good vertical distribution of grout, multiple nested injection points were used. The vertical barrier was constructed by injecting the reactive grout mix as a liquid into multi-level injection wells. Figure 5.6 shows the injection well design. To ensure good vertical placement of the grout, four injection intervals will be used, each served by a 0.5 inch (in) diameter PVC injection well or injection tubing. The conceptual figure below shows a well with a 20-ft thick injection zone. Figure 5.6 shows the plan view of the multi-level injection well.

The injection well system was designed to allow for repeated rapid placement without the need for individual geologic logs at each injection point. Because of the heterogeneous nature of site geology, it was anticipated some of the injection points will likely contact clay and will likely not accept any grout. As these units already have a low permeability, this will not compromise the performance of the barrier. The goal was inject grout in the mobile porosity, primarily the sands and more permeable silts that intersect the flux reduction barrier.

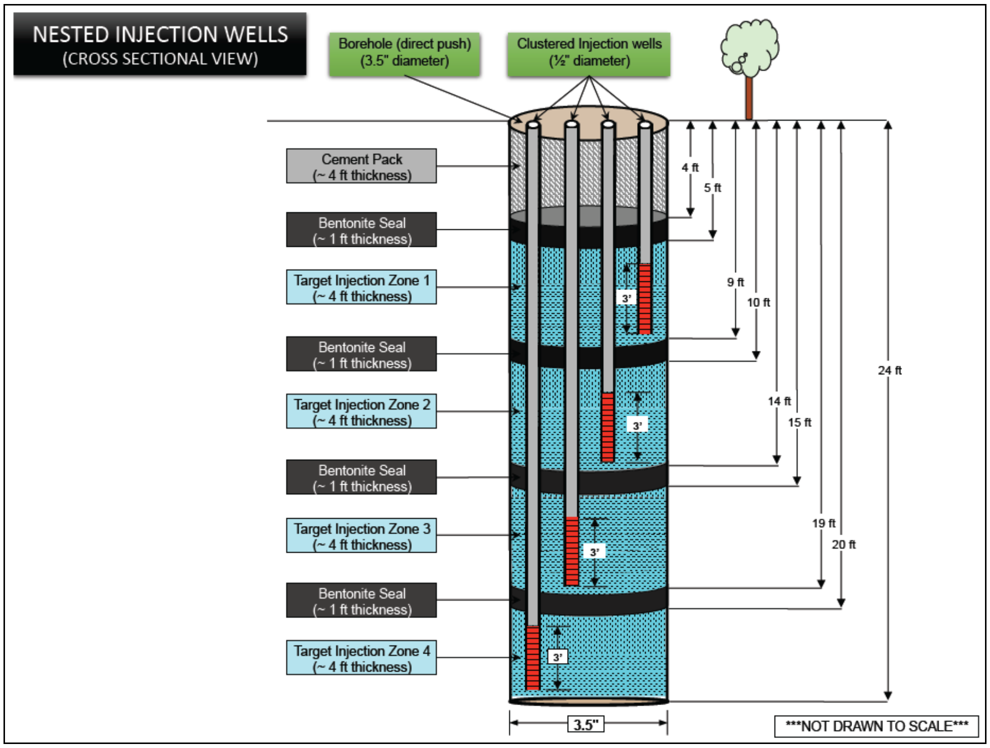


Figure 5.6: Conceptual Diagram of Direct Push Multi-Level Injection Wells With Four Separate Injection Zones

Installation of Treatment Cell Barriers

Each cell in the Small-Scale demonstration was constructed in the configuration shown in Figure 5.7 below.

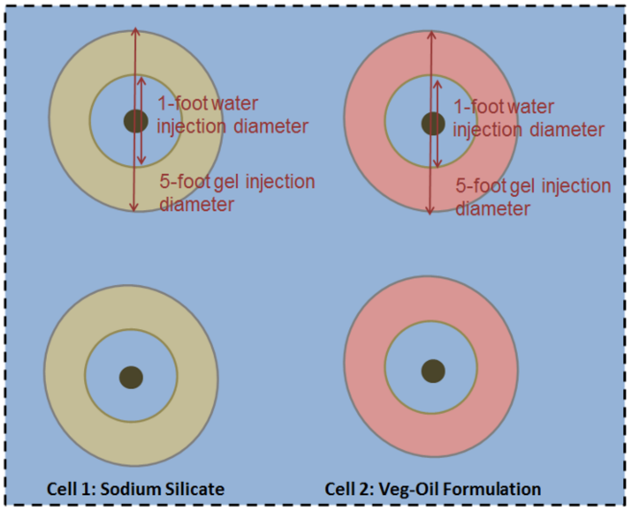


Figure 5.7: Small-Scale Demonstration Configuration

Two conventional NaSi grout barriers around two of the wells and two veg-oil formulations grout barriers were designed. The barriers were constructed by first injecting several hundred gallons (gal) of grout in liquid form; because the grout takes several hours to harden, the grout injection would be followed by the injection of clean water to: (1) push the unhardened grout out the ring; and (2) create an untreated zone around the well.

The approximate barrier construction parameters and injection volumes are as follows:

- Treatment barrier vertical depth: ~5 ft bgs to 30 ft bgs
- Approximate thickness of permeable portion of injection points: 10 ft
- Volume of grout mix per injection point: 420 gal
- Total number of injection points: 4
- Total volume of grout mix: 1680 gal

As described in Section 5.3.1 (Injection Skid Design), an injection skid was used to mix the chemical grout formulations to the specified concentrations. During the injections, measurements of process variables will be recorded on a frequent basis.

Post-Barrier Aquifer Transmissivity

As described in Section 5.2.1, groundwater was pumped from each pumping or injection well for 4 hours continuously after the installation of the barrier cells.

Evaluation of Injection Material and Aquifer Transmissivity Reduction

The Small-Scale demonstration was conducted in October 2015. As described above, the low transmissivity of the water-bearing unit at the test site precluded use of conventional constant rate pumping tests. Instead, two different measurement methods were employed: (1) comparison of how much groundwater could be extracted in 8 hours; and (2) constant head injection tests.

In the first method the key performance metric was the ratio of extracted volumes of water were calculated as follows:

$$r = \frac{V_f}{V_i}$$

where,

r = Ratio of volumes
V_i = Volume extracted before installation of barrier
V_f = Volume extracted after installation of barrier

A lower value of “r” corresponding to better performance of the barrier, with a performance goal of 90% reduction in groundwater flow.

When the first method produced unreliable results, the second method was employed where a constant head injection test was performed and the flow vs. time data were analyzed for each location to yield a hydraulic conductivity. This was compared to slug test values conducted by CH2M-Hill at the existing monitoring well at the site.

