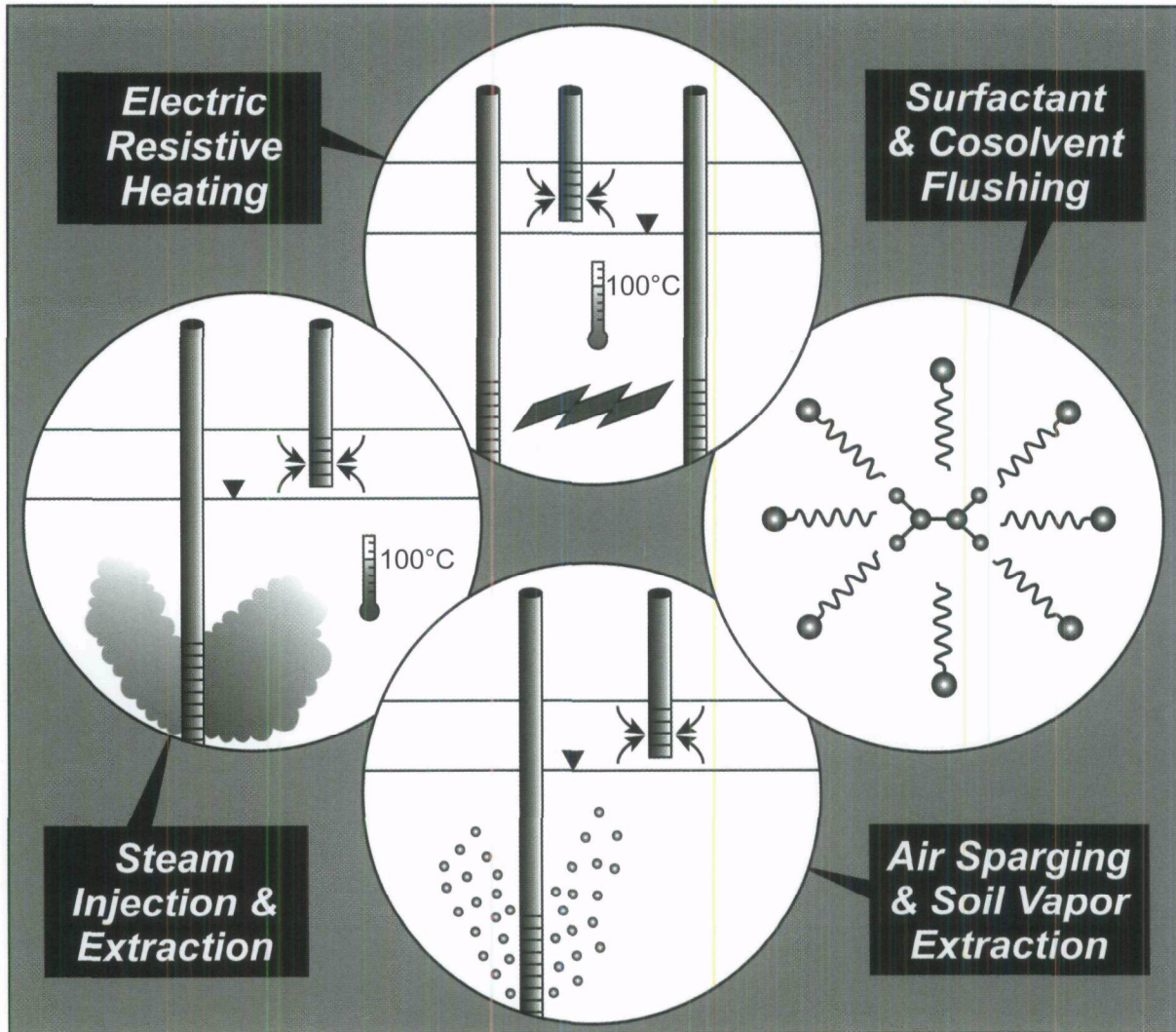


Synthesis Report on Five Dense, Nonaqueous-Phase Liquid (DNAPL) Remediation Projects



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SYNTHESIS REPORT ON FIVE DENSE, NONAQUEOUS-PHASE LIQUID (DNAPL) REMEDICATION PROJECTS

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NOTICE

Work described herein was performed by GeoTrans, Inc. (GeoTrans) for the U.S. Environmental Protection Agency (USEPA), Land Remediation and Pollution Control Division of the National Risk Management Research Laboratory. Work conducted by GeoTrans was performed under EPA contract 68-C-02-092 to Dynamac Corporation, Ada, Oklahoma. Mention of tradenames or commercial products does not constitute endorsement or recommendation for use.

FOREWORD

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Sally Gutierrez, Director
National Risk Management Research Laboratory

TABLE OF CONTENTS

NOTICE.....	ii
FOREWORD.....	iii
LIST OF FIGURES.....	vii
LIST OF TABLES.....	ix
EXECUTIVE SUMMARY.....	x
1.0 INTRODUCTION.....	1-1
2.0 LAUNCH COMPLEX 34, CAPE CANAVERAL, FLORIDA.....	2-1
2.1 PROJECT BACKGROUND.....	2-1
2.2 SITE CHARACTERIZATION.....	2-2
2.3 TECHNOLOGY DESCRIPTION AND OPERATION: RESISTIVE HEATING.....	2-3
2.3.1 GENERAL TECHNOLOGY DESCRIPTION.....	2-3
2.3.2 TECHNOLOGY AS APPLIED DURING THE PROJECT.....	2-3
2.3.3 PERFORMANCE ASSESSMENT – METHODOLOGY.....	2-4
2.3.4 PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS.....	2-5
2.3.5 ECONOMIC ANALYSIS.....	2-7
2.4 TECHNOLOGY DESCRIPTION AND OPERATION: STEAM INJECTION/EXTRACTION.....	2-7
2.4.1 GENERAL TECHNOLOGY DESCRIPTION.....	2-7
2.4.2 TECHNOLOGY AS APPLIED DURING THE PROJECT.....	2-8
2.4.3 PERFORMANCE ASSESSMENT – METHODOLOGY.....	2-9
2.4.4 PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS.....	2-10
2.4.5 ECONOMIC ANALYSIS.....	2-12
2.5 EVALUATION OF TECHNOLOGIES.....	2-12
2.5.1 PROJECT SUCCESS RELATIVE TO PROJECT GOALS.....	2-12
2.5.2 PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK.....	2-13
2.5.3 CONSIDERATIONS FOR THOSE CONTEMPLATING A TECHNOLOGY APPLICATION AT ANOTHER SITE.....	2-14
2.6 DOCUMENTS REVIEWED.....	2-15
3.0 DOVER NATIONAL TEST SITE, DOVER AIR FORCE BASE, DELAWARE.....	3-1
3.1 PROJECT BACKGROUND.....	3-1
3.2 SITE CHARACTERIZATION.....	3-1
3.3 TECHNOLOGY DESCRIPTION AND OPERATION.....	3-1
3.3.1 GENERAL TECHNOLOGY DESCRIPTIONS.....	3-1
3.3.2 TECHNOLOGIES AS APPLIED DURING THE PROJECT.....	3-2
3.3.3 PERFORMANCE ASSESSMENT – METHODOLOGY.....	3-4

3.3.4	PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS.....	3-4
3.3.5	ECONOMIC ANALYSIS.....	3-6
3.4	EVALUATION OF TECHNOLOGIES.....	3-6
3.4.1	PROJECT SUCCESS RELATIVE TO PROJECT GOALS.....	3-6
3.4.2	PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK.....	3-6
3.4.3	CONSIDERATIONS FOR THOSE CONTEMPLATING TECHNOLOGY APPLICATIONS AT ANOTHER SITE.....	3-7
3.5	DOCUMENTS REVIEWED.....	3-8
4.0	PANELS 1 AND 5, OPERABLE UNIT 2, HILL AIR FORCE BASE, UTAH	4-1
4.1	PROJECT BACKGROUND	4-1
4.2	SITE CHARACTERIZATION.....	4-2
4.3	TECHNOLOGY DESCRIPTION AND OPERATION: SURFACTANT ENHANCED AQUIFER REMEDIATION.....	4-3
4.3.1	GENERAL TECHNOLOGY DESCRIPTION.....	4-3
4.3.2	TECHNOLOGY AS APPLIED DURING THE PROJECT.....	4-3
4.3.3	PERFORMANCE ASSESSMENT – METHODOLOGY.....	4-4
4.3.4	PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS.....	4-5
4.3.5	ECONOMIC ANALYSIS.....	4-6
4.4	EVALUATION OF TECHNOLOGY	4-7
4.4.1	PROJECT SUCCESS RELATIVE TO PROJECT GOALS.....	4-7
4.4.2	PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK.....	4-7
4.4.3	CONSIDERATIONS FOR THOSE CONTEMPLATING A TECHNOLOGY APPLICATION AT ANOTHER SITE.....	4-7
4.5	DOCUMENTS REVIEWED.....	4-9
5.0	LORING AIR FORCE BASE, LIMESTONE, MAINE.....	5-1
5.1	PROJECT BACKGROUND	5-1
5.2	SITE CHARACTERIZATION.....	5-1
5.3	TECHNOLOGY DESCRIPTION AND OPERATION.....	5-3
5.3.1	GENERAL TECHNOLOGY DESCRIPTION.....	5-3
5.3.2	PERFORMANCE ASSESSMENT.....	5-4
5.3.3	ECONOMIC ANALYSIS.....	5-4
5.4	EVALUATION OF SER TECHNOLOGY	5-4
5.4.1	PROJECT SUCCESS RELATIVE TO PROJECT OBJECTIVES	5-4
5.4.2	CONSIDERATIONS FOR THOSE CONTEMPLATING AN APPLICATION AT ANOTHER SITE.....	5-5
5.5	DOCUMENTS REVIEWED.....	5-6

6.0	SAGES DRY CLEANERS, JACKSONVILLE, FLORIDA	6-1
6.1	PROJECT BACKGROUND	6-1
6.2	SITE CHARACTERIZATION.....	6-1
6.3	TECHNOLOGY DESCRIPTION AND OPERATION.....	6-3
6.3.1	PERFORMANCE ASSESSMENT	6-6
6.3.2	ECONOMIC ANALYSIS.....	6-7
6.4	EVALUATION OF SERB TREATMENT TRAIN TECHNOLOGY.....	6-8
6.4.1	PROJECT SUCCESS RELATIVE TO PROJECT GOALS.....	6-8
6.4.2	PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK AND CONSIDERATIONS FOR APPLYING THE TECHNOLOGY AT ANOTHER SITE	6-8
6.5	DOCUMENTS REVIEWED.....	6-9
7.0	CONCLUSIONS.....	7-1
7.1	SUMMARY OF PROJECT RESULTS	7-1
7.2	COMMON LESSONS LEARNED	7-1
7.3	LESSONS LEARNED FOR FUTURE DEMONSTRATION PROJECTS.....	7-3

LIST OF FIGURES

Figure 2-1.	Test Plot Layout at Luaunch Complex 34, Cape Canaveral, Florida (Battelle, 2003A).....	2-17
Figure 2-2.	Upper Sand Soil Sampling Results (a) before and (a) after resistive heating (Battelle, 2003a).....	2-18
Figure 2-3.	Middle Fine-Grained Soil Sampling Results (a) before and (b) after resistive heating (Battelle, 2003a).....	2-19
Figure 2-4.	Lower Sand soil sampling results (a) before and (b) after resistive heating (Battelle, 2003a).....	2-20
Figure 2-5.	Upper Sand ground water concentrations (a) before and (b) after resistive heating (Battelle, 2003a).....	2-21
Figure 2-6.	Middle Fine-Grained ground water sampling results (a) before and (b) after resistive heating (Battelle, 2003a).....	2-21
Figure 2-7.	Lower Sand ground water sampling results (a) before and (b) after resistive heating (Battelle, 2003a).....	2-22
Figure 2-8.	Upper Sand soil sampling results (a) before and (b) after steam injection/extraction (Battelle, 2003a).....	2-23
Figure 2-9.	Middle Fine-Grained soil sampling results (a) before and (b) after steam injection/extraction (Battelle, 2003a).....	2-24
Figure 2-10.	Lower Sand soil sampling results (a) before and (b) after steam injection/extraction (Battelle, 2003a).....	2-25
Figure 2-11.	Upper Sand ground water sampling results (a) before and (b) after steam injection/extraction (Battelle, 2003a).....	2-26
Figure 2-12.	Middle Fine-Grained ground water sampling results (a) before and (b) after steam injection/extraction (Battelle, 2003a).....	2-26
Figure 2-13.	Lower Sand ground water sampling results (a) before and (b) after steam injection/extraction (Battelle, 2003a).....	2-27
Figure 3-1.	Layout of a test cell with locations indicated for injection/extraction wells, multilevel sampling ports (MLS), and PCE release points (Wood and Enfield, 2004)	3-9
Figure 3-2.	PCE concentrations and ethanol (cosolvent) concentrations over the course of the demonstration in two different extraction wells (Wood and Enfield, 2004).....	3-10
Figure 3-3.	Cumulative mass removed by the AS/SVE. The noticeable increases in mass removal correspond to periods where the sparging configuration was changed and/or when a ground water flow pattern was induced (Wood and Enfield, 2004).....	3-11
Figure 3-4.	Cumulative PCE mass removed as a function of time (a) and as a function of pore volumes. Changes in mass removal correspond to changes in injection/extraction configuration	3-12

Figure 3-5. The cumulative PCE and n-propanol mass removed (Wood and Enfield, 2004)3-13

Figure 4-1. Operable Unit 2 with locations of Panel 1 and Panel 5 indicated (URS, 2003).....4-10

Figure 4-2. Schematic of Operable Unit 2 cross-section at Panel 1 (URS, 2003)4-11

Figure 5-1. Conceptual model of geology for the Quarry Site, Loring Air Force Base5-12

Figure 5-2. Location of the DNAPL zone at the Quarry Site, Loring Air Force Base5-13

LIST OF TABLES

Table 5-1. Chronology of Remediation Activities at the Loring Site.....	5-7
Table 5-2. EPA Site Program Objectives	5-8
Table 5-3. Detailed Technology Objectives for the Quarry Site, Loring Air Force Base	5-9
Table 5-4. Supplemental Technology Objectives for the Quarry Site, Loring Air Force Base	5-10
Table 5-5. Summary of Costs	5-11

EXECUTIVE SUMMARY

Dense non-aqueous phase liquid (DNAPL) poses a difficult problem for subsurface remediation because it serves as a continuing source to dissolved phase ground water contamination and is difficult to remove from interstitial pore space or bedrock fractures in the subsurface. Numerous technologies have been developed for DNAPL remediation, but demonstrations of these technologies have had mixed results.

This document summarizes the performance and results of DNAPL removal demonstration projects at five sites with the purpose of informing the hydrogeology and remedial engineering community of the results and lessons learned from these demonstrations. The five projects and the technologies demonstrated for each project are as follows:

1. Launch Complex 34, Cape Canaveral, Florida
 - Thermally-enhanced remediation with resistive heating
 - Thermally-enhanced remediation with steam injection/extraction
2. Dover National Test Site, Dover Air Force Base, Delaware
 - Cosolvent flushing
 - Surfactant flushing
 - Air sparging/soil vapor extraction (SVE)
 - Cosolvent DNAPL mobilization
 - Complex sugar flushing
3. Panels 1 and 5, Operable Unit 2, Hill Air Force Base, Utah
 - Surfactant enhanced aquifer remediation (SEAR)
4. Quarry Site, Loring Air Force Base, Limestone, Maine
 - Thermally-enhanced remediation of fractured bedrock with steam injection
5. Sages Dry Cleaners, Jacksonville, Florida
 - Cosolvent flushing and enhanced bioremediation

Most of the technologies were successful at removing contaminant mass from the subsurface, and project performance varied with the degree of project planning and site conditions. The project teams from four of the above 10 technology demonstrations claimed mass removal at approximately 90%. Some technology demonstrations removed less than 70%, and the Loring demonstration, which was conducted in fractured bedrock with limited primary and secondary porosity, removed very little mass from the subsurface (i.e., much less than 10% of the target mass).

Each of the projects is discussed and evaluated for success relative to the project objectives and within a financial/regulatory framework that is typical of most contaminated sites. Lessons learned and considerations for future applications based on each project are provided along with lessons learned for conducting future demonstration projects.

Some of the common lessons learned from the various projects are as follows:

- All of the DNAPL technologies discussed have the potential to remove substantial mass from the subsurface, including several demonstrations that report approximately 90% or more mass recovery. In all cases, however, DNAPL remained in the subsurface (albeit in much reduced quantities), and soil and dissolved concentrations were sufficiently high to merit additional active

remediation. Site teams (including facility managers, contractors, and Remedial Project Managers) may consider the likelihood that substantial contamination will remain in the subsurface after application of one of these technologies at another site.

- Technology performance was heavily dependent on site-specific planning and on site-specific setting. For example, the SEAR application at Panels 1 and 5 in Operable Unit 2 at Hill Air Force Base entailed substantial planning, including laboratory analysis, field studies, and numerical modeling. In addition, target areas were relatively permeable with hydraulic conductivities exceeding 100 ft per day. Contaminant mass removal from this demonstration was successful (although an unknown amount of contaminant mass remains in the subsurface). Contrastingly, the steam injection/extraction demonstration at Loring Air Force Base was conducted in a fractured bedrock environment that the site team knew had very limited porosity. The contaminant mass removal from this technology was limited.
- Hydrogeological parameters appear to have played a large role in technology performance. The following table summarizes the site-specific hydrogeological factors that appear to have substantially impacted the performance of each technology. Application of these technologies at other sites under different hydrogeologic conditions, such as a higher or lower hydraulic conductivity, may significantly alter the performance of these technologies.

TEST SITE AND TECHNOLOGY(IES)	HYDROGEOLOGICAL FACTORS THAT INFLUENCED TEST PERFORMANCE
Launch Complex 34, Cape Canaveral, Florida <ul style="list-style-type: none"> • Resistive heating • Steam injection/extraction 	<ul style="list-style-type: none"> • The relatively permeable Upper Sand unit likely facilitated recovery of contaminant vapors. • The relatively shallow test area (40 ft of saturated thickness) likely assisted with heating the vertical interval from the bottom of the test cell to the vapor recovery system.
Dover National Test Site, Dover Air Force Base <ul style="list-style-type: none"> • Cosolvent flushing • AS/SVE • SEAR • Cosolvent mobilization • Complex sugar flushing 	<ul style="list-style-type: none"> • The hydraulically isolated test cells likely facilitated technology implementation and allowed for recirculation of remedial fluids. • The relatively permeable formation with a hydraulic conductivity of 8 ft per day to 34 ft per day likely improved dispersal of the injected remedial fluids and DNAPL recovery. • The absence of a confining layer enabled vapor recovery for the AS/SVE test.
Operable Unit 2, Hill Air Force Base <ul style="list-style-type: none"> • SEAR 	<ul style="list-style-type: none"> • The high permeability of the formation with a hydraulic conductivity over 100 ft per day likely improved dispersal of the injected remedial fluids and recovery of DNAPL. • The clay formation surrounding the paleochannel, where the technology was tested, likely helped contain DNAPL and the injected remedial fluids.
Quarry Site, Loring Air Force Base <ul style="list-style-type: none"> • Steam enhanced remediation 	<ul style="list-style-type: none"> • The low primary and secondary porosity of the fractured rock formation (on the order of 3% and 1%, respectively) significantly reduced the delivery of steam (heat) to the subsurface and had a significant negative affect on technology performance.
Sages Dry Cleaner <ul style="list-style-type: none"> • Cosolvent flushing • Passive, enhanced bioremediation 	<ul style="list-style-type: none"> • DNAPL in thin “stringers” complicated DNAPL removal. • The relatively permeable formation (10 ft per day to 20 ft per day) likely improved dispersal of the injected remedial fluids.

- Because none of the demonstrations had results that eliminated the need for further active remediation, it would be difficult to determine the financial benefit of these technology applications had they been conducted for the purpose of reducing life-cycle remediation costs.
- In addition, to an uncertain amount of additional active remediation required, other factors also contribute to complicating the application of the financial information from these demonstrations to other sites. For example, the SEAR application at Operable Unit 2 at Hill Air Force Base utilized existing infrastructure that would generally not be available at other sites considering use of this technology. Also, the tests conducted at the Dover National Test Site benefited from recycling treated water with elevated PCE concentrations because the test cells were hydraulically isolated from the surrounding aquifer. Recycling this water at another site would likely either require additional treatment than that used during the demonstration or additional cost for isolating the target area to be treated. Data suggests that the resistive heating application at Launch Complex 34 released substantial TCE vapor to the atmosphere and that TCE may have migrated from the test plot in the subsurface. A more comprehensive ground water and vapor recovery system that would have limited this contaminant release would likely have added substantially to the costs provided.
- Several of the technology demonstrations may have had negative impacts on the environment or on future remedial activities. For example data suggest that the resistive heating application at Launch Complex 34 resulted in unwanted contaminant migration (to the atmosphere and within the subsurface). Four of the five technologies implemented at the Dover National Test Site left residual reagents in the aquifer (e.g., surfactants or cosolvents) that may complicate future ground water treatment by air stripping or granular activated carbon. The SEAR application at Hill Air Force base resulted in the production of methyl isobutyl ketone (MIBK), in the test area, potentially creating a new environmental hazard. In addition the site contractor reports that the SEAR application has increased annual operations and maintenance costs for the ongoing treatment system by \$20,000 to \$50,000 per year.

The DNAPL removal demonstration projects described in this report and in other documents have proven the ability of the technologies to remove substantial contaminant mass in many cases. Therefore, there is questionable value in additional demonstrations of the same technologies with the sole purpose of quantifying mass removal. There is substantial value, however, to conducting demonstrations of these technologies to provide more comprehensive information regarding the ability of the technologies to reduce life-cycle costs or reduce the time to closure within a reasonable time frame (e.g., 30 years). For this reason, the remediation community would benefit from considering the following:

- Project demonstrations could be developed to attempt to achieve more refined remedial objectives, rather than to remove contaminant mass. Such demonstrations would more closely reproduce the conditions that most remedial site managers face. To accomplish this, demonstration project managers might consider working with the site regulator to determine a set of achievable site conditions that would eliminate the need for further active remediation. Similarly, project managers and engineers could determine a set of achievable site conditions that would substantially reduce operations and maintenance costs for future remedial efforts. The demonstration projects could then continue until the identified sets of conditions have either been met or until an unacceptable amount of money has been spent and an acceptable (and potentially lower-cost) long-term remedy has been put in place. It is recognized that these demonstrations would likely occur over several years, potentially with multiple applications of mass removal technologies and/or actual implementation of subsequent source control measures.

- Involving site regulators in demonstration projects can also be helpful in that the site regulators can help the project team determine the measures that would need to be taken to prevent unintentional spreading or release of contamination or to address the results of unintentional spreading or release of contamination.
- Project demonstrations could be conducted in the types of settings and with the type of infrastructure that would be found at the typical site. For example, further demonstrations in hydraulically isolated test cells have reduced value (unless the isolation is a component of the technology being tested) because the cell isolation affords the demonstration team advantages that are not generally available at other sites. Similarly, the use of existing infrastructure such as an existing pump and treat system or wastewater treatment plant may be an advantage that is not necessarily available at other sites. It is recognized that using this infrastructure allows the demonstration to be conducted for a more reasonable price; therefore, if such infrastructure is used, it may be appropriate to provide realistic cost estimates for providing that infrastructure or a similar level of treatment at another site.

1.0 INTRODUCTION

Dense non-aqueous phase liquid (DNAPL) poses a difficult problem for subsurface remediation because it serves as a continuing source to dissolved phase ground water contamination and is difficult to remove from interstitial pore space or bedrock fractures in the subsurface. Numerous technologies have been developed to attempt DNAPL remediation, but demonstrations of these technologies have had mixed results, making it difficult for site managers to decide whether or not to consider a particular DNAPL remediation technology for their site.

This document summarizes the performance and results of DNAPL removal demonstration projects at five sites with the purpose of informing the hydrogeology and remedial engineering community of the results and lessons learned from these demonstrations. The five projects and the technologies demonstrated for each project are as follows:

1. Launch Complex 34, Cape Canaveral, Florida
 - Thermally-enhanced remediation resistive heating
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 - Cosolvent DNAPL mobilization
 - Complex sugar flushing
3. Panels 1 and 5, Operable Unit 2, Hill Air Force Base, Utah
 - Surfactant enhanced aquifer remediation (SEAR)
4. Loring Air Force Base, Limestone, Maine
 - Thermally-enhanced remediation of fractured bedrock with steam injection
5. Sages Dry Cleaners, Jacksonville, Florida
 - Cosolvent flushing and enhanced bioremediation

Each project summary includes the following components:

- Project background
- Site characterization
- Description and operation of technology(ies)
 - Description of technology application
 - Performance assessment
 - Economic Analysis
- Evaluation of Technology(ies)
 - Evaluation of project/technology success
 - Considerations for future applications
- Documents Reviewed

Each of the described projects uses different units to represent the amount of DNAPL or contaminant mass that is in the subsurface or that has been removed from the subsurface. The units for each project are generally retained from project to project. When comparing the results from one project to another, the percentage of mass removal (unitless) is used.

The conclusion of this document summarizes the results of these technology demonstrations and common lessons learned for applying the technologies at other sites. It also provides lessons learned regarding future DNAPL removal technology demonstrations/experiments. Specific lessons learned and conclusions are provided in the “evaluation” section for each technology.

2.0 LAUNCH COMPLEX 34, CAPE CANAVERAL, FLORIDA

2.1 PROJECT BACKGROUND

This project, conducted at Launch Complex 34 in Cape Canaveral, Florida in 1999, tested the technical and economical performance of the following three technologies in remediating trichloroethene (TCE) DNAPL: in-situ chemical oxidation (ISCO), electrical resistive heating, and steam injection. The technologies were independently tested in three different plots within the DNAPL plume. The project was organized and funded by the Interagency DNAPL Consortium (IDC), which consists of the following U.S. government agencies:

- Department of Energy (DoE)
- Environmental Protection Agency (EPA)
- Department of Defense (DoD)
- National Aeronautics and Space Administration (NASA)

The IDC contracted Battelle to plan and evaluate tests, and the EPA Superfund Innovative Technology Evaluation (SITE) program provided quality assurance oversight and field support. Current Environmental Solutions (CES) implemented the resistive heating application, and Integrated Water Resources, Inc. (IWR) implemented the steam injection/extraction application. Several experts from academia, industry, and government served as a Technical Advisory Group to the project. In addition, Patrick Air Force Base, the EPA R.S. Kerr Environmental Research Center, and the Interstate Technology Regulatory Council (ITRC) played supporting roles by contributing funding, reviewing plans, or promoting technology transfer. The information in this section is based on the February 2003 Battelle report titled *Demonstration of Resistive Heating Treatment of a DNAPL Source Zone at Launch Complex 34 in Cape Canaveral, Florida* (Battelle, 2003a) and the September 2003 Battelle report titled *Demonstration of Steam Injection/Extraction Treatment of a DNAPL Source Zone at Launch Complex 34 in Cape Canaveral, Florida* (Battelle, 2003b).

The project had the following technical objectives for each of the technologies:

- Estimate the DNAPL mass removal due to the tested technology
- Estimate the changes in aquifer quality due to the treatment
- Evaluate the fate of the DNAPL removed from each plot
- Verify the technology operating requirements and costs

The mass removal objective was considered the primary objective, and the other objectives were considered important, but secondary to this primary objective. The Technology Advisory Group further suggested a remedial goal of 90% DNAPL mass removal for each of the tested technologies.

The project progressed according to the following timeline:

February 1999	Battelle conducted preliminary characterization of the study area consisting of the three test plots
June 1999	Battelle conducted pre-demonstration assessments of the resistive heating and ISCO plots
September 1999 to July 2000	Resistive heating and ISCO were applied to their specific plots and progress was monitored
August 2000 to December 2000	Battelle conducted post-demonstration assessments of the resistive heating and ISCO plots

December 2000	Battelle conducted a pre-demonstration assessment of the steam injection plot
July 2001 to December 2001	Steam injection was applied to a specific plot within the study area and progress was monitored
February 2002	Battelle conducted a post-demonstration assessment of the steam injection plot

This synthesis report discusses the resistive heating and steam injection applications.

2.2 SITE CHARACTERIZATION

Preliminary site characterization suggested that between 20,600 kg and 40,000 kg of solvent may be present in the subsurface near the Engineering Support Building at Launch Complex 34, where the test plots are located. Characterization efforts conducted prior to the tests suggest that DNAPL is limited to the surficial aquifer, which extends to a depth of 45 ft bgs and is underlain by a thin (1.5 to 3.0 ft thick) clay layer. It is noted, however, that subsequent studies not discussed in the 2003 reports suggest DNAPL extends to a depth of at least 75 ft bgs (Casparly, 2006). The test plots, illustrated in Figure 2-1, are aligned in a row, with the steam injection plot in the center and the ISCO and resistive heating plots located on either side. Each test plot extends to the clay layer at a depth of 45 ft bgs and is 75 ft by 50 ft in the horizontal dimensions, partially extending beneath the Engineering Support Building. The technology demonstrations were not designed to address the DNAPL beneath the clay layer.

The hydrostratigraphy of the surficial aquifer is described in the following table.

UNIT	THICKNESS (FT)	SEDIMENT DESCRIPTION	MEASURED HYDRAULIC CONDUCTIVITY (FT/DAY)	AQUIFER DESCRIPTION
Upper Sand	20-26	Fine sand and shell fragments	0.14 to 13.7	Unconfined, direct recharge from surface
Middle Fine-Grained	10-15	Fine grained silty/clayey sand	2.1 to 4.9	Low-permeability, semi-confining layer
Lower Sand	15-20	Medium sized sand and shell fragments	2.7 to 3.3	Semi-confined

During the assessments, the ground water was approximately 4 to 5 ft below ground surface, and the hydraulic gradient was relatively flat across the study area (consistently under 0.001 ft per ft).

The pre-demonstration assessments included characterizing contamination in all three hydrostratigraphic units within the surficial aquifer. The following table provides information regarding TCE contamination magnitude and extent in each of the units of the resistive heating and steam injection test plots.

TEST PLOT	UNIT	MAXIMUM MEASURED TCE CONCENTRATIONS GROUND		ESTIMATED TOTAL TCE MASS (KG)*	ESTIMATED TCE MASS AS DNAPL (KG)**
		GROUND WATER (MG/L)	SOIL (MG/KG)		
Resistive Heating	Upper Sand	1,100	>10,000	11,313	10,490
	Middle Fine-Grained	1,070	>10,000		
	Lower Sand	922	>10,000		
Steam Injection	Upper Sand	650	>1,000	10,435	9,301
	Middle Fine-Grained	970	>5,000		
	Lower Sand	1,300	>10,000		

* Based on linear interpolation of ground water and soil TCE concentrations for all three hydrostratigraphic units combined

** Based on interpolated volumes where soil concentrations exceeded 300 mg/kg for all three hydrostratigraphic units combined

DNAPL was not observed in any of the monitoring wells, but the dissolved concentrations are close to the solubility of TCE (1,100 mg/L), indicating that DNAPL is present. Other parameters, including alkalinity, total dissolved solids, iron, calcium, and sulfate were measured as part of site characterization, but are not reported here.

2.3 TECHNOLOGY DESCRIPTION AND OPERATION: RESISTIVE HEATING

2.3.1 GENERAL TECHNOLOGY DESCRIPTION

Resistive heating uses electricity to heat subsurface soils to above 100 °C. Volatile and semi-volatile organic compounds are removed from the subsurface by direct volatilization or by steam stripping as water vapor migrates to the surface. Research indicates that contaminant destruction may also occur due to accelerated abiotic and/or biotic processes. A network of vapor extraction wells in the vadose zone extracts the volatilized contaminants and water vapor and brings them to the surface to be addressed by either treatment or condensation and off-site disposal.

2.3.2 TECHNOLOGY AS APPLIED DURING THE PROJECT

The resistive heating vendor initially used 13 electrodes to deliver electricity to the subsurface, with three of the electrodes installed at an angle of 18 degrees to the vertical to access the portion of the test plot underlying the Engineering Support Building. The electrodes were installed to a depth slightly above the clay layer that underlies the surficial aquifer, and each electrode consisted of two conducting intervals: one from 23 ft to 30 ft bgs (in the Upper Sand) and the other from 38 ft to 45 ft bgs (in the Lower Sand). The electrodes were later upgraded to improve heating in the shallow zone to account for increased water recharge from hurricanes that occurred during the test.

Twelve vapor extraction wells were initially installed with 2-ft screens to depths of 4 to 6 ft bgs to recover the vapors. Vertical and horizontal wells were later added to improve extraction. A surface cover was also used to enhance vapor recovery and reduce the likelihood of vapors escaping to the atmosphere. The extracted vapor and steam passed through an air-water knockout drum, a heat exchanger, a condensate collection drum, and a centrifugal blower. The off-gas from the blower was treated by a 20,000-pound granular activated carbon (GAC) unit. An additional 1,000-pound GAC vessel and an 800-pound silica bed impregnated with potassium permanganate were used to remove vinyl chloride in the off-gas. Some of the steam condensate passed through a 1,000 pound liquid phase GAC unit and through a cooling tower to provide cooling for the heat exchanger. The remaining condensate was transported to an on-site wastewater treatment facility.

The following table provides a timeline of the resistive heating and soil vapor extraction.

TIMEFRAME	ACTIVITY	ENERGY DELIVERED (KW-H)	TEMPERATURE (°C) BEFORE/AFTER HEATING APPLICATION
8/18/00 to 9/30/00	First heat application	216,915	Top of Aquifer: 30/47 Bottom of Aquifer: 24/92
9/30/99 to 12/12/99	Break in operation	Hurricane damaged power system, electrodes upgraded, extraction system and drainage upgraded	
12/12/99 to 3/24/00	Second heat application	821,100	Top of Aquifer: 39/100 Bottom of Aquifer: 75/124
3/24/00 to 5/11/00	Break in heating	Power supply replacement and delays associated with rocket launches, vapor recovery system continues to operate	
5/11/00 to 7/12/00	Third heat application	687,800	Top of Aquifer: 60/100 Bottom of Aquifer: 82/124
7/12/00 to 9/19/00	Heating off	Vapor recovery system continues to recover vapors	

There were several events that occurred during this project that are unique to the setting of this site. Hurricanes Floyd (9/10/1999) and Irene (10/17/1999) hit the site, damaging the power supply and raising the water table approximately 4.5 ft. As a result, the system was inoperable until December 1999. The addition of this water partially cooled the upper reaches of aquifer and flooded the vapor extraction system. The project team suggested that the cooling effect of the precipitation condensed TCE vapors near the ground surface, resulting in migration out of the test plot. In addition, the inoperability of the vapor recovery system likely led to the release of TCE to the atmosphere.

The project team reported the following issues that required engineering and/or administrative measures to maintain health and safety during the project:

- Insulating the ground surface from the high voltage electricity to prevent electrocuting personnel or damaging equipment
- Minimizing or avoiding contact with steam released from the monitoring wells during sampling

2.3.3 PERFORMANCE ASSESSMENT – METHODOLOGY

The performance assessment methodology was based on the four objectives, with particular emphasis on DNAPL mass removal from the test plot. The assessment included a pre-demonstration and a post-demonstration assessment. Estimates of DNAPL mass were based on linear interpolation and kriging of TCE concentrations in soil samples collected during these two assessments. The pre- and post-demonstration assessments each included 12 cores with 23 samples collected at 2-ft intervals in each core. The project team defined DNAPL as present when the TCE concentration in soil was greater than 300 mg/kg, based on a calculation of equilibrium TCE partitioning using the method of Feenstra et al. (1991).

The other objectives were addressed as follows:

- To evaluate changes in aquifer quality, the project team collected and analyzed the following information during the pre- and post-demonstration assessments.
 - Dissolved concentrations of chlorinated volatile organic compounds inside and outside of the test plot
 - Concentrations of common ions, total dissolved solids, total organic carbon, biological oxygen demand, and other parameters
 - Hydraulic conductivity of the aquifer
 - Microbial populations of the aquifer
- To evaluate the fate of TCE in the test plot, the project team collected and analyzed the following information:
 - Chloride concentrations in the ground water, which would be present if TCE was mineralized into carbon dioxide and chloride
 - Hydraulic gradients to determine approximate magnitude and direction of ground water flow
 - Potassium ion concentrations from the ISCO test and useful as a tracer
 - Surface emission tests of contaminant vapors
 - Contaminant concentrations in soil outside of the test plot

- Contaminant concentrations in the semi-confined aquifer underlying the test plot
- To evaluate the operating requirements and costs, the project team reviewed a report provided by the vendor that summarized the requirements and costs. The project team also incorporated costs associated with the pre- and post-demonstration assessments.

2.3.4 PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS

Project-Specific Objective: Quantifying DNAPL Mass Recovery

The following table summarizes the change in total TCE mass and DNAPL mass as a result of the resistive heating based on linear interpolation of the pre- and post-demonstration soil samples. Figures 2-2 through 2-4 illustrate the pre- and post-demonstration TCE soil concentrations.

UNIT	PRE-DEMONSTRATION		POST-DEMONSTRATION		CHANGE IN MASS (%)	
	TOTAL TCE (KG)	DNAPL (KG)	TOTAL TCE (KG)	DNAPL (KG)	TOTAL TCE	DNAPL
Upper Sand	183	70	141	35	-23	-50
Middle Fine-Grained	611	447	304	124	-50	-72
Lower Sand	10,519	9,973	656	179	-94	-98
Total (Entire Plot)	11,313	10,490	1,101	338	-90*	-97*

* An undetermined amount of this mass removal may have been mass that migrated from the test plot to the surrounding aquifer.

The above results show that approximately 93% of the total TCE mass and 95% of the DNAPL mass in the test plot were present in the Lower Sand prior to the test. The results also show that based on the assessment methodologies employed by the project team, the technology met the stated remedial goal of removing more than 90% of the DNAPL mass from the test plot. According to the post-demonstration results, the Lower Sand contained the majority of the remaining TCE and DNAPL mass; however, the distribution of this mass between the three hydrostratigraphic units was much more even after the test than it was at the beginning of the test. The project team's interpretation of the post-demonstration assessment suggests that approximately 60% of the remaining TCE mass and 50% of the remaining DNAPL mass were present in the Lower Sand. Mass removal percentages from the shallow and middle units were lower than that of the Lower Sand, and according to Figures 2-2 and 2-3, it appears that TCE concentrations may have increased in some portions of the Upper Sand and Middle Fine-Grained Unit (e.g., SB-1/SB-201, SB-2/SB-202, SB-3/SB-203), particularly near boundaries of the test plot. The project team hypothesized that this may have resulted from potential condensation of TCE vapors in the shallow zone prior to being extracted.

Based on the analyses of the project team using linear interpolation, the technology met the remediation goal of 90% DNAPL removal from the test plot. Results from kriging (rather than linear interpolation) are consistent for total TCE removed, but an analysis was not done for DNAPL removed because the project team felt that too few relevant data points were available. It is questionable, however, how much mass of the mass removal was mass migration from the test plot as a result of the resistive heating application given the increase in mass at some sampling locations along the test plot boundary.