5.4.3 Large-Scale Demonstration

The Large-Scale demonstration was not performed because the performance metrics established for the Small-Scale Demonstration were not achieved. The general site characterization strategy to measure the performance of the Large-Scale Demonstration is provided in the Final Technical Report.

Page Intentionally Left Blank

6.0 PERFORMANCE ASSESSMENT

6.1 EVALUATION OF FLOW-REDUCTION MATERIALS

6.1.1 Selection of Two Different Flow-Reduction Materials

As previously discussed, two grout materials were tested: (1) a NaSi grout with organic hardener; and (2) the Solutions-IES silica gel/veg oil grout material.

6.1.2 On-Site Gel Tests with Site Soils

On-site gel tests were conducted in order to confirm the selected mixture concentration, as well as assess the impact of site soils and groundwater chemistry on actual gel time (Figure 6.1).

As such, gel tests were conducted with various grout mixture concentrations in VOA vials (without site soil) and small jars (with site soils). Mixtures of the NaSi grout consisted of 10% NaSi by volume and 1 to 5% by volume of DBE. Mixtures of the vegetable oil formulation consisted of 7.5% NaSi by volume, 5.2 % vegetable by volume, and 0.5 to 3% by volume of DBE.

Results of the on-site gel tests indicated that both grout types gelled with site soils, with approximate gel times of 2.5 hrs for the NaSi grout and 2.0 hrs for the vegetable oil formulation.

Figure 6.1: On-Site Gel Tests with Site Soils

6.2 INJECTION WELL AND BARRIER CONSTRUCTION

Four injection points were constructed (S-1, S-2, ES-1, and ES-2) in a clear area at Site 17 near Building 1569 (Figure 6.2). Each well was constructed with 2-ft injection zones at depths ending in a clay unit approximately 14.5 ft bgs, 18 ft bgs, 21.5 ft bgs, and 25 ft bgs. Table 6.1 summarizes well construction details for each injection point.

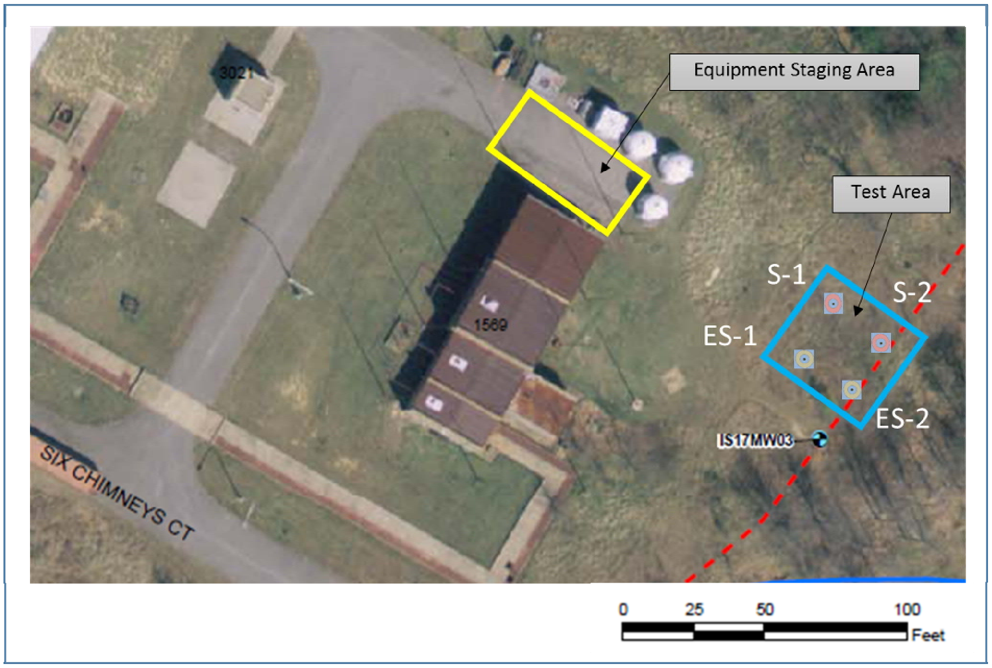


Figure 6.2: Location of the Phase 1 Demonstration at Site 17 at the Indian Head NSF

Table 6.1: Injection Point Construction Details

Well ID	Depth Interval Label	Stickup (ft)	Total Depth (ft btoc)	Screen Interval Length (ft)	Top of Screen Interval (ft bgs)	Bottom of Screen Interval (ft bgs)
S-1	14.5	1.7	16	2	12.4	14.4
	18	1.7	20	2	16.1	18.1
	21.5	1.7	21	2	17.5	19.5
	25	1.7	27	2	23.1	25.1
ES-1	14.5	1.65	16	2	12.8	14.8
	18	1.65	20	2	16.1	18.1
	21.5	1.65	23	2	19.6	21.6
	25	1.65	27	2	23.1	25.1
ES-2	14.5	1.8	16	2	12.0	14.0
	18	1.8	20	2	16.3	18.3
	21.5	1.8	23	2	19.4	21.4
	25	1.8	27	2	23.0	25.0
S-2	14.5	1.65	16	2	12.8	14.8
	18	1.65	20	2	16.0	18.0
	21.5	1.65	23	2	19.6	21.6
	25	1.65	27	2	23.0	25.0

The injection skid as well as the following components were assembled on-site (Figure 6.3): (i) associated mixing tanks; (ii) tote of NaSi; (iii) drum of DBE; (iv) drum of vegetable oil; (v) poly-tank with water; and (vi) generator for skid operation.

Figure 6.3: Injection Skid Assembly with all Components

A pre-barrier groundwater extraction test was conducted at all four injection points immediately after construction. The pre-barrier extraction tests indicated that injection point S-1 likely had construction problems that sealed the injection ports that resulted in very low extracted volumes (1.5 gal in 3 hours). As such, S-1 was abandoned and no injections were done in well S-1.

After the pre-barrier extraction tests, exact mixtures and volumes of the silica gel grout mix were created in the mixing tanks (one for water and NaSi or Solutions IES material, and the other for water and DBE). The injection skid allowed for the mixing and injection of the grout mix into multiple depths simultaneously. Table 6.2 below summarizes the injected volume into each interval and injection point, and ranges from 46 to 112 gal.