Project-Specific Objective: Evaluating Changes in the Aquifer

TCE concentrations in the resistive heating plot were measured on two occasions after heating stopped: once in November/December 2000 (5 to 6 months after heating stopped) and once in June 2001 (approximately 11 months after heating stopped). The TCE results from the two events were similar, and contour plots based on a compilation of both data sets are presented in Figures 2-5 through 2-7 alongside the pre-demonstration TCE ground water concentrations. The distribution of TCE concentrations in

ground water after the test showed a general decrease and a redistribution of TCE mass in ground water; however, the results are difficult to interpret because the number of monitoring points within the test plot is limited, and samples were not necessarily collected from the same monitoring wells during the pre- and post-demonstration assessments.

Maximum concentrations remained relatively unchanged in both the Upper and Lower Sands. Ground water concentrations of cis-1,2-dichloroethylene (cis-1,2-DCE), generally increased, which the project team attributed to degradation of TCE accelerated by the heating. Vinyl chloride concentrations in ground water remained low relative to the other compounds and generally unchanged as a result of heating. The following table provides the concentration ranges of these three compounds in ground water from monitoring wells in each of the stratigraphic units.

COMPOUND	UNIT	PRE-DEMONSTRATION CONCENTRATION RANGE (MG/L)	POST- DEMONSTRATION CONCENTRATION RANGE (MG/L)
TCE	Upper Sand	935 to 1,100	647 to 820
	Middle Fine-Grained	960 to 1,070	60 to 174
	Lower Sand	730 to 892	3 to 920
Cis-1,2-DCE	Upper Sand	4 to 6	14 to 95
	Middle Fine-Grained	5 to 26	9 to 80
	Lower Sand	2 to 23	3 to 52
Vinyl chloride	Upper Sand	<5	0.022 to <50
	Middle Fine-Grained	<5	<0.010 to 1.7
	Lower Sand	<5 to <83	0.032 to <50

Other chemical parameters, such as chloride, total dissolved solids, and total organic carbon, generally remained the same or increased. The hydraulic conductivity remained the same order of magnitude before and after the test.

Project-Specific Objective: Evaluating Fate of TCE

The project team reports difficulty in evaluating the fate of TCE addressed by resistive heating. Of the 10,212 kg of TCE estimated to be removed during the test, sampling of recovered vapor accounted for only 1,947 kg. The fate of the remaining 8,265 kg (81%) of TCE mass may have been one or more of the following:

- Mineralization to carbon dioxide and chloride through biotic and/or abiotic processes
- Migration from the test plot in the subsurface
- Migration to the underlying semi-confined aquifer
- Emission to the atmosphere
- Volatilization losses due to sampling hot soil cores during the post-demonstration assessment

The project team was unable to quantify the loss of TCE to each of these mechanisms. Increased concentrations of cis-1,2-DCE suggests the potential for degradation. Increased TCE concentrations in monitoring wells surrounding the test plot (e.g., IW-171) and in soil samples along the test plot boundary suggest the potential for contamination to have migrated from the test plot. The presence of TCE in the semi-confined aquifer suggests the potential for vertical migration; however, these samples were collected after the test, and subsequent reports indicate wide-spread DNAPL contamination below the confining layer that was likely present before the test. Substantial emission to the atmosphere was confirmed by vapor sampling during and after the test. Concentrations as high as 13,000 ppbv were evident in ambient air at multiple times. With respect to losses during sampling, the project team reports that precautions taken during sampling and testing of the sampling procedure suggest relatively low or insignificant losses.

Project-Specific Objective: Determining Operating Requirements and Costs

The discussion of operating requirements has already been addressed, and operating cost requirements are covered in the following section.

2.3.5 ECONOMIC ANALYSIS

The project costs can be separated into three categories: site characterization, technology application, and performance assessment. The following table summarizes the costs for each of these categories and provides a total for the overall project.

CATEGORY AND COST ITEM	COST	% OF TOTAL COST
Site Characterization (for all three test plots) <ul style="list-style-type: none"> • Work Plan • Field work <ul style="list-style-type: none"> ○ 12 continuous cores to 45 ft ○ Installation of 36 monitoring wells ○ Soil/ground water sampling and analysis • Site characterization report 	\$25,000 \$165,000 \$65,000	6%
Test Plot Characterization Subtotal*	\$85,000*	
Resistive Heating Application (directly from vendor) <ul style="list-style-type: none"> • Design and submittals • Mobilization of equipment • Temporary utilities setup • Air, water, and limited soil analyses • Condensate collection and storage • Gas/vapor collection system • Waste containment • Transport/disposal of drill cuttings • Resistive heating operations • Electricity used • Site restoration • Demobilization of equipment • Final report 	\$45,808 \$63,230 \$7,007 \$17,806 \$5,175 \$38,952 \$4,620 \$39,713 \$196,194 \$72,484 \$5,380 \$58,837 \$13,536	42%
Resistive Heating Application Subtotal	\$568,742	
Waste Disposal Paid by Facility (NASA)	\$44,000	3%
Performance Assessment <ul style="list-style-type: none"> • Pre-demonstration assessment • Demonstration assessment • Post-demonstration assessment 	\$208,000 \$240,000 \$215,000	49%
Performance Assessment Subtotal	\$663,000	
Project Total	\$1,360,742	100%

* 33.3% of cost for characterization of three test plots

2.4 TECHNOLOGY DESCRIPTION AND OPERATION: STEAM INJECTION/EXTRACTION

2.4.1 GENERAL TECHNOLOGY DESCRIPTION

Steam injection/extraction involves boiling water above-ground and injecting the resulting steam into the aquifer to heat the aquifer and facilitate removal of volatile and semi-volatile organic compounds. The addition of steam results in increased volatilization of these compounds, steam stripping, and destruction by biotic and/or abiotic processes. The addition of heat also improves the solubility and mobility of DNAPL and contaminants in the subsurface increasing their ability to be extracted in the liquid phase. A

network of vapor extraction wells in the vadose zone are used to extract the contaminants and water vapor and bring them to the surface to be addressed by either treatment or condensation and off-site disposal.

2.4.2 TECHNOLOGY AS APPLIED DURING THE PROJECT

The steam injection/extraction system installed at Launch Complex 34 consisted of two steam injection well clusters (each consisting of a shallow and a deep well), eight deep liquid extraction wells, seven shallow liquid extraction wells, three shallow vapor extraction wells within the footprint of the Engineering Support Building, and three shallow vapor extraction trenches. The steam injection wells were installed near the center of the test plot with screen intervals from 7 to 22 ft bgs (Upper Sand) and 32 to 46 ft bgs (Lower Sand). Stranded thermocouples were installed in 13 locations to monitor temperature to a depth of approximately 45 ft bgs in and around the test plot. A surface cover was placed over the test plot and surrounding area to help reduce vapor emissions and improve vapor recovery. The dimensions of the surface cover and other parameters, including how much air to inject along with the steam, were determined by a helium tracer test in which helium was injected into the subsurface and the percentage of helium recovered was measured.

IWR injected a mixture of air and steam into the aquifer instead of just steam in an effort to reduce the likelihood of condensation of contaminant vapors in the vadose zone. Steam was injected at an average rate of 2,000 pounds per hour at 80% quality (e.g., 80% vapor and 20% liquid) at an injection pressure of 22 psig in the Lower Sands and 11 psig in the Upper Sands. Air was injected at approximately 200 pounds per hour. Above ground, extracted vapors passed through a heat exchanger to condense the majority of the vapors and a water knockout tank to remove the condensed moisture (liquid) from the vapor stream. The liquid from the water knockout tank (a mixture of water and DNAPL) was passed through a DNAPL separation tank to separate DNAPL from the water. The DNAPL was containerized for off-site disposal while the extracted water and the liquid from the DNAPL separation tank were pumped to an air stripper and liquid phase GAC units for treatment. The remaining extracted vapors and the off-gas from the air stripper were treated by a thermal oxidizer. The thermal oxidizer included a caustic scrubber to neutralize the hydrochloric acid generated from the thermal destruction of the TCE. A 20,000-gallon process container was used to containerize the treated water so that it could be sampled prior to discharge. Treated water was discharged by infiltration far from the test plot. The following table provides a timeline of the resistive heating and soil vapor extraction.

TIMEFRAME	ACTIVITY	POUNDS OF STEAM DELIVERED	TEMPERATURE (°C) BEFORE/AFTER HEATING APPLICATION
7/19/01 to 7/26/01	Initial steaming (6 to 24 hrs per day)	210,562	Top of Aquifer: 26.5/31 Middle of Aquifer: 27/57 Bottom of Aquifer: 27/121
7/21/01 to 8/26/01	Irregular steaming and vapor extraction (steam 6 to 9 hrs per day)	79,105	Top of Aquifer: 33/37 Middle of Aquifer: 66/73 Bottom of Aquifer: 116/119
8/27/01 to 11/30/01	Regular steaming and vapor extraction	2,198,804	Top of Aquifer: 37/110 Middle of Aquifer: 73/114 Bottom of Aquifer: 119/115
12/01/01 to 12/09/01	<ul style="list-style-type: none"> • Thermal oxidizer malfunction. • No steaming. • Irregular vapor extraction only. 	N/A	Top of Aquifer: 111/111 Middle of Aquifer: 115/116 Bottom of Aquifer: 116/115
12/10/01 to 12/20/01	Regular steaming and vapor extraction	613,111	Top of Aquifer: 111/109 Middle of Aquifer: 115/114 Bottom of Aquifer: 116/115
Steam System Shutdown			
12/21/01 to 12/28/01	Vapor extraction only	N/A	Top of Aquifer: 110/111 Middle of Aquifer: 114/114 Bottom of Aquifer: 115/116

The site team did not cite hurricanes or weather as a complication during this test. Temporary shut down in site activities were generally related to equipment malfunctions that were addressed in a relatively timely manner. The entire period of operation from the beginning of the steam injection and the end of vapor extraction was 164 days.

Routine monitoring of the operation included temperature monitoring of the formation as well as temperature, flow rates, and TCE concentrations in the extracted vapor and liquid. Perhaps as a lesson learned from the resistive heating test pilot, the monitoring wells within the test plot were not sampled during the entire steam period to avoid potential contact with steam that had accumulated in the monitoring wells.

2.4.3 PERFORMANCE ASSESSMENT – METHODOLOGY

The performance assessment methodology was based on the four objectives, with particular emphasis on DNAPL mass removal. The assessment included a pre-demonstration and a post-demonstration assessment. Estimates of DNAPL mass were based on linear interpolation and kriging of TCE concentrations in soil samples collected during these two assessments. The pre- and post-demonstration assessments each included 12 cores with 23 samples collected at 2-ft intervals in each core. The project team defined DNAPL as present when the TCE concentration in soil was greater than 300 mg/kg.

The other objectives were addressed as follows:

- To evaluate changes in aquifer quality, the project team collected and analyzed the following information during the pre- and post-demonstration assessments.
 - Dissolved concentrations of chlorinated volatile organic compounds inside and outside of the test plot
 - Concentrations of common ions, total dissolved solids, total organic carbon, biological oxygen demand, and other parameters
 - Hydraulic conductivity of the aquifer
 - Microbial populations of the aquifer
- To evaluate the fate of the TCE in the test plot, the project team collected and analyzed the following information:
 - Chloride concentrations in the ground water, which would be present if TCE was mineralized into carbon dioxide and chloride
 - Hydraulic gradients to approximate magnitude/direction of ground water migration
 - Potassium ion, which would have been injected during the ISCO test, but could serve as a conservative tracer once injected
 - Surface emission tests of contaminant vapors
 - Contaminant concentrations in soil outside of the test plot
 - Contaminant concentrations in the semi-confined aquifer underlying the test plot
- To evaluate the operating requirements and costs, the project team reviewed a report provided by the vendor that summarized the requirements and costs. The project team also incorporated costs associated with the pre- and post-demonstration assessments.

2.4.4 PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS

Project-Specific Objective: Quantifying DNAPL Mass Recovery

The following table summarizes the change in total TCE mass and DNAPL mass as a result of the resistive heating based on linear interpolation of the pre- and post-demonstration soil samples. Figures 2-8 through 2-10 illustrate the pre- and post-demonstration TCE soil concentrations.

UNIT	PRE-DEMONSTRATION		POST-DEMONSTRATION		CHANGE IN MASS (%)	
	TOTAL TCE (KG)	DNAPL (KG)	TOTAL TCE (KG)	DNAPL (KG)	TOTAL TCE	DNAPL
Upper Sand	838	555	97	32	-88	-94
Middle Fine-Grained	1,962	1,674	273	173	-86	-90
Lower Sand	7,635	7,072	1,176	779	-85	-89
Total (Entire Plot)	10,435	9,301	1,546	984	-85*	-89*

* An undetermined amount of this mass removal may have been mass that migrated from the test plot to the surrounding aquifer.

The results show that approximately 73% of the total TCE mass and 76% of the DNAPL mass was present in the Lower Sand prior to the test. The results also show that based on the assessment methodologies employed by the project team, the technology almost met the stated remedial goal of removing more than 90% of the DNAPL mass. According to the post-demonstration results, the mass removed was approximately 85% to 89%, and the percent distribution of mass among the three hydrostratigraphic units remained relatively similar before and after the test. For example, the TCE mass in the Lower Sand was 76% after the test compared with a very similar 73% before the test. Based on a review of the soil concentration contours before and after the test, it appears that the majority of mass that was not removed was present along the perimeter of the test plot. In the Middle Fine-Grained unit, it appears that contamination may have been displaced from the center of the test plot toward the Engineering Support Building, which is evident by the concentration increase at SB-33/233 for that unit.

Based on the analyses of the project team using linear interpolation, the technology almost met the remediation goal of 90% DNAPL removal from the test plot. Results from kriging (rather than linear interpolation) are consistent for total TCE removed, but an analysis was not done for DNAPL removed because the project team felt that too few relevant data points were available. It is questionable, however, how much of the mass removal may have been mass migration from the test plot, as a result of the steam application.

Project-Specific Objective: Evaluating Changes in the Aquifer

TCE concentrations in the steam injection/extraction plot were measured in February 2002, approximately two months after heating stopped. Contour plots based on the data are presented in Figures 2-11 through 2-13 alongside the pre-demonstration TCE ground water concentrations.

The distribution of TCE concentrations in ground water after the test showed a general decrease and a redistribution of TCE mass in ground water; however, the results are difficult to interpret because the number of monitoring points within the test plot is limited and samples were not necessarily collected from the same monitoring wells during the pre- and post-demonstration assessments. For example, in the Upper Sand unit, the TCE concentration in PA-17S decreased from 650 mg/L to 145 mg/L and the concentration in PA-16S increased from <0.002 mg/L to 6.13 mg/L. However, PA-2S, which had a concentration of 0.33 mg/L during the pre-demonstration assessment and had substantial influence on contouring, was not sampled during the post-demonstration. Ground water concentrations of cis-1,2-DCE decreased in the PA-17 cluster, but increased in the PA-16 cluster. It is unclear if the increases resulted from degradation of TCE or from a redistribution of cis-1,2-DCE concentrations throughout the test plot.

Vinyl chloride concentrations in ground water were low relative to the other compounds in the test plot after the demonstration. Concentrations of vinyl chloride prior to the demonstration were generally undetectable, but the detection limits were high (over 20 mg/L) due to the high concentrations of TCE. The following table provides the concentration ranges of these three compounds in ground water from monitoring wells in each of the stratigraphic units.

COMPOUND	UNIT	PRE-DEMONSTRATION CONCENTRATION RANGE (MG/L)	POST-DEMONSTRATION CONCENTRATION RANGE (MG/L)
TCE	Upper Sand	<0.002 to 650	6.1 to 145
	Middle Fine-Grained	0.081 to 210	1.8 to 14
	Lower Sand	280 to 860	2.7 to 210
cis-1,2-DCE	Upper Sand	<0.002 to 21	1 to 19
	Middle Fine-Grained	0.010 to 260	2 to 8
	Lower Sand	35 to 38	0.2 to 52
Vinyl chloride	Upper Sand	<0.004 to <83	0.098 to <0.2
	Middle Fine-Grained	<0.008 to <20	0.128 to 0.17
	Lower Sand	<33 to <83	0.013 to 0.15

Other chemical parameters, such as chloride, total dissolved solids, and total organic carbon, generally remained the same. This may have been due to the influx of water from the surrounding aquifer by the extraction system. The hydraulic conductivity as determined from slug tests remained the same order of magnitude before and after the test except at PA-17S, where the hydraulic conductivity decreased by almost an order of magnitude from 13.7 ft per day to 1.8 ft per day.

Project-Specific Objective: Evaluating Fate of TCE

The project team reports difficulty in evaluating the fate of TCE addressed by this application. The project team estimates that approximately 7,400 ± 2,200 kg of the initial TCE was recovered in the vapor recovery system. That is, using the middle of this range, approximately 83% of the mass reduction in the aquifer was recovered by the vapor recovery system. The fate of the remaining TCE mass may have been one or more of the following:

- Mineralization to carbon dioxide and chloride through biotic and/or abiotic processes
- Migration from the test plot in the subsurface
- Migration to the underlying semi-confined aquifer
- Emission to the atmosphere
- Volatilization losses due to sampling hot soil cores during the post-demonstration assessment

The project team was unable to quantify the loss of TCE to each of these mechanisms. Data for biotic or abiotic mineralization is generally inconclusive, because changes in the cis-1,2-DCE concentrations may have partially resulted from redistribution of the contaminant and chloride concentrations were not elevated as a result of an influx of ground water from outside of the test plot. Increased TCE concentrations in one monitoring well (PA-14D) outside of the test plot suggest the potential for contamination to have migrated from the test plot, but it is unclear if this increase resulted from a redistribution of TCE contamination outside of the test plot rather than migration of TCE contamination from within the test plot. TCE concentrations in the semi-confined aquifer decreased in one well (from approximately 7.84 mg/L to 416 mg/L), but increased in another well from (736 mg/L to 1,240 mg/L) in another well. It is unclear if the increase in one well is due to mass migrating from the test plot during the steam injection/extraction test or a redistribution of TCE mass that was already present in that underlying aquifer. Surface emission to the atmosphere was confirmed by vapor sampling during and after the test, but concentrations from sampling during and after the steam injection/extraction test (as high as 280 ppbv) were relatively low compared to the concentrations measured during and after the resistive heating application (as high as 13,000 ppbv). With respect to losses during sampling, the project team reports that

precautions taken during sampling and testing of the sampling procedure suggest relatively low or insignificant losses.

Project-Specific Objective: Determining Operating Requirements and Costs

The discussion of operating requirements has already been addressed, and operating cost requirements are covered in the following section.

2.4.5 ECONOMIC ANALYSIS

The project costs can be separated into three categories: site characterization, technology application, and performance assessment. The following table summarizes the costs for each of these categories and provides a total for the overall project.

CATEGORY AND COST ITEM	COST	% OF TOTAL COST
Site Characterization (for all three test plots) <ul style="list-style-type: none"> • Work Plan \$25,000 • Field work \$165,000 <ul style="list-style-type: none"> ○ 12 continuous cores to 45 ft ○ Installation of 36 monitoring wells ○ Soil/ground water sampling and analysis • Site characterization report \$65,000 Test Plot Characterization Subtotal*	\$85,000*	5%
Resistive Heating Application (directly from vendor) <ul style="list-style-type: none"> • Design and plans \$120,000 • Surface plant set-up \$168,000 • Well installation \$130,000 • Air, water, and limited soil analyses \$72,070 • Operations \$420,411 • Electricity used \$13,902 • Water \$941 • Fuel (propane and diesel) \$82,210 • Project management and reporting \$131,129 Steam Injection/Extraction Application Subtotal	\$1,146,075	64%
Waste Disposal Paid by Facility (NASA)	\$55,100	3%
Performance Assessment <ul style="list-style-type: none"> • Pre-demonstration assessment \$208,000 • Demonstration assessment \$100,000 • Post-demonstration assessment \$215,000 Performance Assessment Subtotal	\$523,000	28%
Project Total	\$1,809,175	100%

* 33.3% of cost for characterization of three test plots

2.5 EVALUATION OF TECHNOLOGIES

2.5.1 PROJECT SUCCESS RELATIVE TO PROJECT GOALS

The resistive heating application generally met the project goals. The test was successfully implemented, and the project team determined that over 90% of the mass was removed from the test plot. Some of this mass, however, may have simply migrated from the test plot in the subsurface. The project team also evaluated changes in many aquifer parameters as a result of the heating and documented the operating requirements and costs of implementing the technology. The project team determined various potential fates for the TCE that was removed from the source area; however, it had difficulty in quantifying the distribution of TCE among these various fates. For example, the project team determined that

approximately 19% of the removed TCE was captured by the vapor recovery system. The remaining TCE was either destroyed or migrated from the test plot, but, despite a comprehensive sampling assessment, the project team could not identify how much TCE met either of these fates.

The steam injection/extraction application almost met the primary project goal of 90% DNAPL mass removal (85% removal estimated). In addition, the project team evaluated changes in many aquifer parameters as a result of the heating and documented the operating requirements and costs of implementing the technology. The project team was also able to determine various fates for the TCE that was removed from the source area, but like the resistive heating application, had difficulty in quantifying the distribution of TCE among these various fates. The team, however, was able to recover much more of the TCE mass through the vapor recovery system than the resistive heating team achieved for their application. Overall, it appears that less TCE migrated from the test plot during the steam injection/extraction application than during the resistive heating test plot. The steam injection/extraction system may have even remediated contamination outside of the test plot area due to the substantial ground water extraction that took place along the perimeter of the test plot throughout the application.

2.5.2 PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK

In a financial and regulatory framework, a successful heating application would likely either reduce the time frame to site cleanup to some finite time (e.g., within 30 years) or substantially reduce life-cycle costs. Despite the substantial mass removal by both technology demonstrations, the project teams estimate that substantial TCE mass and DNAPL remained in the test plots after the applications. For the resistive heating test, the project team estimates that approximately 328 kg of TCE (the equivalent of approximately 61 gallons) remained in the form of DNAPL, and the maximum TCE dissolved concentrations were as high as 900 mg/L following the test. For the steam injection test, the project team estimates that approximately 984 kg of TCE (the equivalent of approximately 178 gallons) remained in the form of DNAPL and maximum TCE dissolved concentrations were as high as 650 mg/L following the test. Given these post-application conditions for both technologies, source material is still present in the subsurface, and active remediation would likely still be needed for both cases to either remove additional mass or control migration. Thus, despite the upfront investments of approximately \$568,000 for resistive heating or \$1.2 million for steam injection/extraction (both excluding potential additional characterization and assessment relative to other technologies), the contamination would likely still require active remediation over a period of several years to decades.

With respect to cost, the project teams estimated unit costs per pound of TCE removed and per cubic yard treated. The resistive heating team estimated a cost of \$29 per pound of TCE removed and \$104 per cubic yard treated (excluding characterization and demonstration), and the steam injection/extraction team estimated a cost of \$61 per pound of TCE removed and \$192 per cubic yard treated (excluding characterization and demonstration). These unit costs, however, are unreliable estimates as to how much it might cost to remove TCE or treat a volume of the subsurface because they would likely be much higher if the technology applications were continued until restoration was achieved or until suitable conditions for monitored natural attenuation were achieved.

With respect to contaminant fate and transport, it is unclear how much TCE migrated from either test plot in the subsurface as a result of the tests. However, it appears that the ground water extraction and vapor recovery system with the steam injection/extraction test was more effective at mitigating contaminant migration than was the system for the resistive heating application. It is even likely that the steam injection/extraction system remediated some contaminant mass from outside of the test plot. This difference in mass recovery with the vapor recovery system seems to have more to do with recovery system design than with the heating processes. Therefore, another application of the resistive heating may be able to provide equal recovery to that observed with this steam injection/extraction system. However, this difference in recovery between these two particular tests makes it difficult to compare the costs. For

the resistive heating application to provide similar containment in the subsurface to the steam injection/extraction, ground water extraction at the perimeter may have been necessary, and this would add substantially to cost.

The release of TCE vapors to the atmosphere may also be problematic to regulators concerned with transferring contaminants from one medium to another. For the resistive heating test, the project team measured concentrations as high as 13,000 ppb above the test plot, and for the steam injection/extraction test, the project team measured concentrations as high as 280 ppb. These results indicate that steam injection/extraction test's vapor recovery system was much more effective than that of the resistive heating test. From a health and safety perspective these concentrations are well below the OSHA Permissible Exposure Limit (PEL) of 100 ppm averaged over an eight-hour period (29 CFR 1910.1000 Table Z-2), but may still be a concern of local regulators regarding air quality if overall emissions (e.g., pounds of TCE emitted per hour) are high. Once again, the performance of the steam injection/extraction recovery system relative to the resistive heating recovery system likely accounts for some of the overall cost difference between the two tests.

2.5.3 CONSIDERATIONS FOR THOSE CONTEMPLATING A TECHNOLOGY APPLICATION AT ANOTHER SITE

Demonstrations of resistive heating and steam injection/extraction provide the following lessons learned for site teams considering implementing these technologies at their site.

- Both technologies have demonstrated success in removing substantial mass from an unconsolidated aquifer with fine grained sands and brackish water quality. Mass removal at depth and beneath an active building occurred. Site teams that are aiming for substantial mass removal and have a specific, non-negotiable objective to restore a DNAPL impacted aquifer may benefit by considering these technologies. Based on the mass remaining in the aquifer after the tests, mass removal at depth appeared to be more comprehensive for the resistive heating test than it did for the steam injection/extraction test.
- Despite success in removing DNAPL and contaminant mass for both tests, additional active remediation will likely be required either by extending the duration that these technologies are applied and/or by using other technologies to remove remaining contaminant mass. For this reason, unit cost estimates provided by the project teams would likely underestimate actual costs for remediation.
- Weather patterns, particularly heavy rain, could adversely affect these technologies as was experienced during the resistive heating application. Infiltration of rain water may cool the upper reaches of the aquifer, allowing contaminant vapors to condense below the ground surface, and rising water levels may make vapor recovery systems inoperable. Site teams might consider applying these technologies during a dry season or in areas that have limited rainfall. Regardless of cooling provided by infiltration, sufficient heating in shallow zones is necessary to prevent TCE from condensing below the ground surface. Ground water extraction in the test plot may also help control rising water levels.
- Heating results in substantial vapor (water and contaminant) production, and a conservatively designed vapor recovery system is needed to minimize the likelihood of vapors escaping from the test plot at unacceptable rates. Uncontrolled emission rates from the steam injection/extraction test were relatively limited (compared to the resistive heating test), perhaps as a result of the conservative vapor extraction system or the extensive surface cover applied by the steam project team. Air monitoring of both the vapor recovery system and ambient air can help a project team record the amount of vapor recovered and the potential emissions that escape recovery. The project team may want to set ambient air concentration limits that would trigger shutting down the heating. It should be noted that the aquifer will retain heat and will continue to emit vapors at high levels, even after the heating is shut down. Operation of the vapor recovery system for

several weeks after steaming is discontinued may be appropriate. The highest ambient TCE concentrations during this test were noted during the post-demonstration assessment, approximately two months after heating was discontinued. Because vapor production can continue even after heating has been discontinued, the vapor recovery and treatment system is a likely part of the system that merits redundancy in terms of readily available spare parts or excess capacity.

- The heating of the aquifer could lead to spreading of contamination outside of the target area. Ground water monitoring in both horizontal and vertical directions would help identify if migration is occurring. In addition, measuring ground water elevations in adjacent piezometers can help determine the direction of ground water flow (e.g., away from the test plot or toward the test plot). If migration is a concern, the site team might include measures for providing containment, including pumping and treating surrounding ground water or installation of impermeable barriers.
- Heating of the aquifer with high voltage electricity leads to additional hazards than are normally encountered during more traditional remedial technologies. In particular, this project team noted two potential hazards to consider:
 - Insulating the ground surface from high voltage electricity
 - Implementing engineering and administrative controls to avoid contact with high pressure steam in monitoring wells while the aquifer temperature is elevated (even after heating has been discontinued)

The latter hazard would also be an issue associated with a steam injection/extraction application.

- A site team would benefit by establishing clear goals to be achieved by these technologies and considering how these goals apply to overall site remediation. If 90% mass removal will not reduce the remediation duration to a reasonable time frame or will not result in eliminating the need for further active remediation, the site team might question the value of implementing the technology at its site.
- Although the technologies removed substantial mass over a relatively short time period in the hydrogeologic setting of Launch Complex 34, it is unclear how the technology would perform under other conditions, such as fractured bedrock, ground water with high iron or manganese concentrations, ground water with the potential for scaling, or ground water with other non-volatile compounds/contaminants that may increase in concentration as water is vaporized for the zone of application. For this reason, site teams would benefit by reviewing applications at similar sites (to assess likelihood of success) prior to conducting a pilot study (which is expensive as shown by these studies).

2.6 DOCUMENTS REVIEWED

Battelle, 2003a, *Demonstration of Resistive Heating Treatment of a DNAPL Source Zone at Launch Complex 34 in Cape Canaveral Air Force Station, Florida*, Final Innovative Technology Report, February 19.

Battelle, 2003b, *Demonstration of Steam Injection/Extraction Treatment of a DNAPL Source Zone at Launch Complex 34 in Cape Canaveral Air Force Station, Florida*, Final Innovative Technology Report, September 30.

Casparly, J.R., 2006 *Phased Goals and Performance Metrics for Restoration of a Complex DNAPL Site*, Battelle Conference, May.

Feenstra, S.D., et al., 1991, A Method for Assessing Residual NAPL Based on Organic Chemical Concentrations in Soil Samples, *Groundwater Monitoring Review*, Vol 11, No. 2.

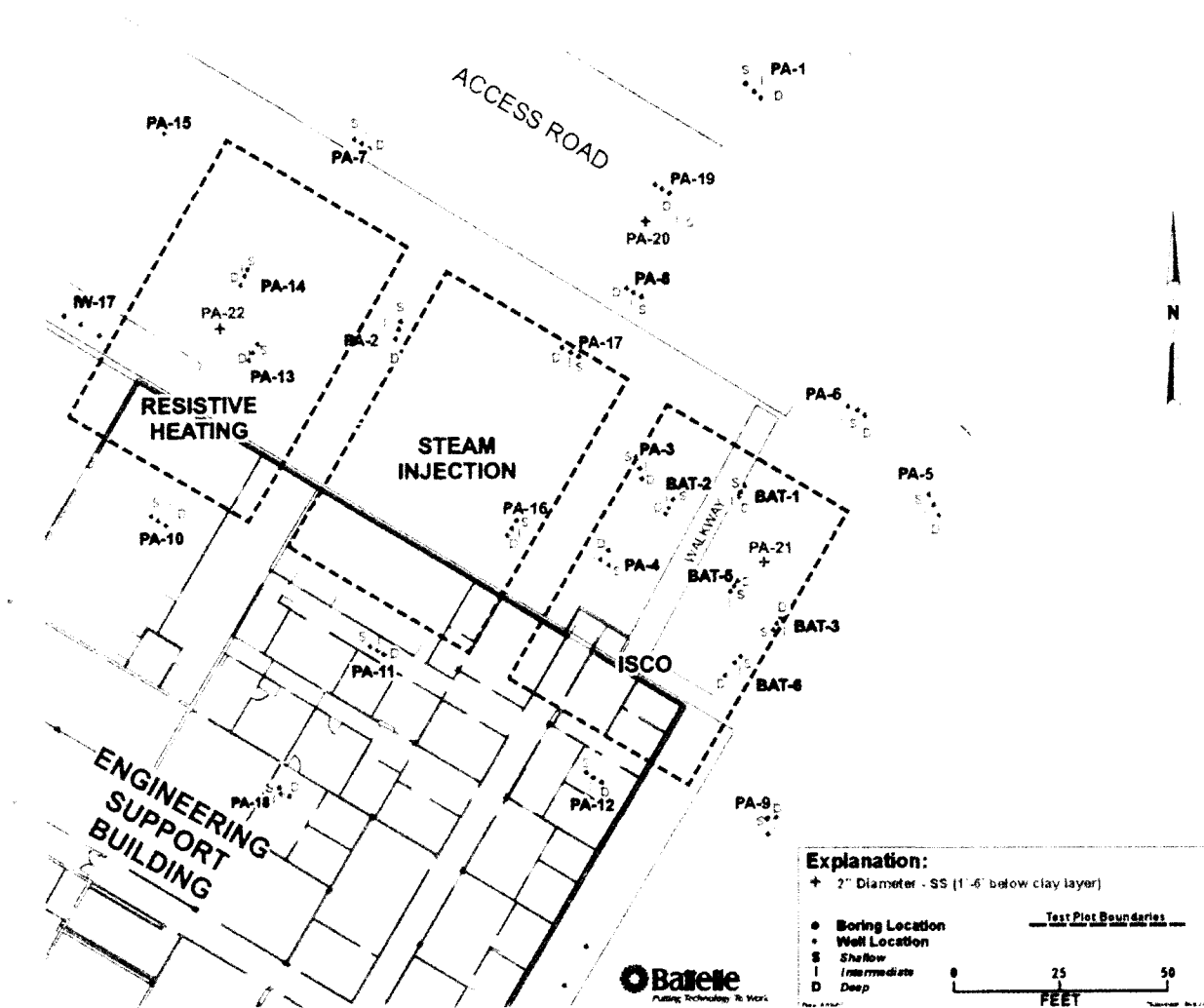


FIGURE 2-1. TEST PLOT LAYOUT AT LAUNCH COMPLEX 34, CAPE CANAVERAL, FLORIDA (BATTELLE, 2003A)

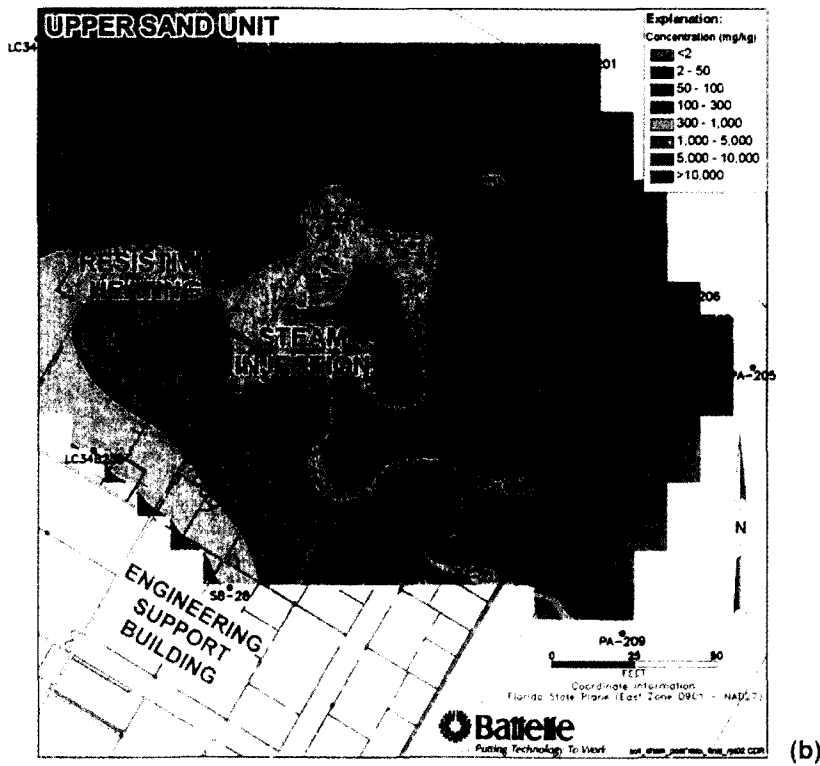
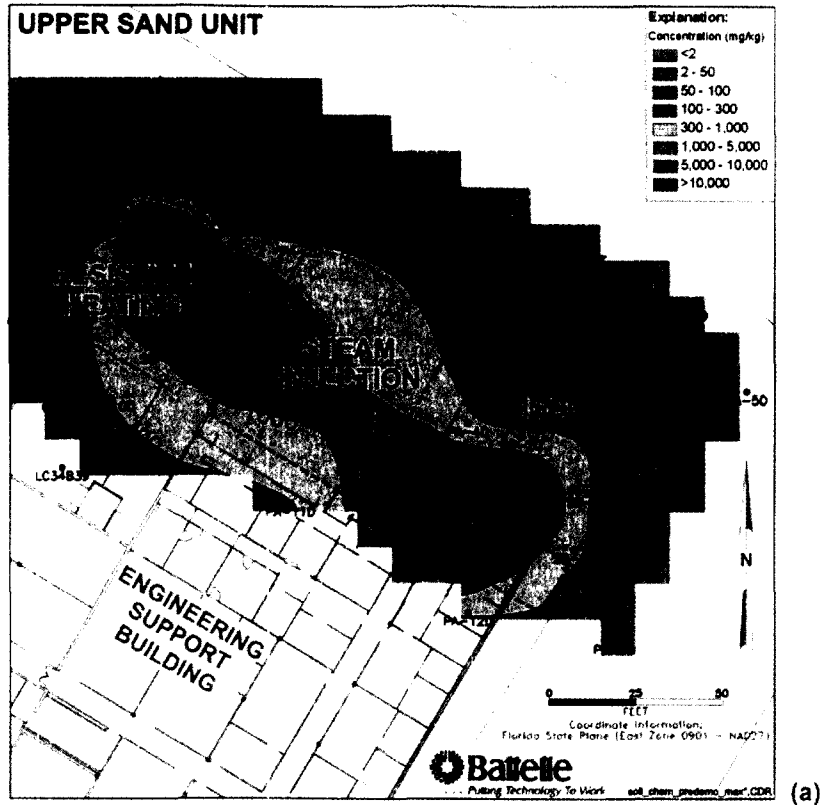
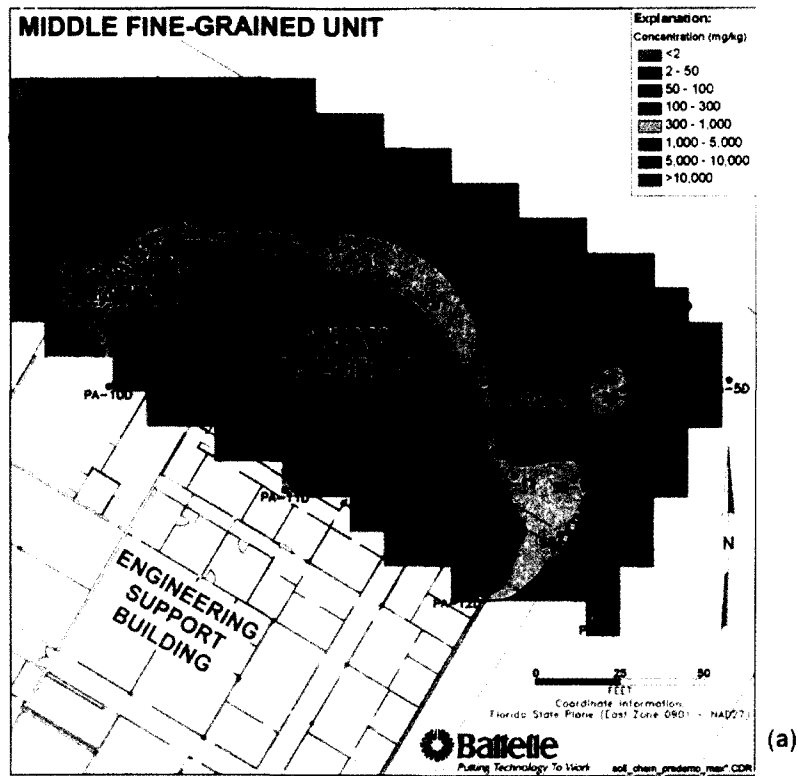
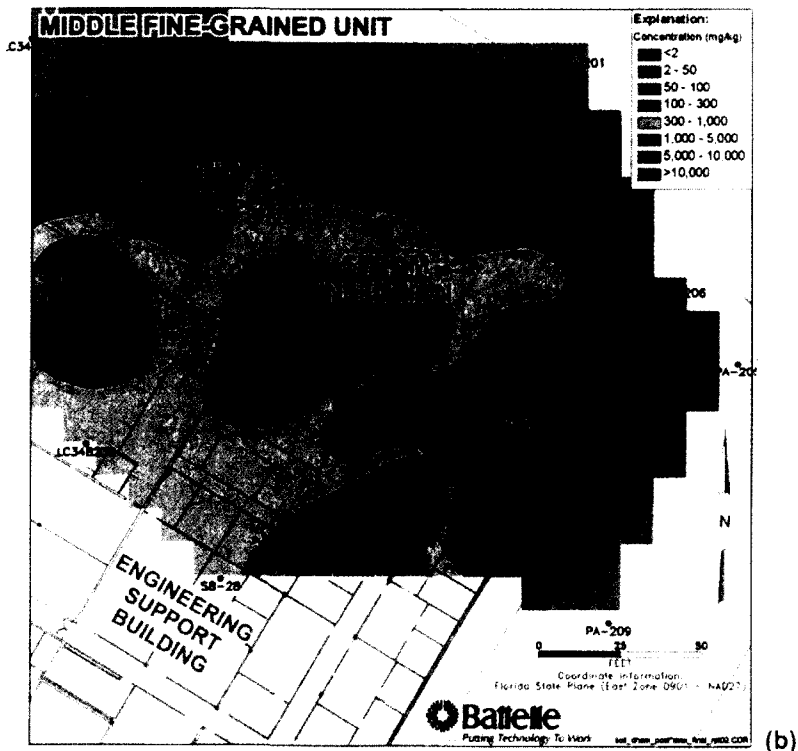