Table 6.2: Grout Volumes Injected per Interval

Well ID	Depth Interval Label	Volume Liquid Grout Injected (gal)	Chase Water Injected (gal)
S-1*	14.5	--	--
	18	--	--
	21.5	--	--
	25	--	--
ES-1	14.5	95	5
	18	110	6
	21.5	107	7
	25	105	6
ES-2	14.5	55	7
	18	49	8
	21.5	49	7
	25	46	7
S-2	14.5	99	7
	18	111	8
	21.5	112	9
	25	112	9

*S-1 abandoned due to inability to extract groundwater

6.3 EVALUATION OF REDUCTION OF MASS FLUX

6.3.1 Results: Before/After Extraction Tests

Water levels were measured at all four locations before conducting pre-barrier extraction tests. Peristaltic pumps equipped with manifold were used to pump from each depth simultaneously per Injection Point for 4 hours. Pumping start and pumping end times were recorded, as well as a total volume pumped. Post-barrier extraction tests were conducted in an identical fashion to the pre-barrier tests and were conducted for four hours.

As seen in Table 6.3 below, the pre-Barrier Extraction test indicated very low yield (extraction rate average of ~0.02 gallons per minute [gpm] per well) from the formation indicating lower permeability than anticipated based on existing hydraulic conductivity data.

The data did not appear to be reliable due to one or more of the following reasons: (i) low pre-barrier extraction test volumes; (ii) well construction; (iii) the low permeability nature of the aquifer; or iv) lack of time for sufficient rebound in the aquifer.

Table 6.3: Volume Groundwater Removed During Pre- and Post-Barrier 4-Hour Extraction Tests

Injection Well	Injected Grout	Pre-Barrier Extracted Volume Total (gal)	Post-Barrier Extraction Volume Total (gal)	Pre-Barrier Extraction Rate (gpm)	Post-Barrier Extraction Rate (gpm)
S-1	None	1.5	--	0.01	--
S-2	NaSi	13.1	18	0.05	0.08
ES-1	EVO + NaSi	2.9	5.25	0.01	0.02
ES-2	NaSi	5.4	7	0.02	0.03

6.3.2 Results: Constant-Head Water Injection Test

Due to the unclear results from the pre/post barrier extraction tests, a constant-head water injection test was conducted in November 2015. The test was conducted to determine the hydraulic conductivity of the aquifer after grout barrier injections.

Pre-Test Revaluation of MW-3 Slug Test Data

CH2M-Hill (2008) performed four slug tests at MW-3 and estimated the hydraulic conductivity of the formation was in the 0.5 to 1.2 ft per day range with an average of 0.90 ft per day. During the drilling of the Small-Scale Demonstration test wells, new detailed stratigraphic data were available. GSI reanalyzed the data from 2008 assuming: (1) 6 ft of permeable saturated thickness (silt or sand) vs. an original estimate of 15 ft; and (2) confined conditions. The reanalysis with the new data reduced the average hydraulic conductivity of the transmissive zone to 0.63 ft per day.

Constant-Head Test Setup

The constant head pump test (injection test) consisted of injection of water into well clusters located within the previously injected grout barrier to determine the barrier's effect on the hydraulic conductivity of the aquifer. Water injections were conducted at well clusters ES-1, ES-2, and S-2. Figure 6.2 shows the locations of the well clusters. Three wells within the saturated zone at each cluster were equipped with injection well heads and connected to the water storage vessels with garden hoses (see Figure 6.2 for well head injection assemblies).

To maintain constant-head conditions throughout the duration of the test, the water storage vessels were staged at an elevation of approximately 26 ft above the injection well clusters (see Figure 6.4). The water vessels were located between 90 and 110 ft from the injection wells. To ensure that a constant-head was maintained for the duration of the test the water levels were continually maintained through addition of water to the vessels (see Figure 6.4). The elapsed time of the test and the volume of water injected into each well cluster were recorded during the test. The injection test was conducted for approximately five hours.

Constant-Head Test Analysis and Results

The hydraulic conductivity of the formation within the grout barrier was estimated with the AQTESOLV software using the Jacob-Lohman curve solution to best approximate aquifer parameters (see Figure 6.4 for an example screen shot). As shown below, the constant-head test estimate indicates that hydraulic conductivities of the aquifer within the grout barrier ranged from approximately 0.20 ft/day to 0.27 ft/day. This represents an approximate 64% reduction in the average formation hydraulic conductivities as compared to pre-barrier installation conditions (see Table 6.4 and Figure 6.6).

Table 6.4: Aquifer Hydraulic Conductivities With and Without Barrier

ES: Silica Gel/Emulsified Oil Test Locations. S: Silica Gel Alone Test Locations.

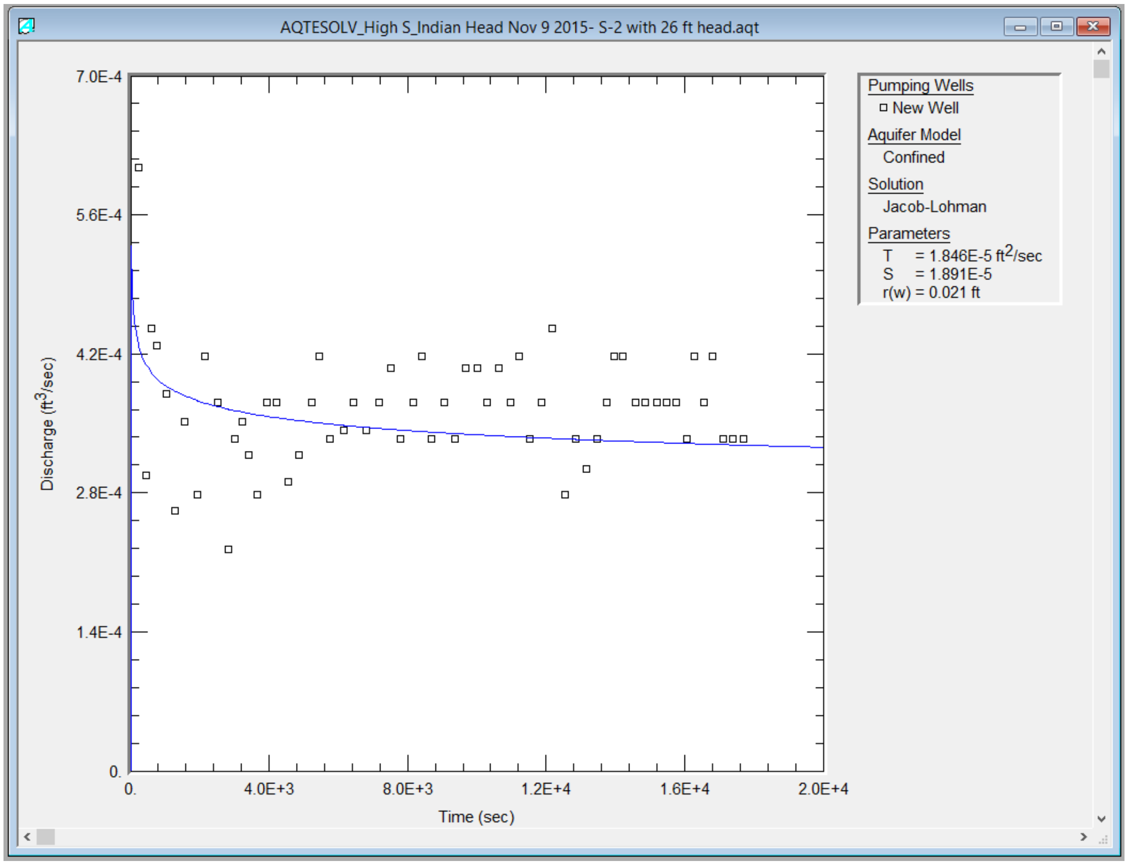
Test Phase	Location	Hydraulic Conductivity (ft/day)
No Barrier*	*MW-03*	*0.84*
		0.51
		0.76
		0.42
	Average	**0.63**
With Barrier**	*ES-1*	*0.20*
	ES-2	*0.21*
	S-2	*0.27*
	Average	**0.23**
Average Hydraulic Conductivity Reduction		**64%**