FIGURE 2-2. UPPER SAND SOIL SAMPLING RESULTS (A) BEFORE AND (B) AFTER RESISTIVE HEATING (BATTELLE, 2003A)

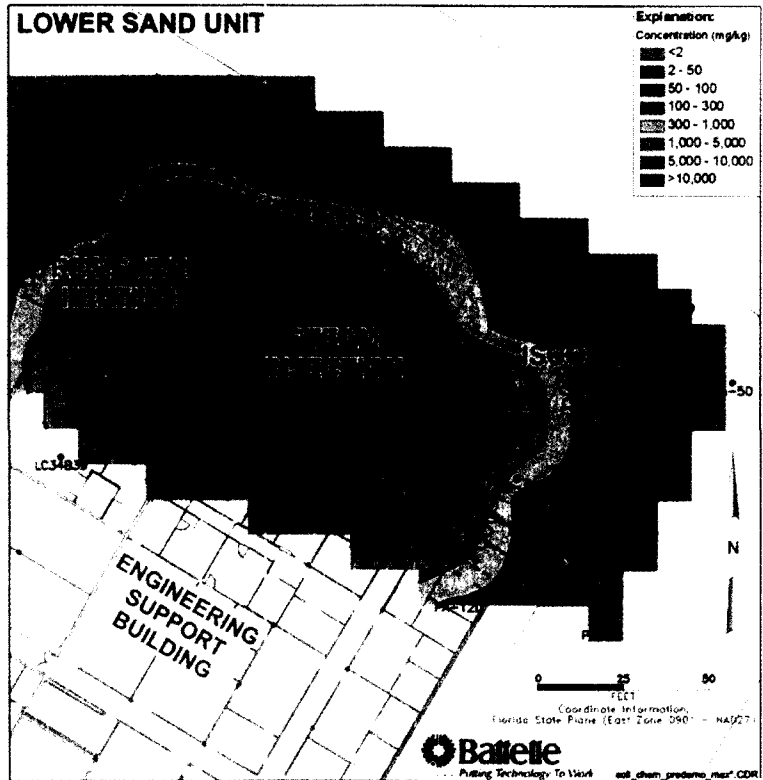


(a)

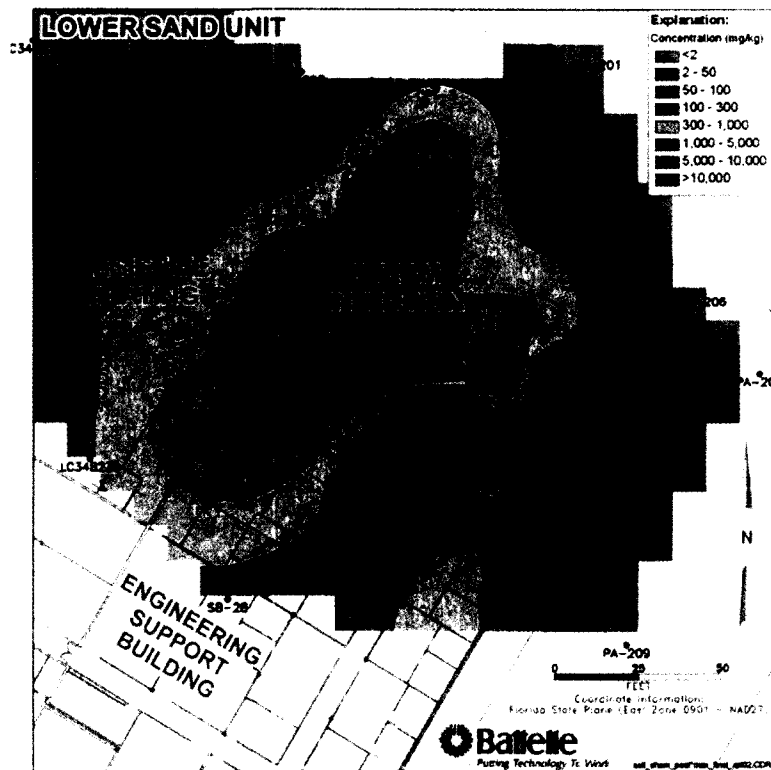


(b)

FIGURE 2-3. MIDDLE FINE-GRAINED SOIL SAMPLING RESULTS (A) BEFORE AND (B) AFTER RESISTIVE HEATING (BATTELLE, 2003A)



(a)



(b)

FIGURE 2-4. LOWER SAND SOIL SAMPLING RESULTS (A) BEFORE AND (B) AFTER RESISTIVE HEATING (BATTELLE, 2003A)

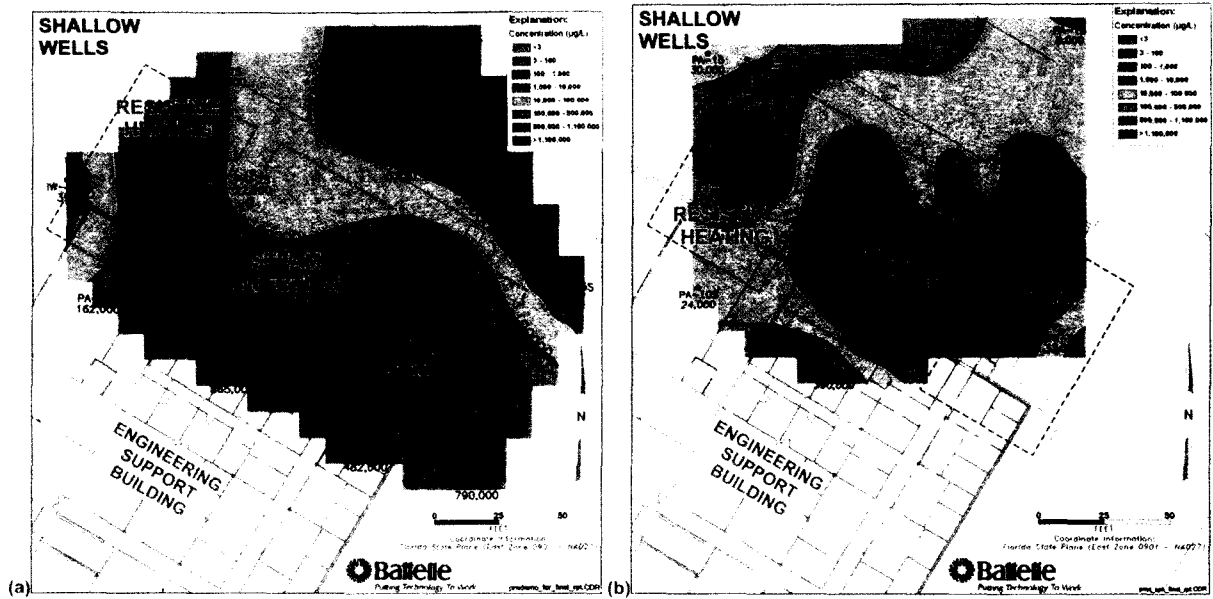


FIGURE 2-5. UPPER SAND GROUND WATER CONCENTRATIONS (A) BEFORE AND (B) AFTER RESISTIVE HEATING (BATTELLE, 2003A)

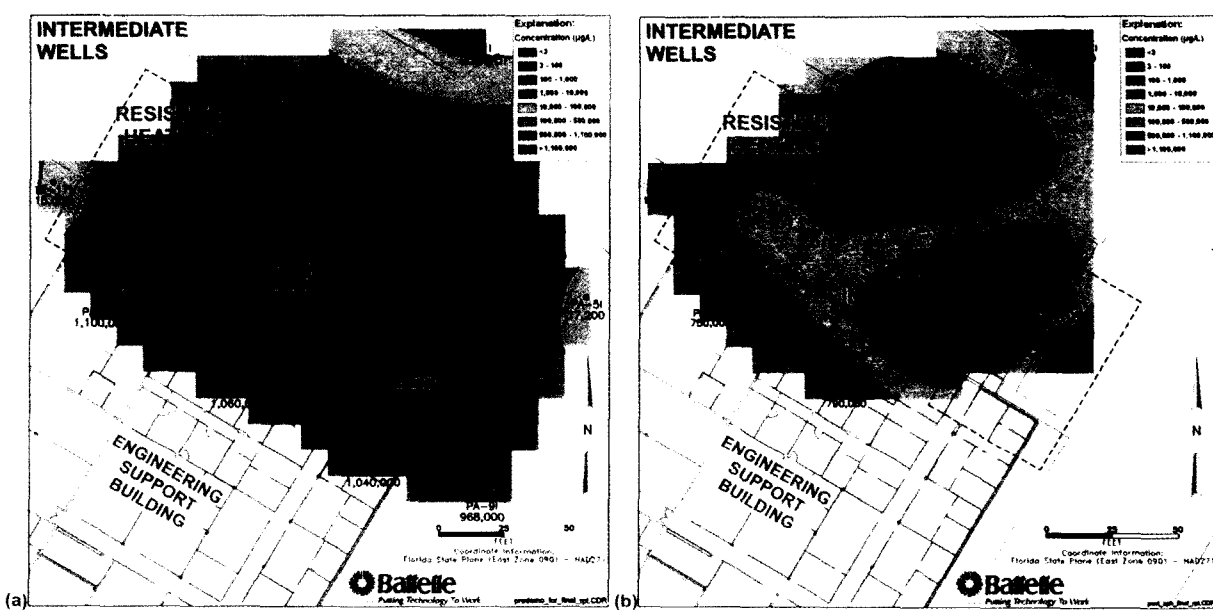


FIGURE 2-6. MIDDLE FINE-GRAINED GROUND WATER SAMPLING RESULTS (A) BEFORE AND (B) AFTER RESISTIVE HEATING (BATTELLE, 2003A)

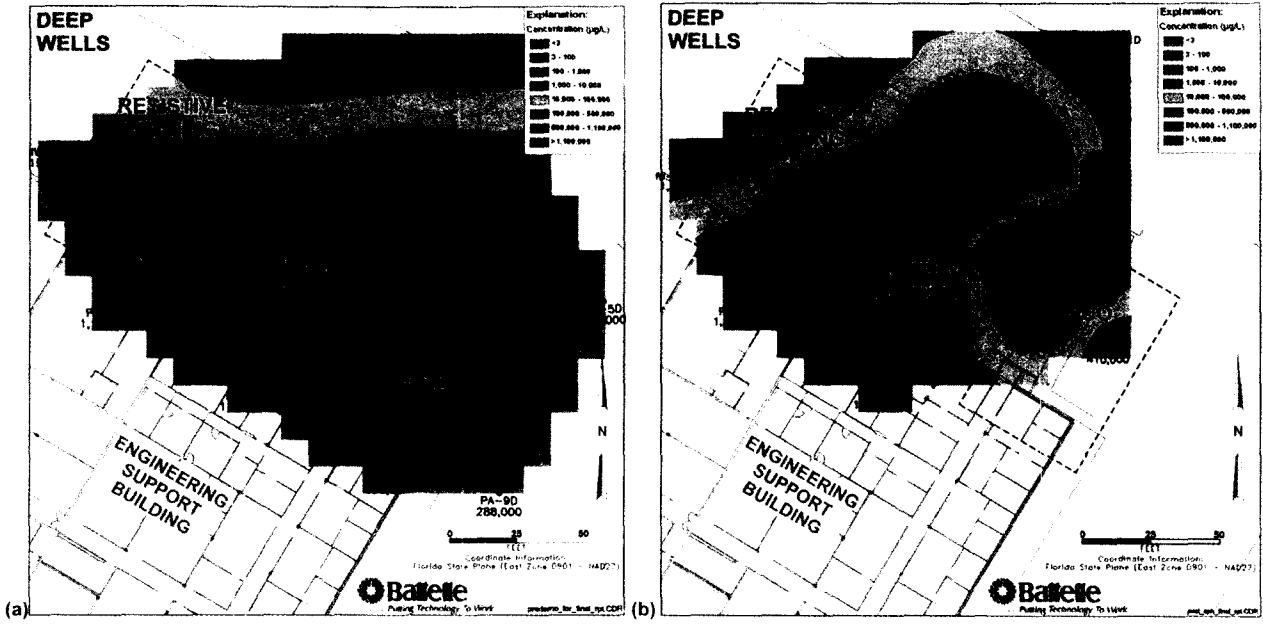
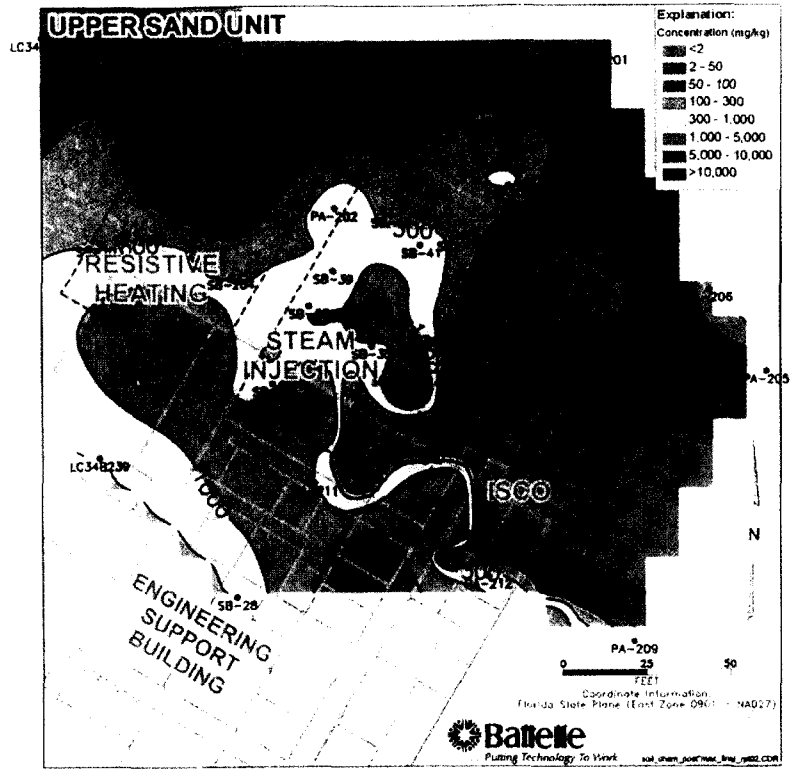
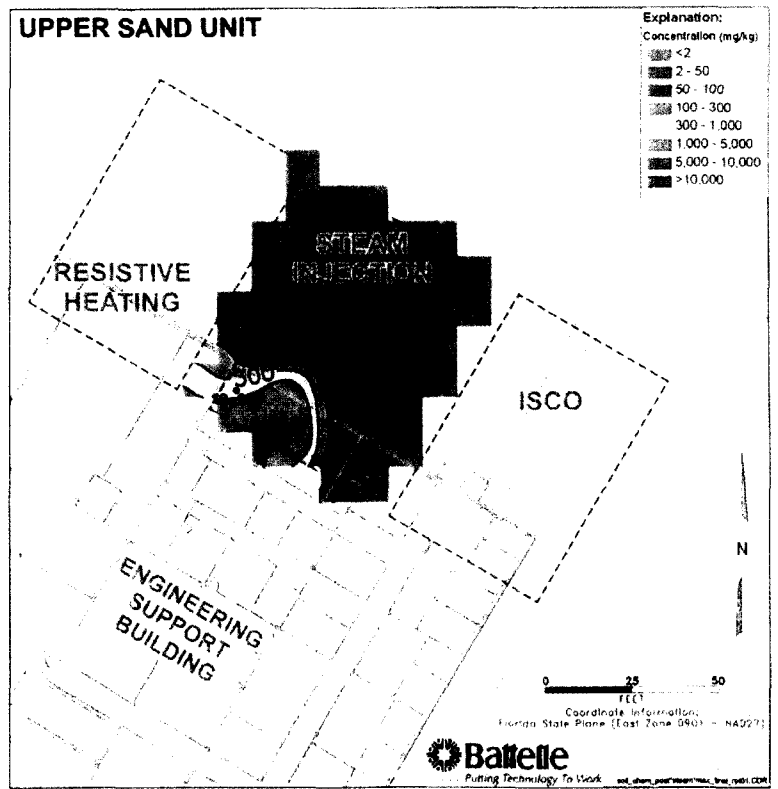


FIGURE 2-7. LOWER SAND GROUND WATER SAMPLING RESULTS (A) BEFORE AND (B) AFTER RESISTIVE HEATING (BATTELLE, 2003A)



(a)



(b)

FIGURE 2-8. UPPER SAND SOIL SAMPLING RESULTS (A) BEFORE AND (B) AFTER STEAM INJECTION/EXTRACTION (BATTELLE, 2003A)

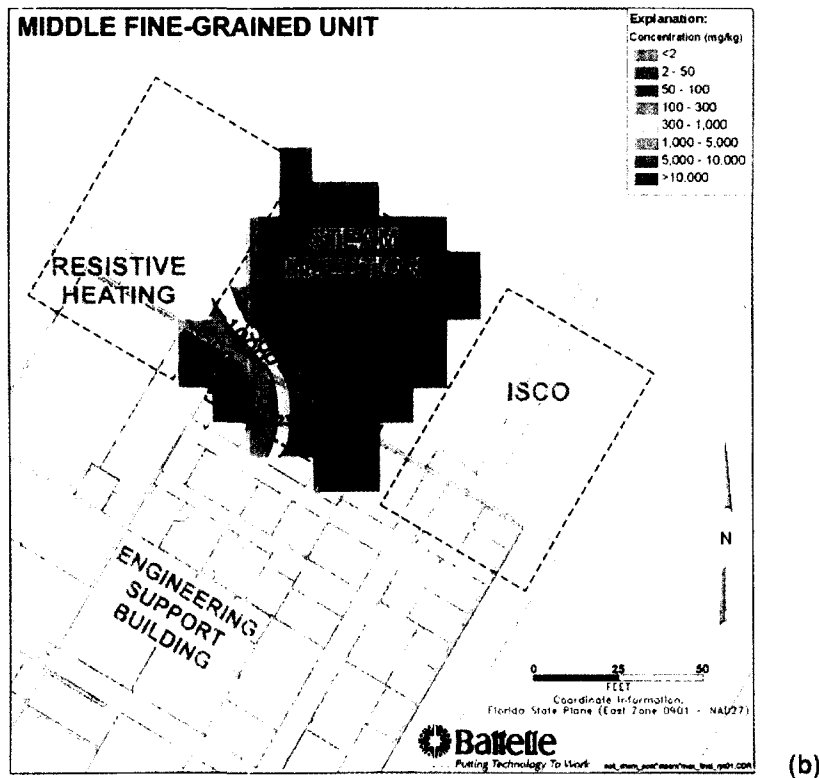
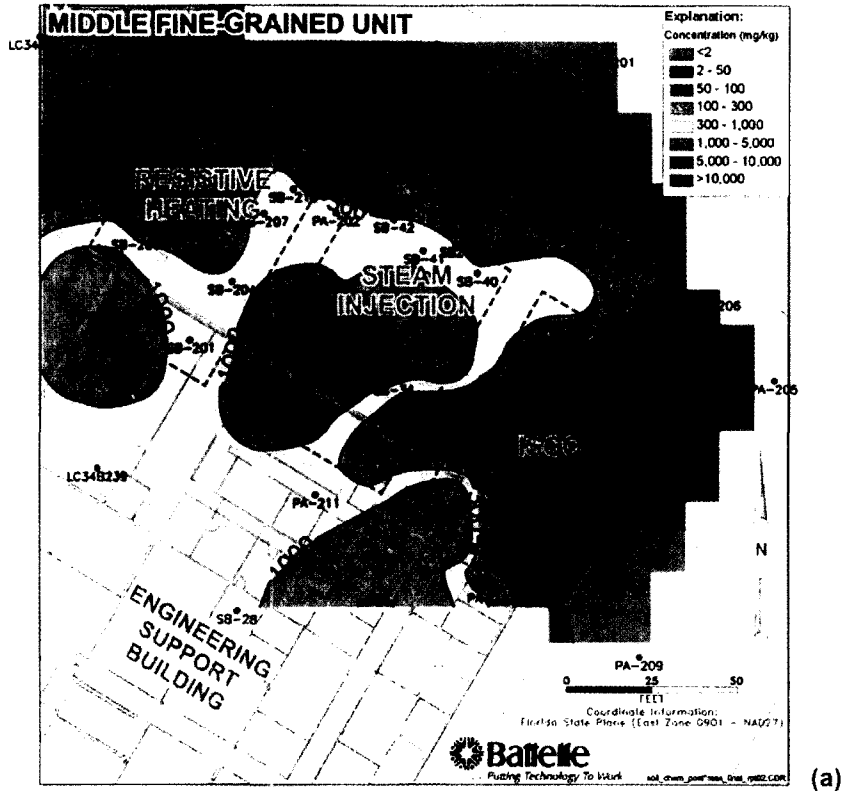
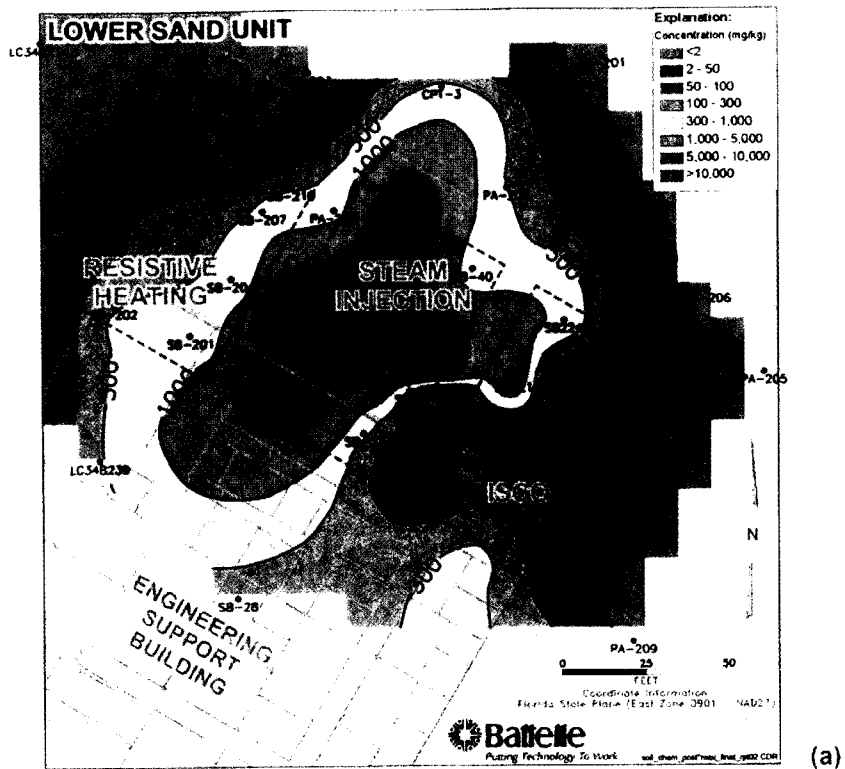
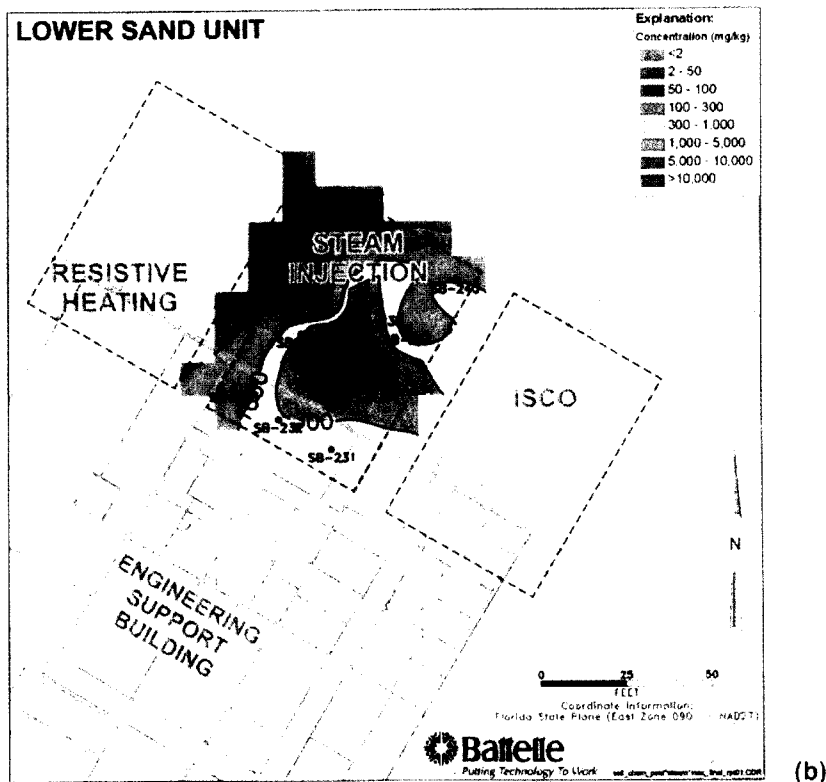


FIGURE 2-9. MIDDLE FINE-GRAINED SOIL SAMPLING RESULTS (A) BEFORE AND (B) AFTER STEAM INJECTION/EXTRACTION (BATTELLE, 2003A)



(a)



(b)

FIGURE 2-10. LOWER SAND SOIL SAMPLING RESULTS (A) BEFORE AND (B) AFTER STEAM INJECTION/EXTRACTION (BATTELLE, 2003A)

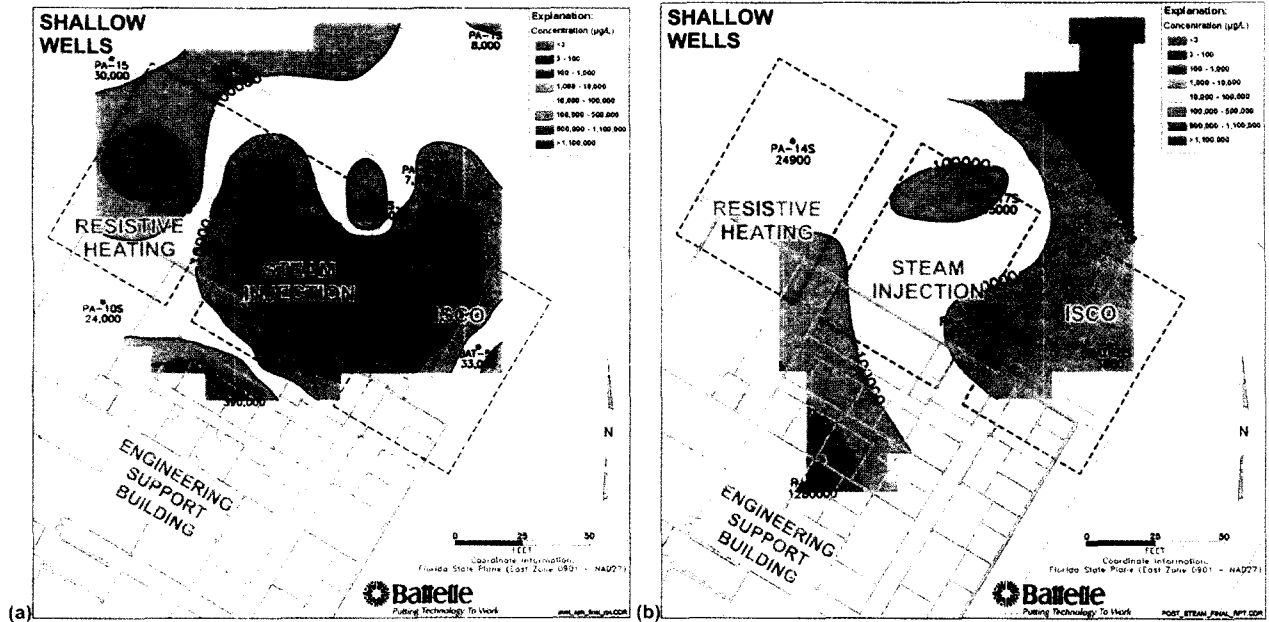


FIGURE 2-11. UPPER SAND GROUND WATER SAMPLING RESULTS (A) BEFORE AND (B) AFTER STEAM INJECTION/EXTRACTION (BATTELLE, 2003A)

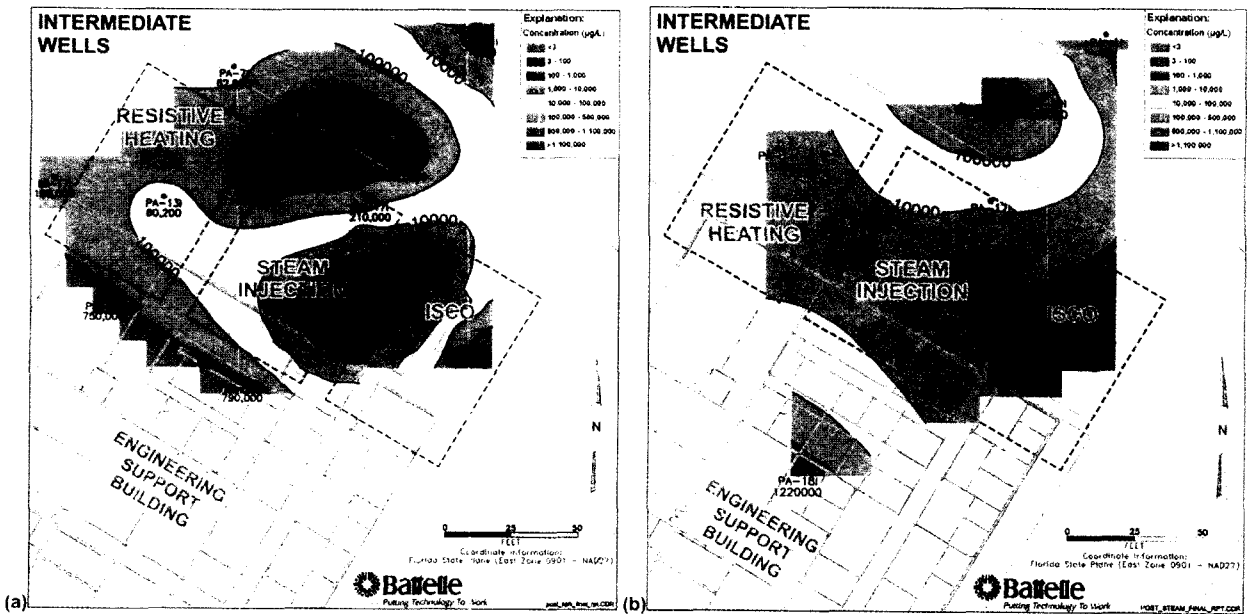


FIGURE 2-12. MIDDLE FINE-GRAINED GROUND WATER SAMPLING RESULTS (A) BEFORE AND (B) AFTER STEAM INJECTION/EXTRACTION (BATTELLE, 2003A)

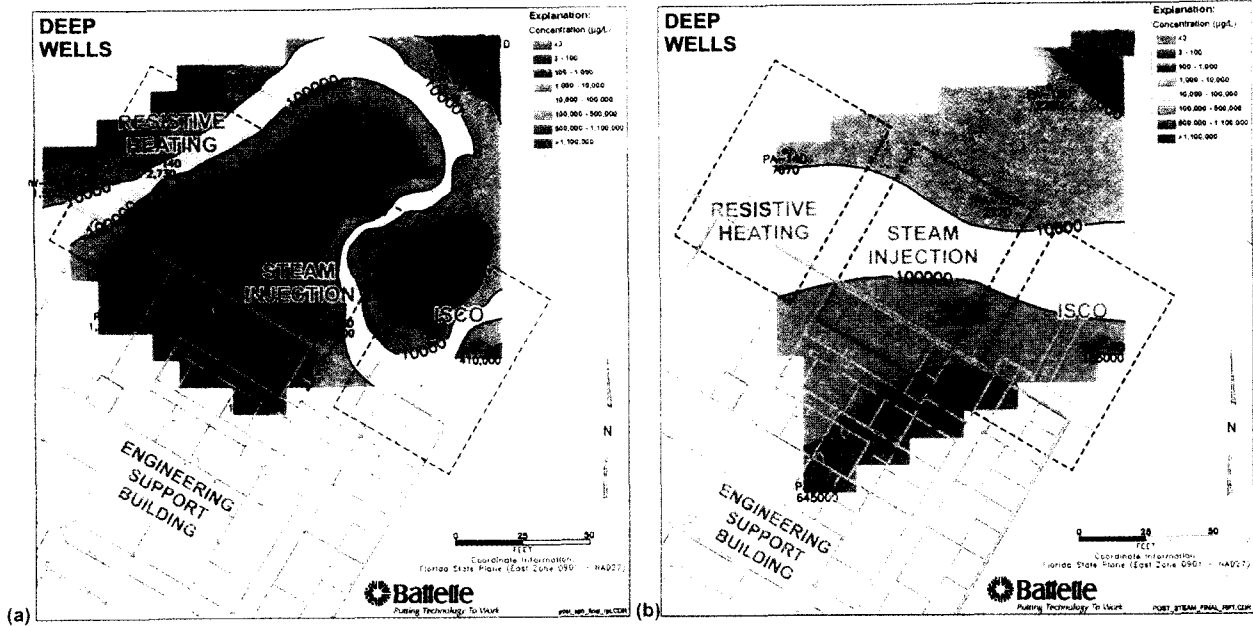


FIGURE 2-13. LOWER SAND GROUND WATER SAMPLING RESULTS (A) BEFORE AND (B) AFTER STEAM INJECTION/EXTRACTION (BATTELLE, 2003A)

3.0 DOVER NATIONAL TEST SITE, DOVER AIR FORCE BASE, DELAWARE

3.1 PROJECT BACKGROUND

The project, which was conducted between May 1998 and October 2000, tested the technical and economical performance of the following five technologies for remediating tetrachloroethene (PCE) DNAPL: cosolvent solubilization, air sparging/soil vapor extraction (AS/SVE), surfactant enhanced remediation (SEAR), cosolvent mobilization, and complex sugar flushing. The technologies were tested independently in two isolated test plots that were intentionally impacted with known volumes of PCE. The project, titled the Enhanced Source Removal Technology Demonstration Project, was a collaborative effort between the EPA National Risk Management Research Laboratory (NRMRL) and the Air Force Research Laboratory with funding from the Strategic Environmental Research and Development Program (SERDP). Several other parties from academia, government, and industry were involved in demonstrating the technologies. As part of the same program, additional technology demonstrations were conducted at Operable Unit 1 of Hill Air Force Base, which is impacted by LNAPL. Because these other demonstrations address LNAPL instead of DNAPL, they are not discussed here.

The project had the technical objective of determining DNAPL mass removal achieved by each technology and to determine the effectiveness of partitioning tracer tests in characterizing the amount of DNAPL present. The tests were conducted at the Dover National Test Site (DNNTS) at the Dover Air Force Base, Delaware. This test site is located on an uncontaminated portion of the Base, and is designed to be a controlled release test facility. Two test plots, physically isolated from each other and from the surrounding aquifer with interlocking, sealed sheet pile were used for the tests. Each test plot measured 4.6 m by 3 m (approximately 15.1 ft by 10 ft), and was outfitted with 12 wells for injection or extraction, 18 PCE release points, and 18 multilevel sensors for measuring tracer concentrations. The layout of a test cell is depicted in Figure 3-1.

Information in this section is based on the draft 2004 report titled *Field Evaluation of Enhanced DNAPL Source Removal by Wood and Enfield* (Wood and Enfield, 2004).

3.2 SITE CHARACTERIZATION

The DNNTS geology consists of a surficial aquifer with silty, poorly sorted sands underlain by silty clay that acts as an aquitard. The average hydraulic conductivity of the surficial aquifer ranges from 2.4 m per day to 10.4 m per day (approximately 8 ft per day to 34 ft per day) based on pump tests. Boring logs reportedly indicate alternating layers of silty sand, poorly sorted sand, and well sorted sand. The test cells extend to a depth of approximately 12 m (approximately 40 ft) below ground surface (bgs). The injection/extraction wells are screened between 6.1 m and 12.5 m (20 and 40 ft) bgs and are completed 4 ft into the clay confining layer to act as sumps for DNAPL collection.

The contaminant magnitude and extent varied for each technology tested because PCE was added directly to the test cells prior to each technology test. The section describing results and conclusions for the tests discusses the amount of PCE present before and after each technology test.

3.3 TECHNOLOGY DESCRIPTION AND OPERATION

3.3.1 GENERAL TECHNOLOGY DESCRIPTIONS

Cosolvent solubilization is a technique that flushes a mixture of water and water miscible organic solvents (such as alcohols) through the contaminated aquifer to increase the solubility of the contaminant. By

increasing the solubility, more contaminant is dissolved from the non-aqueous phase into ground water, effectively increasing the dissolved contaminant concentration in ground water. Extracting ground water with a higher contaminant concentration results in higher mass removal for a given extraction rate.

AS/SVE involves injecting air in the saturated zone and allowing volatile organic compounds (VOCs) to partition into air from NAPL or dissolved in ground water. When the VOC-laden air reaches the unsaturated zone, it is extracted with a soil vapor extraction system.

SEAR improves the solubility of NAPL through the formation of micelles. The surfactants have two ends, a hydrophilic end that is attracted to water and a hydrophobic end that is attracted to NAPL. The surfactant surrounds the NAPL with the hydrophobic end directed inward toward the NAPL and the hydrophilic end extending outward into the surrounding water. With this approach surfactants are flushed through the contaminant zone, form micelles, and then are extracted and treated.