**From CH2M-Hill, 2008 slug test data reanalyzed to update saturated thickness information.*

*** From constant head injection tests (see Appendix F)*

Although test results indicate a reduction in the hydraulic conductivities of the aquifer there are uncertainties associated with the constant-head test and the interpretation of the test results. In particular, the estimation of the aquifer parameters in AQTESOLV relies on a best-fit approximation of the Jacob-Lohman solution curve to injection test data, which as shown on Figure 6.5 could entail a wide range of estimates. Therefore, the results of the constant-head test should be viewed as best guess estimates based on field test data. Nevertheless, the results of the injection test conducted at Site 17 at Indian Head NSF indicate that a significant reduction (64%) in the hydraulic conductivity of the aquifer was achieved at locations where the grout barrier was installed, but did not achieve the 90% reduction performance metric.

Figure 6.4: Well Head Injection Assemblies (Left) and Water Vessels Setup for the Constant-Injection Test


AQTESOLV_High S_Indian Head Nov 9 2015- S-2 with 26 ft head.aqt

Pumping Wells
□ New Well

Aquifer Model
Confined

Solution
Jacob-Lohman

Parameters
T = 1.846E-5 ft^2/sec
S = 1.891E-5
r(w) = 0.021 ft

Figure 6.5: Example AQTESOLV Estimation of Aquifer Parameters for the Constant-Head Injection Test Conducted at the Indian Head NSF Site

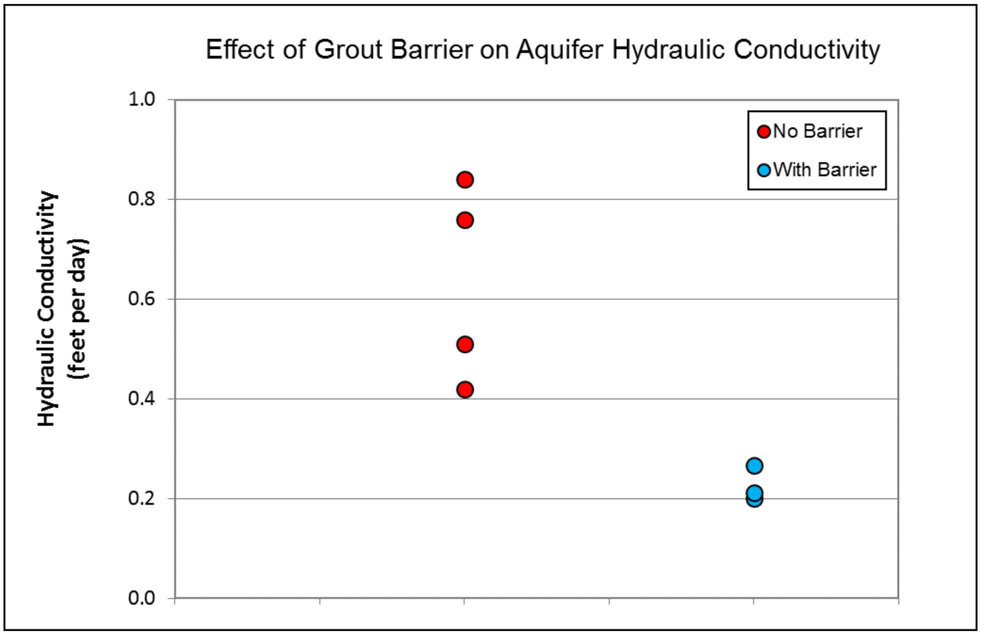


Figure 6.6: Aquifer hydraulic conductivities at Site 17 at Indian Head NSF

Page Intentionally Left Blank

7.0 COST ASSESSMENT

The demonstration study included carefully tracking the cost of implementing the field demonstration program. Subsequently, cost data were used to estimate the expected cost of implementing a flux reduction barrier at a hypothetical site. As such, Section 7.1 summarizes the costs tracked associated with the demonstration and presents actual demonstration costs, while Sections 7.2 and 7.3 describe the expected costs for routine application of this technology.

7.1 FIELD DEMONSTRATION COSTS TRACKED

The demonstration study included three key cost elements: (i) project planning and preparation, (ii) field program implementation, and (iii) data evaluation and reporting as outlined below.

Costs for the project planning and design element of the study involved labor and supplies for the following: (i) treatability study for including a novel vegetable oil formulation in the grout (by subcontractor); (ii) site selection and coordination with the site Project Manager (PM); (iii) engineering design of injection skid; (iv) testing and specification of injection grout and formulation and (v) detailed design to adapt technology to site-specific needs (partially in parallel to Phase II work). A single test Passive Flux Meter was also deployed to evaluate the suitability of the site for a Phase II application of the technology at the site.

Costs for the field program included (i) purchase of equipment and supplies to complete the injection; (ii) construction, transportation, and start-up support of the injection construction, (by subcontractor); (iii) clearing of utilities and installation of injection points (by subcontractors); (iv) rental of equipment such as a water tank for potable water, generator, pumps, etc.; and (v) associated labor and costs for installation and performance assessments.

Data evaluation and reporting include labor time for analyzing Phase 1 results. Detailed costs for each of the cost elements of the demonstration study are provided in Table 7.1 below.

Table 7.1: Summary of Actual Costs for Field Demonstration

Cost Category	Subcategory	Description	Cost
PROJECT PLANNING AND DESIGN	Treatability Study	Material/Labor (Solutions-IES; Lump Sum)	$49,900
	Engineering Design and Site Assessment	Labor	$55,000
		Grout mix materials and testing	$1,550
		Misc. equipment (Passive Flux Meter and testing beakers, etc.)	$4,220
FIELD PROGRAM AND PERFORMANCE ASSESSMENT	Injection Skid and Materials	Injection Skid and Start-Up Support (Subcontractor)	$50,008
		Injection Materials and delivery (1 Sodium silicate tote, 1 dibasic ester drum)	$3,026
		Injection Materials and delivery (1 vegetable oil drum)	$1,154
	Installation and Start-Up	Utility Clearance Subcontractor	$1,650
		Drilling Subcontractor - drilling 4 injection points	$8,730
		Poly Tank Water Subcontractor - rental of tank and ~3,000 gallons of water delivery	$2,970
		Equipment Rental (Generator, forklift)	$5,506
		Labor	$11,500
		Other Expenses (meals, lodging, travel, consumables)	$12,110
	Extraction Tests	Equipment Rental (1 water level meter, 4 pumps)	$576
		Labor	$6,900
	Constant-Head Tests	PolyTank Water Subcontractor - rental of tank and ~1,000 gallons of water delivery	$1,715
		Labor	$6,900
	Decomissioning	Disposal of Purge Water and remaining materials, including lab analysis for waste characterization	$3,813
		Transportation of Skid to Houston	$4,812
		Labor	$700
	Data evaluation and reporting	Labor	$5,000
		Total Costs	***$232,040***

7.2 COST DRIVERS

The cost of implementing flux reduction barriers is driven by the following factors: (i) treatment depth, (ii) site geology and injection point spacing. These factors influence the total volume of injection material required, as well as the drilling time for injection point installation.

7.3 COST ANALYSIS

7.3.1 Estimated Costs at a Hypothetical Site

Applicable costs associated with the field program element of the demonstration study have been employed to develop costs for full-scale implementation of a flux reduction barrier for remediation of affected groundwater. Based on a typical application of the technology at a hypothetical site, full-scale implementation costs have been estimated. Some tasks and associated costs incurred during the field demonstration would not be applicable for a full-scale implementation of the technology; therefore, costs for these items have not been included for the full-scale remediation.

Costs of a full-scale installation of a flux reduction barrier were estimated using the following assumptions regarding the site:

- Treatment Area: A rectangular are with the dimensions of 218 ft by 200 ft, corresponding to an area of 43,600 ft^2 (i.e., slightly more than one acre) and a total perimeter of length of 836 ft.
- Injection Point Spacing: 4 ft along perimeter
- Depth of Treatment Zone: From 5 ft bgs to 35 ft bgs, corresponding to barrier thickness of 30 ft
- Porosity of Treatment Zone: 30%

Table 7.2 highlights parameters and additional information of assumptions.

Costs were also dependent on the following considerations:

- Grout: Standard NaSi solution with DBE hardener having the following composition: 10% NaSi, 5% DBE, 85% water (by volume)
- Cost for Grout Components: Cost of NaSi, DBE, water and water tank rental projected based on incurred field demonstration costs.
- Time for Implementation: Drilling and injection time estimated based on experience gained during field demonstration.
- Decommissioning: Decommissioning costs estimated to be identical to the incurred field demonstration costs.
- Additional Work: No performance assessment tests to be conducted.

Table 7.3 below summarizes the results of the projected costs at the hypothetical site. As such, for a 1-acre site with a total barrier thickness of 30 ft, the total cost of the technology implementation is approximately $996K. Subsequently, the cost per cubic yard is $21/cubic yard (yd^3).

Table 7.2: Parameters and Assumptions of Implementation at a Hypothetical Site

Variable	*Value*	*Units*	*Notes*
Injection Grout Materials			
Radius of Influence of Injection Point	2	ft	
Well Spacing	4	ft	*Source:* Powers, et al., 2007: Construction Dewatering and Groundwater Control: New Methods and Applications, 3d ed.
Perimeter	836	ft	
Number of Injection Points	209		=permeter/well spacing
Volume of Injection Grout Required per Well	136	ft3	Includes 20% overpumping
Total Volume of Injection Grout	28,365	ft3	=number of injection points x volume of injection grout required per well
Total Volume of Injection Grout	212,183	gal	
Cost of Sodium Silicate	$7.3	$/gallon	Incurred costs, includes delivery charges
Cost of Dibasic Ester	$18.4	$/gallon	Incurred costs, includes delivery charges
Cost of Water and Poly Tank Rental	$0.4	$/gallon	Incurred costs, includes delivery charges
Cost of Injection Grout	$1.99	$/gallon	*Assume 10% NaSi, 5% DBE, and 85% water
Total Cost of Injection Grout Materials	*$421,915*	*$*	
Injection Skid			
Capital Cost of Skid + Start-Up Support	$50,000	$	Incurred costs, includes delivery charges
Total Cost for Skid and Generator Rental	*$50,000*	*$*	
Installation and Start-Up			
Drilling Hrs per Injection Point	3		Estimated incurred during field program
Number of Rigs	2		
Total Drilling Time	314	hrs	=number of injection points x Drilling Hrs per injection Point / number of Rigs
Number of work days to complete drilling	40	days	*Assume 9 hrs drilling per day, with 15% safety factor; 5 days per work week
Number of Work Days	40	days	5 days per work week
Total Number of Days	56	days	Includes weekends
Mobilization	$1,500	$	Estimated from incurred costs
Addt'l costs per Injection Point (permits, completion,etc.)	$500	$/injection point	Estimated from incurred costs
Addt'l costs for Injection Points	$104,500	$	= Addt'l costs per Injection Point x Number of Injection Points
Cost per day	$2,000	$/day/truck	Incurred costs
Utility Clearance	$5,000	$	Estimated from incurred costs
Total Drilling Subcontractors	*$336,733*	*$*	
Injection Time			
Hours per Injection Point (4 depths)	4	hrs/point	Estimated incurred during field program
Simultaneous Injections	3	points/ time	Per skid design
Total Injection Time	35	days	*Concurrent injection with drilling, requiring no additional time on site
Other Equipment Rental			
Generator Rental	$1,300	$/month	Incurred costs, includes delivery charges
Generator Total	$2,429	$	=Generator Rental per month x Total number of Days/30
Forklift Rental	$1,050	$/week	Incurred costs, includes delivery charges
Forklift Total	$1,050	$	= Forklift Rental per Week x Number of Weeks. Assume 1 week for install and decomissioning
Car Rentals, Consumables	$100	$/day	Incurred costs
Car Rentals, Consumables Total	$5,606	$	= Car Rentals, Consumables x Total number of Days
Rentals Total	*$9,685*	*$*	
Labor and Other Expenses			
Assume 2 field presonnel onsite	$2,300	$/day	=Typical labor costs/hr x 10 hrs per day
Other exepenses (meals/lodging)	$170	$/day	Typical meals/lodging per day
Total Labor and Other Expenses	*$101,664*	*$*	=Total daily costs x Total number of Days
Decomissioning			
Waste Disposal of remaining materials, including lab analysis for waste characterization	$3,800	$	Incurred costs, includes delivery charges
Transportation of Skid	$4,800	$	Incurred costs
Decomissioning Total	*$8,600*	*$*	