Cosolvent Mobilization involves flushing the contaminant media with a cosolvent or mixture of cosolvents in order to displace the bulk NAPL. Cosolvents are chosen for their ability to lower NAPL/water interfacial tensions and which preferentially partition into the NAPL as they are flushed through the contaminated zone. Reduced interfacial tensions and swelling as a result of cosolvent partitioning causes trapped NAPL globules to be displaced and mobilized in the subsurface.

Complex Sugar Flushing uses large sugar molecules to augment contaminant partitioning into the mobile aqueous phase. Similar to micelles, these molecules have hydrophobic interiors into which contaminants partition. However, because they do not form clusters or micelles the bulk properties of these sugars may differ substantially from surfactant solutions.

3.3.2 TECHNOLOGIES AS APPLIED DURING THE PROJECT

Cosolvent Solubilization

The test involved injection into six wells along the cell border (wells 41, 44, 46, 51, 54, and 56 in Figure 3-1) and extraction through the two wells in the center (wells 45 and 55 in Figure 3-1). Ethanol was used as the cosolvent and a mixture of 70% ethanol to water was maintained by using a combination of 95% ethanol and recycled ethanol from the extraction wells. Injection and extraction were controlled in upper and lower zones of each well. The test was conducted for 38.8 days. A total of 41,700 L of 95% ethanol was delivered to the test cell over the course of the test, and a total of 112,000 L of total fluids was recycled through the test cell. The injection and extraction phases included a general flush through the cell, followed by targeted flushes in areas with high PCE concentrations, followed by a water flush to recover residual ethanol. Extracted fluids were treated with gravity separation, air stripping, and/or granular activated carbon before reuse. The project team did not specify the criteria for determining when to stop the flushing ethanol.

AS/SVE

The system operated for a total of 109 days with periodic shutdowns, changes in air sparge configurations, and ground water recirculation at a rate of approximately 0.1 L per minute beginning from day 57 to day 60. Over the course of the test, eight different AS/SVE configurations and five intentional temporary shutdowns were utilized to redistribute air flow through the aquifer. Sparging was focused at the bottom 2 ft of the formation. Extracted vapors were treated with granular activated carbon. The air sparge injection flow rate was approximately 14 standard cubic ft per minute (scfm), and the soil vapor extraction rate was generally maintained at or above two times the sparge rate. The site team did not specify the criteria for discontinuing system operation.

SEAR

A surfactant solution was injected and extracted into the test cell over the course of 43 days, including periods of no flow to change the configuration. Four configurations were used during the surfactant flood and another two injection/extraction configurations were used during the subsequent water flood, which occurred for nine days. The injection/extraction configurations consisted of both vertical circulation flow patterns and horizontal flow patterns. The extracted fluid was treated with air stripping and then reused, resulting an 82% reduction in the amount of surfactant needed and a 91% reduction in the amount of waste water generated.

The surfactant chosen for the test was based on laboratory testing for performance and lack of interference with tracer tests. The project team selected a water-based solution comprised of 3.3% Aerosol MA80 surfactant (food grade and biodegradable), 3.3% isopropyl alcohol, and 0.4% calcium chloride by weight. A total of 4,266 kg of surfactant was injected, and 3,891 kg was recovered.

The project team did not specify a reason for discontinuing the test.

Cosolvent Mobilization

Based on laboratory studies, the project team selected a cosolvent solution consisting of 70% n-propanol and 30% water by volume plus 175 of calcium chloride per liter. The calcium chloride was added to increase the density of the solution and to assist the n-propanol partition into the NAPL. A total of 24,600 L of n-propanol and 1,455 kg of calcium chloride were used. The solution was injected into the subsurface using 10 injection wells along the outer border of the test cell and two extraction wells in the center of the test cell. A flow rate of approximately 3.2 L per minute was maintained throughout the test. The extracted fluid was treated with an air stripper and reused to reduce chemical usage. The project team reported that approximately 90% to 95% of the PCE in the extracted water was removed via air stripping, but n-propanol was also removed. Therefore, over time, the percentage of n-propanol decreased. At two points of the test, the concentration of PCE in the injection fluid was as high as 400 mg/L and 900 mg/L due to temporary failure of the air stripper. A post-injection water flood was not conducted. The test likely stopped as a result of the continuing loss of n-propanol from air stripping and the reduced mass of this cosolvent available for continued flushing.

Complex Sugar Flushing

The project team chose a horizontal injection pattern, injecting remedial fluid through three injection wells on one side of the test cell and extracting the fluid at a line of four extraction wells on the opposite side of the test cell. The average flow rate for the 54-demonstration was 1-2 liters per minute. The remedial fluid consisted of technical grade cyclodextrin dissolved in water at a concentration of approximately 20% by weight. Approximately 38,000 liters of the fluid was used for injection. The extracted fluid was treated by an air stripper to remove the PCE, and the fluid was reused for injection. Over the course of the demonstration, a cyclodextrin concentration of approximately 15% by weight was maintained. Approximately seven pore volumes (85,000 L) of remedial fluid was circulated through the test cell, and this was followed by a 14-day flush with water (equivalent to about 2.5 pore volumes) to remove the cyclodextrin from the subsurface. Approximately 90% of the injected cyclodextrin was recovered.

The air stripper was capable of treating influent of 150 mg/L and 15% cyclodextrin to an effluent concentration of 0.015 mg/L, and the average concentration of PCE reinjected into the test cell was approximately 0.1 mg/L. A residual amount of Aerosol-MA remained in the formation from the surfactant flushing demonstration, but the project team concluded that it was at sufficiently low concentration to prevent the formation of micelles and would therefore have a negligible effect on this demonstration. The project team did, however, need to add an anti-foaming agent to prevent foaming in the air stripper.

3.3.3 PERFORMANCE ASSESSMENT – METHODOLOGY

The performance of each technology was assessed by comparing the amount of PCE removed to a known amount present in the test cell prior to each technology demonstration. The known amount of PCE was determined by adding the amount of PCE intentionally introduced to the test cell prior to the demonstration to the amount that remained from the previous demonstration(s). The mass removed for each technology was generally determined using a series of samples collected from each extraction well and/or from the blended water from all of the extraction wells. Monitoring results from multilevel sampling ports could also be used to evaluate PCE concentrations in the test cell, but were not the primary methods of evaluating the technologies.

For each technology, the PCE concentration in the effluent was evaluated to determine the effectiveness of the cosolvent, surfactant, or other remedial fluid. A higher concentration generally indicated a more effective remedial fluid; however, the concentration also depended on the distribution of PCE in the subsurface and the extraction rate. Many of the technology demonstrations considered the amount of PCE removed compared to the number of pore volumes flushed to provide a further evaluation of the remedial fluid effectiveness. This metric is reportedly relatively important for this type of remedial approach given the capital cost of the chemical reagents.

The assessments focused on the amount of PCE removed, rather than the amount of PCE present as DNAPL before and after the demonstrations. The project originally intended to characterize the amount of DNAPL present before and after the demonstration. These results were not reliable due to a number of factors, including the relatively small amount of DNAPL that was added to the test cells (as allowed by the permits). Therefore, although these technologies can be evaluated for effectiveness in removing contaminant mass, it is unclear how effective they are at removing DNAPL.

3.3.4 PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS

Cosolvent Solubilization

The cosolvent solubilization test was the first demonstration conducted in Cell 3. Approximately 91.7 L of PCE was injected into the cell prior to the test, and approximately 8.6 L were removed during tracer tests and/or well gauging prior the test. Therefore, a total of 83.1 L was present in the test cell before the test. Prior to the test aqueous PCE concentrations ranged from 6 mg/L to 19 mg/L, but during the test, the aqueous PCE concentration increased to over 2,000 mg/L during a portion of the test and generally remained above 1,000 mg/L. The demonstration succeeded in removing 53 L of PCE, or approximately 64% of what was present before the test. Given the displacement of approximately 10 pore volumes during the test (both cosolvent flush and the subsequent water flood), this translates to a removal rate of approximately 5.3 L of PCE per pore volume. The data suggest that the test was discontinued while DNAPL removal rates were still relatively high, and when the ethanol concentration reduced (due to the water flushing), the PCE removal similarly decreased. This is evident in Figure 3-2. This suggests that DNAPL was still present and that the test may have been prematurely ended with respect to its capacity to remove DNAPL.

AS/SVE

The AS/SVE test was the first demonstration conducted in Cell 2. Approximately 66 L of PCE were injected into the cell prior to the test, and approximately 2.4 L were removed during tracer tests and well gauging prior to the test. Therefore, a total of 63.6 L of PCE was present in the test cell prior to the test. This technology differed from the other technologies conducted during this project in that the mechanism for aggressively removing PCE did not involve increasing its solubility. Rather, it involved stripping the PCE from the subsurface using air injection. Based on concentrations in the recovered vapor, the project test estimated removal of approximately $57 \text{ L} \pm 6.6\text{L}$, or $90\% \pm 10\%$. In terms of the percentage of PCE removed, this technology test was the most effective of the five tested technologies. It was also the longest test (109 days) from start to finish. The cumulative mass removal is shown in Figure 3-3. It is

evident that the mass removal rate was highest when the air sparging configuration changed. For example, the air sparging configuration changed three times during the first 19 days, corresponding to the removal of approximately 30 kg of PCE. A significant increase in mass removal was also documented along with ground water recirculation at day between days 57 and 60. Mass removal again increased with new configurations on day 82 and the several reconfigurations that continued few days through the end of the test. It appears likely that continued mass removal could continue with additional air sparging with continued sparge point reconfiguration and ground water circulation.

SEAR

The SEAR test was the second demonstration conducted in Cell 3. Prior to the test, approximately 70.4 L of PCE was present (accounting for PCE remaining from the cosolvent demonstration, additional PCE added to the test cell, and limited PCE removed during well gauging and tracer testing). Approximately 44 L to 45 L of the PCE was removed, translating to removal of approximately 65%. Aqueous phase concentrations prior to the test ranged from 37 to 190 mg/L, and increased to approximately 1,500 to 2,500 mg/L during the test. Although this is a substantial increase in aqueous phase concentration it is much lower than the solubilization capacity of the surfactant solution (42,700 mg/L). Therefore, it appears that mass removal was primarily limited by PCE distribution and potentially by access of the surfactant to all of the PCE. It is noted that 90% of the PCE was removed during the first injection/extraction configuration and that reconfiguring the system had little influence. Additional reconfigurations may or may not have further increased removal. Figure 3-4 shows the PCE removal over time with the first five different injection/extraction configurations indicated. Given the displacement of approximately 10 pore volumes during the test, approximately 4.5 L of PCE was removed per pore volume.

Cosolvent Mobilization

The cosolvent mobilization test was the second demonstration conducted in Cell 2. Based on the amount of PCE remaining from the previous test, additional PCE added to the subsurface, and PCE removed through tracer tests and well gauging, the total PCE in the test cell prior to the demonstration was approximately 56.7 L. A total of 44 L were removed during the test for 78% recovery. The aqueous phase PCE concentration before the test was approximately 80 mg/L. It increased to between 1,000 mg/L and 2,500 mg/L during the demonstration, and decreased to 15 mg/L after the test. No free phase DNAPL recovery was observed, contrary to the expectation of this mobilization test. It is unclear if this is the result of DNAPL being present primarily in the residual phase rather than as free phase, if it is a failure of distribution of remedial fluid during the demonstration, or if it is a failure of the technology in these conditions. Approximately 20 pore volumes were displaced during the test, translating to approximately 2.2 L removed per pore volume. Figure 3-5 demonstrates that the PCE removal rate had slowed to a negligible rate after 30 days of the test. Additional significant mass recovery during this demonstration would likely not have occurred without a change in the injection/extraction configuration.

Complex Sugar Flushing

The complex sugar flushing test was the last demonstration conducted, and it was conducted in Cell 3. A total of 69.8 L of PCE was present before the test. Approximately 33.4 L of PCE was removed for a recovery of 48% of the PCE present before the test. Aqueous concentrations observed before, during and after this test were similar to those observed for the other cosolvency demonstrations. The PCE concentration prior to the test was 42 mg/L. It increased to between 800 mg/L and 1,500 mg/L, and then asymptotically decreased indicating that removal was limited by preferential flow around areas with the remaining DNAPL. Approximately seven pore volumes were displaced during the test, translating to removal of approximately 4.5 L per pore volume.

3.3.5 ECONOMIC ANALYSIS

Little economic data was provided to evaluate these technologies from a cost perspective. In addition, much of the work was conducted by academic institutions, which have a different cost structure than private environmental contractors or vendors that would likely implement the technologies at other impacted sites. Many of the technologies (with the exception of AS/SVE) rely on the same general approach of injecting a remedial solution, extracting ground water with increased levels of the contaminant, treating that water and then reinjecting it to conserve the chemicals that comprise the remedial fluid. Therefore, the primary factors affecting the cost for these technologies are the capital cost of purchasing the reagents, and the cost of treating the extracted water. The cost for the reagents depends on both the amount of reagent used and the unit cost of the reagent.

The cost for treating the water would be heavily dependent on how the remedial solution affected an air stripping or granular activated carbon treatment train. In general, increasing the solubility of contaminants will make them more difficult to remove from process water by air stripping or GAC adsorption. The studies did not uniformly discuss the effectiveness of the air stripping for each technology. However, it was noted that concentrations reinjected during the complex sugar flushing averaged 0.1 mg/L, which represents 99.99% removal, but is also approximately 20 times higher than the MCL. The effectiveness of air stripping or treatment in the other cosolvent or surfactant related tests is likely substantially lower. For example, air stripping during the ethanol cosolvent test was 91% efficient, suggesting that a solution with PCE on the order of 100 mg/L was reinjected into the subsurface. Reinjection was appropriate during these demonstrations conducted in isolated test cells; however, it would be more complicated and likely more expensive in other applications. Additional treatment or isolation of the application area would likely be needed, which would likely substantially add to cost.

3.4 EVALUATION OF TECHNOLOGIES

3.4.1 PROJECT SUCCESS RELATIVE TO PROJECT GOALS

The technology demonstrations generally met the goals of determining the amount of mass removal achieved by the various technologies, but the demonstrations were not able to measure the amount of contamination in the form of DNAPL that was removed or that was present after a demonstration.

All of the technologies that relied on increasing solubility (i.e., all demonstrated technologies except for AS/SVE) performed in a similar manner. PCE mass removal ranged from approximately 48% to 78%. Some of the demonstrations may have been ended prematurely with respect to potential for mass removal, so higher mass removal may have been possible for some of the technologies by either continuing injection/extraction in a current configuration or changing the configuration to alter the ground water flow paths. The AS/SVE demonstration provided the most comprehensive mass removal (approximately 90%), and it appeared that additional mass could be achieved by continuing the test with various sparging configurations and inducing additional ground water flow patterns.

3.4.2 PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK

In a financial and regulatory framework, a successful mass removal technology would likely either reduce the time frame to site cleanup to some finite time (e.g., within 30 years) or substantially reduce life-cycle costs. Despite the substantial mass removal by the demonstrated technologies (with the possible exception of the AS/SVE), substantial contaminant mass remained in the subsurface, with some likely in the form of DNAPL. Although remedial time frames may be shortened as a result of removing mass up to 80% mass, it is unlikely that the remedial time frame would be shortened to a “reasonable time frame” (e.g., 30 years or less). Furthermore, despite the additional upfront investment in such technologies it is unclear how much the associated mass removal would decrease life-cycle costs of the overall remediation. If these technologies were applied in a similar setting (absent the physical isolation with sheet pile) with similar

results, it is likely that continued active remediation would be required. It is even possible that the residual constituents in the subsurface could increase the annual operations and maintenance cost of the long-term remediation system due to potentially decreased efficiency of air stripping and/or granular activated carbon.

An example of a more successful technology application in a financial and regulatory framework would be the achievement of concentrations that the regulating agency would agree could be addressed by monitored natural attenuation. This would likely require complete (or nearly complete) removal of source material and substantially lower aqueous concentrations than what have been observed following these demonstrations.

With respect to contaminant fate and transport, it is unclear how practical it would be to reinject the extracted ground water after the level of treatment provided during these demonstrations. The concentrations reinjected in many of the demonstrated technologies could lead to substantial spreading of the contaminant plume if not otherwise controlled. The unique setting of an isolated test cell would likely be required.

3.4.3 CONSIDERATIONS FOR THOSE CONTEMPLATING TECHNOLOGY APPLICATIONS AT ANOTHER SITE

These demonstrations provide the following lessons learned for site teams considering implementing these technologies at their site.

- If one of the demonstrated technologies that rely on increasing the solubility of DNAPL is considered for a site with similar hydrogeologic characteristics to that at the DNTS, then the site team would likely benefit from considering the following questions:
 - What would be the cost of implementing the technology?
 - What would be the benefit of partial mass removal?
 - How would the technology affect future efforts for source control? Would it decrease annual costs or will it likely lead to increased annual costs?
- The four technologies that rely on increasing the solubility of DNAPL yielded similar results with a range of 48% to 78% mass removal. Although several aspects of the demonstrations were consistent, there were not enough parameters held constant to conclusively determine if the difference in mass removal was due to the reagents used or the effectiveness in dispersing the agents. As a result, if considering one of these technologies, the site team might consider that which has the lowest cost and that which has the least likelihood of negatively impacting future efforts for source control (e.g., least likelihood of reducing performance of an air stripper in a pump and treat system that would be used to hydraulically contain the source area).
- If moving forward with any of the five technologies, there appears to be significant benefit in changing the injection/extraction configuration. Site teams might consider including the flexibility in the injection/extraction systems to allow for multiple flow configurations.
- Although reagent reinjection was a possibility at the DNTS, it may not be feasible or practical at another site. For this reason, the site team would benefit by considering the measures necessary to allow for reinjection (e.g., additional treatment and/or physical isolation) or the amount of reagent needed in the absence of reinjection. The site team may also consider what other benefits were afforded to these test application conducted in small, controlled, well-characterized, isolated test cells compared to more complex, less-studied, non-enclosed source areas that may be encountered at other sites.

- Of the five tested technologies, AS/SVE appeared to be the most effective, with approximately 90% mass removal and the potential for additional mass removal with additional sparge configuration and ground water flow patterns. In addition, unlike the other technologies, treatment of the AS/SVE effluent (vapor) is relatively straightforward and cost-effective. Furthermore, unless there is potential for substantial scaling or biological fouling, AS/SVE would not leave residual that may adversely affect future source control measures. For this reason, of the five technologies tested, AS/SVE may be the most appropriate technology to try first in the type of hydrogeological and geochemical setting found at the DNTS.