Table 7.3: Estimated Costs of Implementation at a Hypothetical One-Acre Site

Cost Category	Subcategory	Description	Estimated Cost	Notes
PROJECT PLANNING AND DESIGN	Treatability Study	n/a	--	Not applicable
	Engineering Design and Site Assessment	Labor	$65,000	Estimated
		Grout mix materials and testing	$1,550	Estimated
		Misc. equipment (testing beakers, etc.)	$500	Estimated
FIELD PROGRAM	Injection Skid and Materials	Injection Skid + Start-Up Support (Subcontractor)	$50,000	See Table 7.3 for parameters and assumptions
		Injection Grout Materials, transportation, and Water + Tank Rental (Sodium silicate tote, dibasic ester drum)	$421,900	See Table 7.3 for parameters and assumptions
	Installation and Strat-Up	Drilling Subcontractors (including utility clearance)	$337,000	See Table 7.3 for parameters and assumptions
		Other Equipment Rental (Generator, forklift, car rental)	$9,700	See Table 7.3 for parameters and assumptions
		Labor + Other Expenses (meals, lodging, travel)	$102,000	See Table 7.3 for parameters and assumptions
	Performance Assessment	N/A	--	
DECOMISSIONING	Decomissioning	Waste Disposal of remaining materials, including lab analysis; labor; transportation of skid.	$8,600	See Table 7.3 for parameters and assumptions
		Total for 1 Acre Site ($)	***$996,250***	
		Treatment Volume (yd^3)	***48,444***	
		Cost per Cubic Yard ($\$/yd^3$)	***$20.6***	

7.3.2 Comparison of Flux Reduction Barriers with Other Technologies

The typical cost of installing a flux reduction barrier for remediation of groundwater affected with chlorinated organics has been compared to the typical cost of implementing an Enhanced In-Situ Bioremediation (EISB) project at a Case 1 Study Site (Table 7.4), as described in Harkness and Konzuk's Chapter 16 in Kueper et al. (2014).

Table 7.4: Description of Case Study Site

Parameter	Case Study Site
Area	1,500 m^2 (16,145 ft^2; 0.11 acre)
Depth to Groundwater	1.5 m (4.9 ft)
Depth to Aquitard	4.5 m (14.8 ft)
Saturated Thickness	3.0 m (9.8 ft)
Porosity	0.3
Groundwater velocity	32 m/yr (105 ft/yr)
Barrier Thickness	3 m (9.8 ft)

Here, the EISB project consists of the following key assumptions (Kueper, et al., 2014):

- Injection of EVO
- EVO applied through a series of 50 injection wells spaced on 5.4 m (17.7 ft) centers distributed across source area

- 2-in diameter injection wells screened across the saturated zone
- Addition of 349 kg (768 lbs) of commercial EVO solution to each injection point, along with 25,090 L (6,630 gal) of groundwater to ensure complete distribution. Two injections assumed.
- Injections will be performed by a two-person crew requiring 26 days of labor including mobilization, setup and breakdown.

Additionally, in order to provide an equal comparison, costs for a Flux Reduction Barrier was estimated for the parameters outlined in the Case Study Site (Table 7.4). Also, a total monitoring time period of source area monitoring wells for 10 years is assumed for both technologies. For Flux Reduction Barriers, assessment of mass flux is included in monitoring, in addition to groundwater analyses.

As seen in Table 7.5 below, the total 10-year project cost for EISB is $1,196K and that of a Flux Reduction Barrier is $640K. The cost per volume of both remedies is $663/yd^3 and $355/yd^3, respectively. Note that these costs per unit volume are much greater than those typically observed at chlorinated solvent sites (McGuire et al., 2016), because (i) the Case Study site is small (0.1 acre and 10 ft of treatment zone thickness); and (ii) total monitoring costs for 10 years after remediation are incorporated.

Table 7.5: Detailed Cost Analysis Comparison between EISB and Flux Reduction Barriers

Cost Element	EISB[1]	Flux Reduction Barriers	Notes
Design			
Laboratory Studies	$25,000	$2,050	
In-field hydraulic and injection testing	$19,000	--	
Detailed design, permitting, and report	$88,000	$65,000	
Procurement	$12,000	--	Included in "Detailed design"
Total Design	**$144,000**	**$67,050**	
Capital			
Mobilization/demobilization	$4,000	--	Included in "Implementation labor"
Injection Skid	--	$50,000	
Well surveying	$4,000	$5,000	
Drilling and well installation	$106,000	$108,623	
Flow control equipment, instrumentation, controls	$114,000	--	
Start-up costs	$7,000	--	
Materials (including amendments, shipping, utilities)	$61,000	$48,633	
Implementation labor, travel, per diem	$65,000	$34,177	
Bioaugmentation	$57,000	--	
Waste management and disposal	$24,000	$8,600	
Field and home office support	$56,000	--	
Contractor oversight	$67,000	--	Included in Drilling and well installation
Reports	$27,000	$27,000	
Total Capital	**$592,000**	**$282,033**	

Notes: 1) Source: Kueper et al., 2014, Table 16.5. Note that monitoring was estimated to be for 10 years for both technologies.

Table 7.5: Detailed Cost Analysis Comparison between EISB and Flux Reduction Barriers (cont'd)

Cost Element	EISB[1]	Flux Reduction Barriers	Notes
O&M (per event/yr)			
Equipment rental	$9,000	--	
Operation – materials (including shipping and electrical)	$61,000	--	
Operation – labor, travel, per diem	$65,000	--	
Operation – oversight	$13,000	--	
Replacement parts and materials, well rehab	$3,000	--	
Field and home office support	$15,000	--	
Reports	$18,000	--	
Total O&M (per injection/yr operations)	**$184,000**	**$0**	No O&M required for barriers
Monitoring Costs (during/post-treatment)			
Monitoring well installation (first year only)	$10,600	$10,600	
Labor (quarterly monitoring)	$7,200	$7,200	
Analytical, groundwater (quarterly monitoring)	$8,000	$8,000	
Waste management and disposal	$1,400	$1,400	
Reports (annual)	$10,000	$10,000	
Mass flux measurements (year 1)	--	$7,440	Assume 2 locations sampled once in year 1
Mass flux measurements (recurring after year 1)	--	$827	Assume 2 locations sampled every 5 years
Total monitoring (year 1)	$37,200	$44,640	Assume quarterly monitoring
Total monitoring (recurring after year 1)	$26,600	$27,427	
Total Monitoring Costs for 10 Years	**$276,600**	**$291,480**	
TOTAL PROJECT COST ($)	**$1,196,600**	**$640,563**	
Treatment Volume (yd^3)	**1,804**	**1,804**	
TOTAL PROJECT COST ($/yd3)	**$663**	**$355**	

Notes: 1) Source: Kueper et al., 2014, Table 16.5. Note that monitoring was estimated to be for 10 years for both technologies.

Additionally, Kueper et al., 2014 presented implementation costs using In-Situ Chemical Oxidation (ISCO), Thermal Treatment, and Pump and Treat at this Case Study Site. Total monitoring costs for these technologies is assumed to be the same as that of EISB, described above for a 10-year project life. As seen in Table 7.6, the total project cost for these technologies ranges from $1,200K to $3,960K, as compared to that of $640K for Flux Reduction Barriers. As such, Flux Reduction Barriers are the more cost-effective technology alternative.

Table 7.6: Cost Comparison of Flux Reduction Barriers with Other Remedial Options

Cost Component	EISB	ISCO	Thermal	Pump and Treat	Flux Reduction Barriers
Design	144	134	248	254	67
Capital	592	705	2080	465	282
O&M	184	990	0	2967	0
Monitoring	277	277	277	277	291
Total ($K)	**1,200**	**2,100**	**2,600**	**3,960**	**640**
Total ($/yd3)	**663**	**1,170**	**1,440**	**2,200**	**355**

*Note: monitoring costs for EISB, ISCO, Thermal, and Pump and Treat assumed to be all for 10 years for comparison purposes. Keuper et al., 2014 listed varying monitoring time periods for these technologies.

8.0 IMPLEMENTATION ISSUES

What Type of Site Conditions Are Needed

- For high efficiency barriers with significant flow reduction, the site must have a lower low permeability unit such as a clay to prevent up flow; and a four sided barrier is recommended (three sided barriers are likely to have lower performance (Section 5.1.3).
- For accessing the lower cost silica gel grouting technology, the hydraulic conductivity of the transmissive unit should be in the range of $5\text{x}10^{-4}$ to 10^{-2} cm/sec.
- The source zone should contain electron donor to realize the benefit of electron acceptor diversion that a barrier provides. Sites with faster groundwater will have more benefit than sites with slow groundwater.

Using Existing Remediation Technology for Barriers

- This ESTCP demonstration was able to use existing remediation technology (direct push rigs and injection skids) to build four small barriers for the Small-Scale Demonstration.
- The mixing process is generally more complex than standard injection-based remediation projects because the injection skid needs to mix three fluids, delivery multiple locations simultaneously, let operators see pressure, flowrate, and have contingency for grout set-up in the injection manifolds. The design described in Section 5.4 and Appendix E worked well.

Designing Permeation Grout Barriers

- Permeation grouting requires filling all the porosity, not just the mobile porosity. This increases the amount of grout required for the barrier as total porosity in the 24% to 44% range are typically used for the volume of grout needed calculation compared to 2% to 10% for the mobile porosity. Note the Small-Scale Demonstration and the calculations in Section 6 assumed 30% porosity for the fine sand present in the test area.
- Munitions can complicate installation, but same holds for any injection based technology.
- The silica gel grout was much more reliable in terms of grouting times when the inorganic hardener (DBE)) was used (Section 5.3). On-site gel tests are important to confirm that the groundwater chemistry will work with the design mix of gel and hardener (Section 6.1.2). This is particularly true at sites with saline groundwater.
- If a direct push rig is used for injection and the injection zone is more than a few ft thick, multi-level injection wells (Section 5.4.2) are important to ensure even vertical distribution of the grout. If a permeation grouting contractor is used, a tube-a-manchette rig will provide good vertical distribution of grout in the barrier.

Design and Performance of Small-Scale Demonstration

- It was difficult to assess performance of the barrier for the Small-Scale Demonstration at the chosen location. Contributing factors include:

- The hydraulic conductivities were relatively low (0.63 ft per day ($2x10^{-4}$ cm/sec) (Section 6.3.2) resulting in low pumping rates (< 0.1 gpm) and low volumes of extracted groundwater during the before- and after-tests (< 20 gal);
- Potential construction problems associated with the multi-level injection wells in a very fine-grained heterogeneous unit (Section 5.4.2) as one injection well had to be abandoned (Section 6.2).
- The "donut" configuration (Section 5.1.2) may have not been efficient at testing the permeation grouting process; a larger demonstration area may have resulted to better test data. However using constant head injection tests, **an average of 64% reduction in flow resulted**, which is significant but below the 90% reduction performance goal. This result, and relatively low hydraulic conductivities in the planned Northern Plume test area, led to the decision not to perform the Large-Scale Demonstration.
- Applications for the flux reduction technology are likely to have better performance at sites with higher permeability and higher groundwater velocity than at the site used for the demonstration, both for demonstrating the hydraulic effect of the barrier and the benefits from electron acceptor diversion.

Novel Grouting Material

- The Solutions-IES grout material consisting of a silica gel/veg oil mix appeared to work as well as conventional silica gel for reducing flow (Table 6.4), but since the Small-Scale Demonstration was performed in a relatively unimpacted zone, the project was unable to test its dechlorination capabilities in the field. The theory behind the gel/oil material is sound as permeation grouting barriers are designed to reduce but not eliminate groundwater flow through them, therefore providing a mechanism for increased treatment with the oil.

9.0 REFERENCES

Adamson, D., McGuire, T., Newell, C., Stroo, H., 2011. Sustained Treatment: Implications for Treatment Timescales Associated With Source-Depletion Technologies. Remediation, Spring 2011.

Annable, M., Hatfield, K., Cho J., Klammer, H., Parker, B., Rao, P., 2005. Environmental Science and Technology.

Berry, R.M. 2000. When Grouting Don't Forget the Soil. Avanti, http://www.avantigrout.com/component/zoo/item/when-grouting-don-t-forget-the-soil

Borden, R.C., Yuncu, B., Shrestha, S.R., Kulkarni, P.R., Newell, C.J., 2014. Draft Treatability Report: Formulation of a Vegetable Oil-Based Material for Contaminant Flux Reduction Barriers. Prepared for ESTCP. August 2014. CH2MHill, 2004. Site-Specific Remedial Investigation Report Sites 11, 13, 17, 21, and 25. April 2004

CH2MHill, 2008. Site 17 Groundwater Feasibility Study, October 2008

CH2MHill, 2012. Site 17 Remedial Action Work Plan, August 2012

CH2MHill, 2014a. Site 17 Investigation after Short-Term Performance Monitoring of the Remedial Action Uniform Federal Policy-Sampling and Analysis Plan, January 2014

CH2MHill, 2014b. Site 17 Annual Report, March 2014

Hatfield, K., Annabe, M., Cho, J., Rao, P.S.C., Klammler, H., 2004. A Direct Passive Method for Measuring Water and Contaminant Fluxes in Porous Media. Journal of Contaminant Hydrology 75, 155-181.

Kamath, R., Newell C., 2008. BIOBALANCE: A Mass Balance Toolkit. Savannah River National Laboratory and U.S. Department of Energy. http://www.gsi-net.com/en/software/free-software/biobalance-toolkit.html

Karol, Reuben H., 2003. *Chemical Grouting and Soil Stabilization,* 3d ed., Marcel Dekker, Inc., New York, New York.

Kim, M., Corapcioglu, M.Y., 2002. Gel barrier formation in unsaturated porous media. Journal of Contaminant Hydrology. 26.

Krembs, F., Siegrist, R., Crimi, M., Furrer, R., Petri, B., 2010. ISCO for Groundwater Remediation: Analysis of Field Applications and Performance. Groundwater Monitoring & Remediation.

Leeson, A, and H. Stroo, 2011. Workshop Report: SERDP and ESTCP Workshop on Investment Strategies to Optimize Research and Demonstration Impacts in Support of DoD Restoration Goals. SERDP/ESTCP, Oct. 2011.

Looney, 2011. Personal communication based on Department of Energy (DOE) experience at several sites.

McDade, J.M., T.M. McGuire, and C.J. Newell. 2005. Analysis of DNAPL Source Depletion Costs at 36 Field Sites, *Remediation*, 2005, 15(2).

McGuire, T.M., McDade, J.M., Newell, C.J., 2006. Performance of DNAPL Source Depletion Technologies at 59 Chlorinated Solvent-Impacted Sites. Groundwater Monitoring & Remediation. Volume 26, Issue 1, pages 73-84, February 2006.

McGuire, T.M., Adamson, D.T., Newell, C.J., Kulkarni, P.R., 2016. Final Report: Development of an Expanded, High-Reliability Cost and Performance Database for In-Situ Remediation Technologies. ESTCP Project ER-201120. March 2016.

McHugh, T.E., J.A. Connor, F. Ahmad, and C. J. Newell, 2003. A Groundwater Mass Flux Model For Groundwater-To-Indoor-Air Vapor Intrusion. in: V.S. Magar and M.E. Kelley (Eds.)

Moridis, G.J., Finsterle, S., 1999. Evaluation of alternative designs for an injectable subsurface barrier at the Brookhaven National Laboratory site, Long Island, New York. Water Resources Research, Vol. 35, No. 10, Pg. 2937-2953.

Moridis, G.J., James, A., Oldenburg, C., 1997. Development of a Design Package for a Viscous Barrier at the Savannah River Site. Land Contamination & Remediation, 5 (3).

Newell, C. J., L. P. Hopkins, and P. B. Bedient, 1990. "A Hydrogeologic Database for Groundwater Modeling", Ground Water, Vol. 28, No. 5.

Newell, C., and C. Aziz, 2004. Long-term sustainability of reductive dechlorination reactions at chlorinated solvent sites. *Biodegradation*, 387-394.

Newell, C., C. Aziz, C., and G. Cox, 2003. *Enhanced Anaerobic Treatment Zones in Groundwater, U.S. Patent No. US 6,562,235 B1.* United States.

Newell, C., Farhat, S.K., Adamson, D.T., Looney B.B. Contaminant Plume Classification System Based on Mass Discharge, 2011. Ground Water, 49(6). Nov-Dec 2011.

Newell, C.J., Kueper, B.H., Wilson, J.T., Johnson, P.C., 2014. Natural Attenuation Of Chlorinated Solvent Source Zones. In: Kueper, B.H., Stroo, H.F., Vogel, C.M., Ward, C.H. (Eds.), Chlorinated Solvent Source Zone Remediation. Springer New York, New York, NY, pp. 459-508. SERDP/ESTP Monograph.

Payne, F. C., J. A. Quinnan, and S. T. Potter, 2008. Remediation Hydraulics, CRC Press.

Powers, J., Corwin, A., Schmall, P., Kaeck, W., 2007. Grouting Methods in Construction Dewatering and Groundwater Control: New Methods and Applications, Third Edition, John Wiley & Sons, In., Hoboken, NJ, USA.

Powers, J. Patrick, Arthur B. Corwin, Paul C. Schmall, and Walter E. Keck, 2007. *Construction Dewatering and Groundwater Control: New Methods and Applications,* 3d ed., John Wiley & Sons, Inc., Hoboken, New Jersey.

RRC, 2014. "Technical Review, Summary of Standards and Procedures, Injection/Disposal Well Permitting, Testing, and Monitoring Manual," Railroad Commission of Texas, Internet, accessed 16 October 2014, available at http://www.rrc.state.tx.us/oil-gas/publications-and-notices/manuals/injectiondisposal-well-manual/summary-of-standards-and-procedures/technical-review/.

Sale, T., C. Newell, H. Stroo, R. Hinchee, and P. Johnson, 2008. Frequently Asked Questions Regarding Management of Chlorinated Solvents in Soils and Groundwater, ESTCP Project ER-0530.

Truex, M., Pierce, EM., Nimmons, MJ., Mattigod, SV, 2011. Evaluation of In-Situ Grouting as a Potential Remediation Method for the Hanford Central Plateau Deep Vadose Zone. Prepared for the U.S. Department of Energy. Prepared by: Pacific Northwest National Laboratory.

Weaver, J. W., and F. D. Tillman, 2005 Uncertainty and the Johnson-Ettinger Model for Vapor Intrusion Calculation, USEPA Document EPA/600/R-05/110, Sept. 2005.

Wiedemeier, T.H., Rifai, H.S., Newell, C.J., and Wilson, J.W., 1999. Natural Attenuation of Fuels and Chlorinated Solvents, John Wiley & Sons, New York. (equation 2.12)

ESTCP

ESTCP Office

4800 Mark Center Drive
Suite 17D08
Alexandria, VA 22350-3605

(571) 372-6565 (Phone)

E-mail: estcp@estcp.org
www.serdp-estcp.org