3.5 DOCUMENTS REVIEWED

Wood, A.L. and C.G. Enfield, 2004 *Field Evaluation of Enhanced DNAPL Source Removal, Final Technical Report*, SERDP Project CU-368, June *DRAFT*

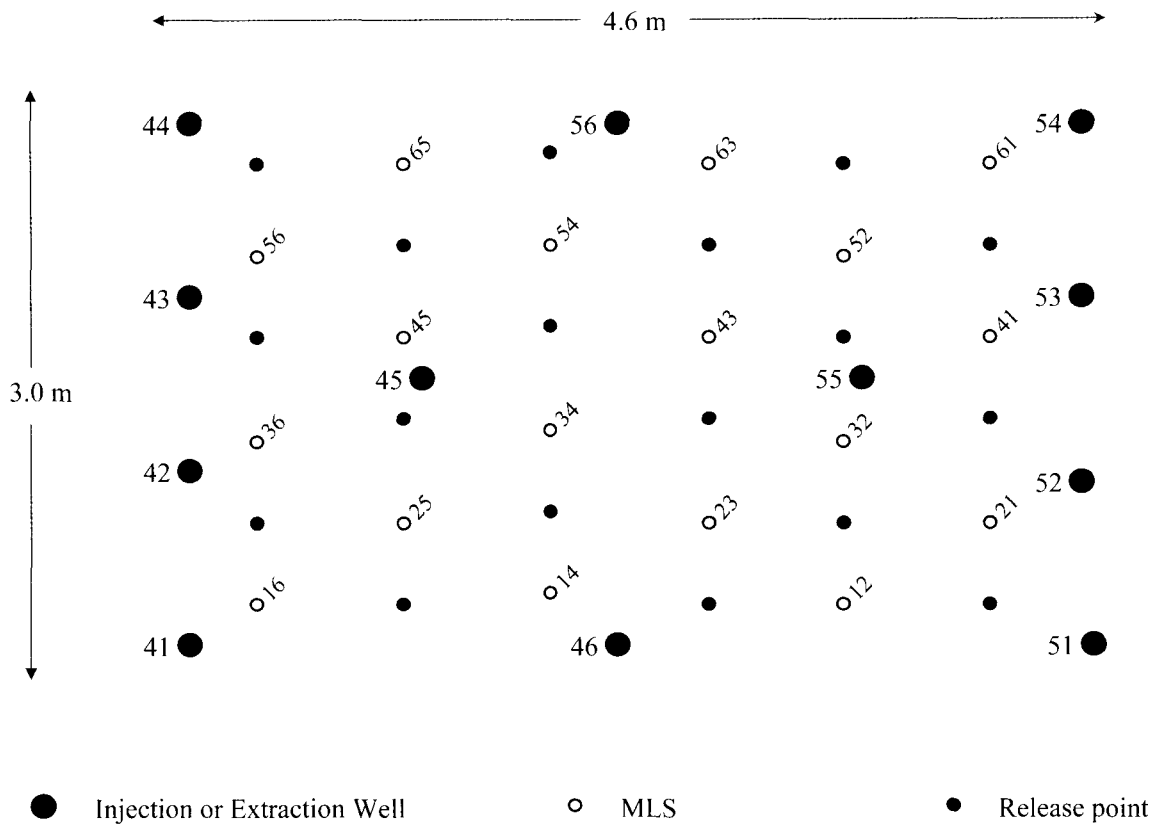


Figure 3-1. Layout of a test cell with locations indicated for injection/extraction wells, multilevel sampling ports (MLS), and PCE release points (Wood and Enfield, 2004)

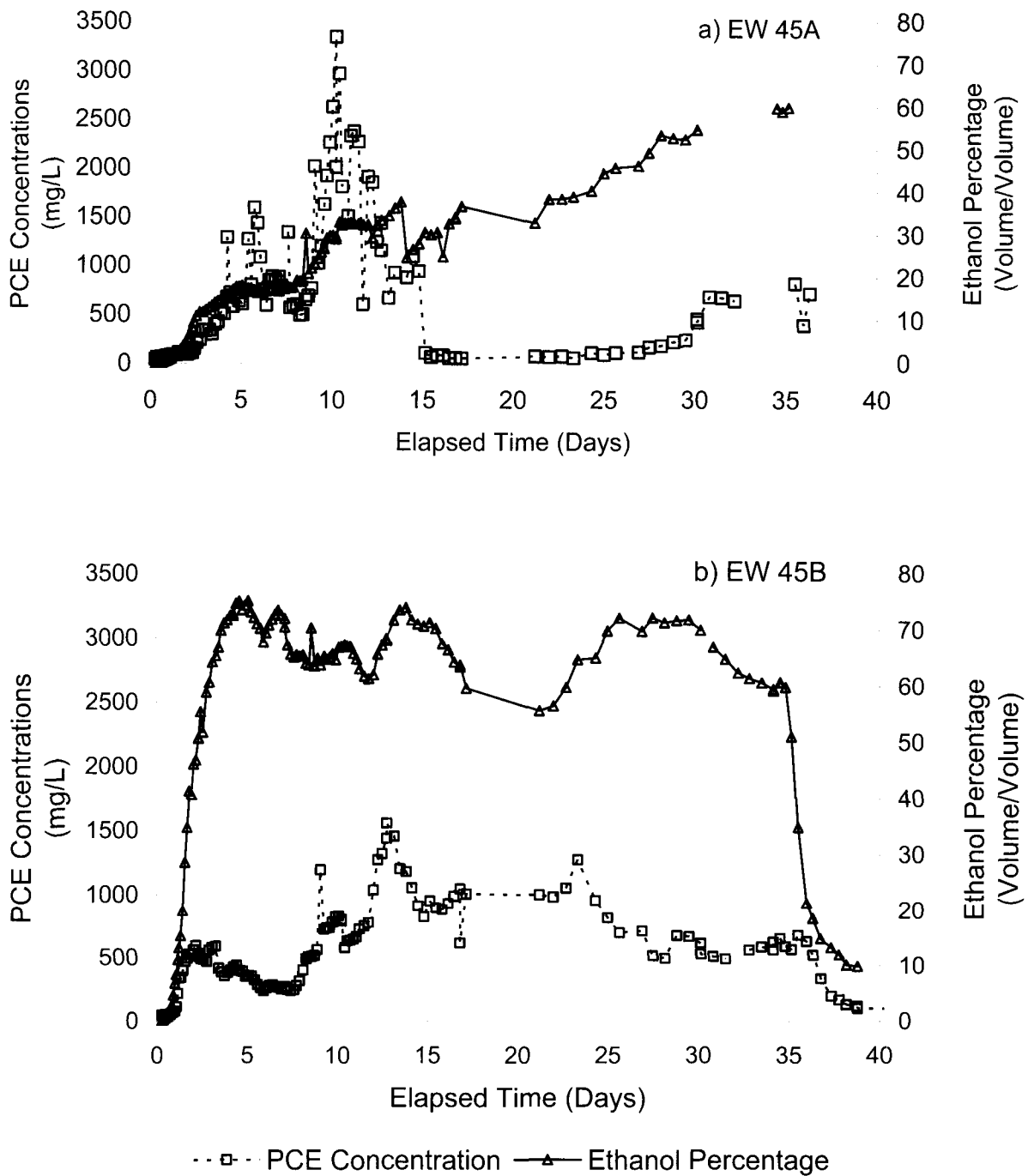


FIGURE 3-2. PCE CONCENTRATIONS AND ETHANOL (COSOLVENT) CONCENTRATIONS OVER THE COURSE OF THE DEMONSTRATION IN TWO DIFFERENT EXTRACTION WELLS (WOOD AND ENFIELD, 2004)

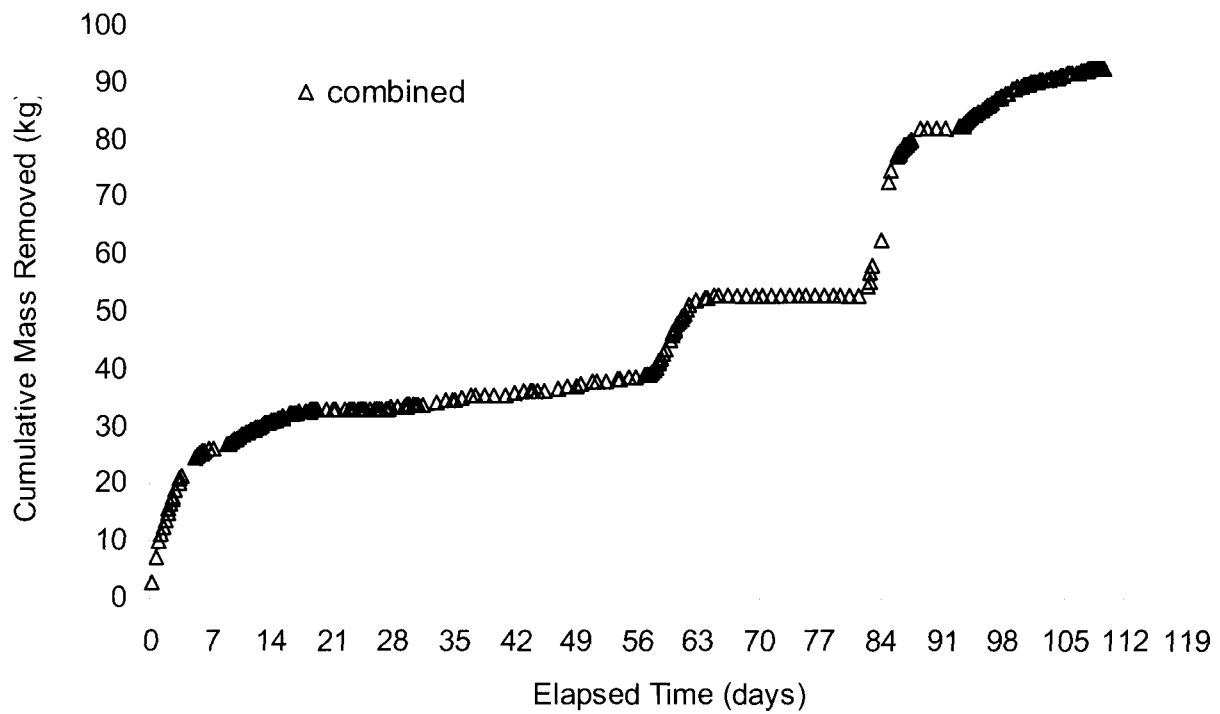


FIGURE 3-3. CUMULATIVE MASS REMOVED BY THE AS/SVE. THE NOTICEABLE INCREASES IN MASS REMOVAL CORRESPOND TO PERIODS WHERE THE SPARGING CONFIGURATION WAS CHANGED AND/OR WHEN A GROUND WATER FLOW PATTERN WAS INDUCED (WOOD AND ENFIELD, 2004)

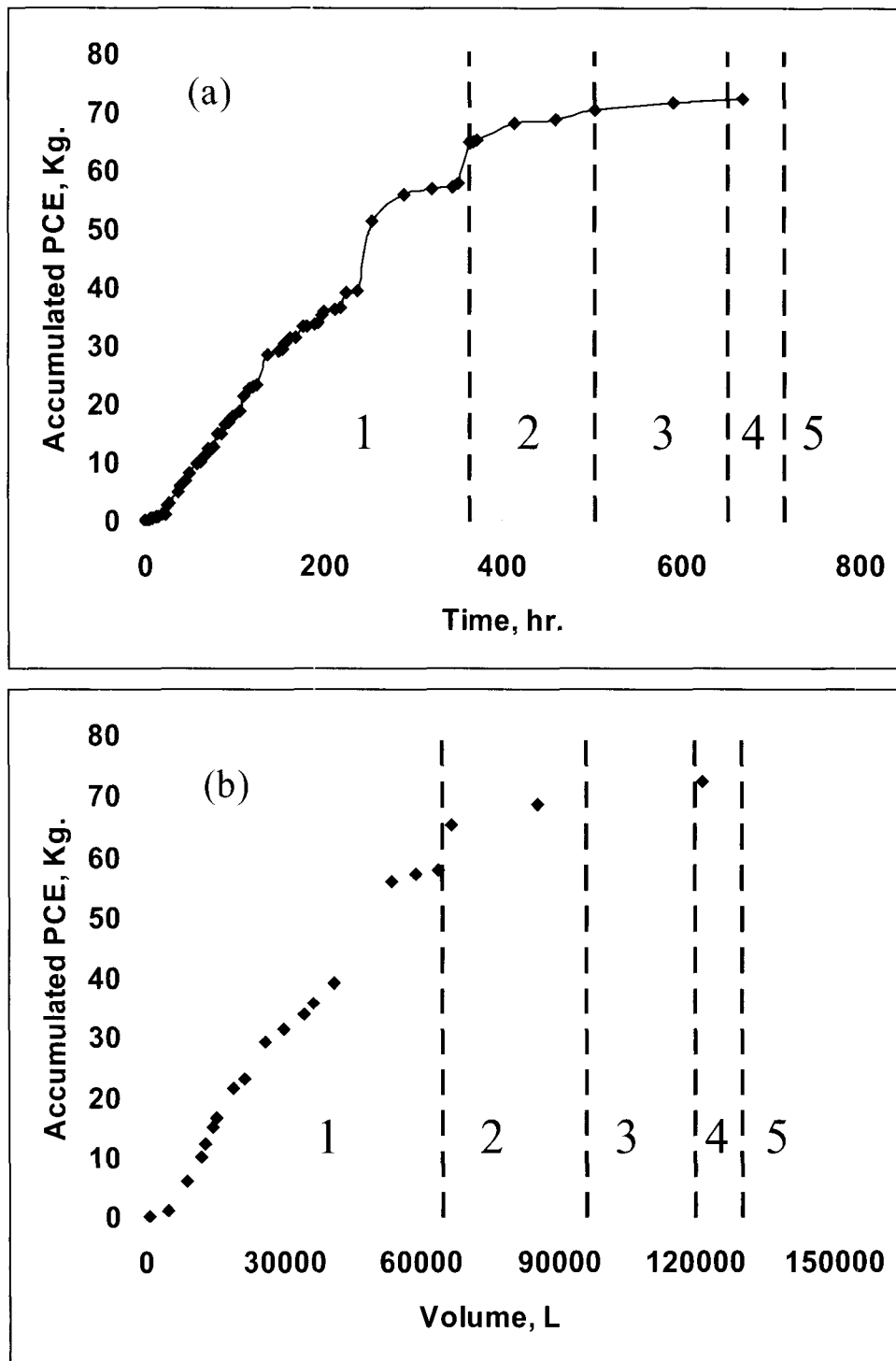


FIGURE 3-4. CUMULATIVE PCE MASS REMOVED AS A FUNCTION OF TIME (A) AND AS A FUNCTION OF PORE VOLUMES. CHANGES IN MASS REMOVAL CORRESPOND TO CHANGES IN INJECTION/EXTRACTION CONFIGURATION (WOOD AND ENFIELD, 2004)

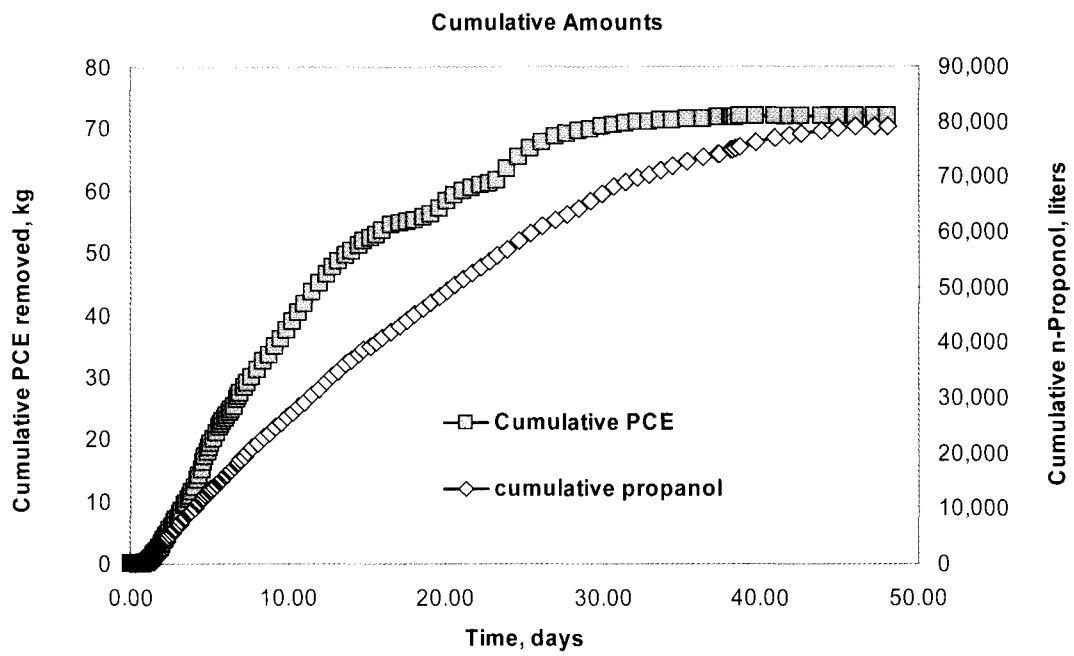


FIGURE 3-5. THE CUMULATIVE PCE AND N-PROPANOL MASS REMOVED (WOOD AND ENFIELD, 2004)

4.0 PANELS 1 AND 5, OPERABLE UNIT 2, HILL AIR FORCE BASE, UTAH

4.1 PROJECT BACKGROUND

This project tested the performance of surfactant-enhanced aquifer remediation (SEAR) with *in-situ* foam generation to remediate DNAPL. It was conducted in Operable Unit 2 of the Hill Air Force Base, Utah in 2001 and 2002. Operable Unit 2 is located along the northeastern boundary of the Base, where disposal of chlorinated organic solvents (primarily TCE) historically occurred. The SEAR technology was tested in two different arrays (panels) of ground water wells in the shallow alluvial aquifer of Operable Unit 2. The two well panels used for these tests were Panel 1 and Panel 5, and the designs of these tests were based on information gathered during a surfactant flooding application conducted in Panel 2 in 1999. The information presented here was obtained from the February 2003 report titled *Panel 1 and 5 Surfactant Enhanced Aquifer Remediation (SEAR) Report, Operable Unit 2, Hill Air Force Base, Utah*, prepared for the Air Force Center for Environmental Excellence and the Environmental Management Division for Hill Air Force Base by URS and Intera.

Other DNAPL removal and remedial activities occurred at Operable Unit 2 prior to the SEAR study. A brief chronology of those activities and the SEAR study is as follows:

1967 to 1975	The area now known as Operable Unit 2 was used for disposal of solvents.
1992	Construction of the Source Recovery System (SRS) designed to pump free phase DNAPL and associated contaminated ground water from Operable Unit 2.
1993	Operation of the SRS begins.
Fall 1996	Construction of a deep soil-mixed containment wall constructed around the extent of the known DNAPL plume.
September 21, 2001 to November 1, 2001	The Panel 1 SEAR application was conducted. <ul style="list-style-type: none">• 11 days of pre-surfactant brine flooding• 13 days of surfactant flooding• 17 days of post-surfactant brine/water flooding
June 5, 2002 to June 13, 2002	Hot spot treatment targeted at DNAPL remaining in the southern half of Panel 1 after initial SEAR application
June 21, 2002 to July 12, 2002	The Panel 5 SEAR application was conducted. <ul style="list-style-type: none">• 3 days of pre-surfactant brine flooding• 7 days of surfactant flooding• 11 days of post-surfactant brine/water flooding
October 28, 2002 to November 12, 2002	Demobilization of SEAR equipment occurred.

The objectives of the SEAR tests were as follows:

- Remove DNAPL from the target zones (well Panels 1 and 5 in the alluvium)
- Conduct a defensible performance assessment of the SEAR application
- Achieve the most effective use of surfactant by controlling its mobility using foam
- Demonstrate hydraulic control over all injected fluids and DNAPL in the well field

In addition, the project team established goals for the treatment of the SEAR wastewater stream:

- Remove as much contaminant (i.e., DNAPL and VOCs) as is practical via gravity separation and steam stripping (which would be provided by the already present SRS)
- Reduce foam generation/stability of the SEAR wastewater stream discharged from the SRS
- Produce a wastewater stream amenable to treatment by conventional wastewater treatment processes and containing no biologically toxic intermediate compounds
- Meet SRS discharge standards, including pH requirements

4.2 SITE CHARACTERIZATION

Investigation of the area now known as Operable Unit 2 began in 1981. This and subsequent investigations found residual DNAPL near the surface and extending vertically to pools of DNAPL over 7 ft thick that had settled to the bottom of a shallow aquifer depression carved in an underlying clay. The depressions were part of a paleochannel that had been carved in the clay. The SRS was installed to collect free-phase DNAPL, and a containment wall was installed to prevent further migration of the DNAPL plume. However, after construction of the wall in the Fall 1996, additional DNAPL was located beyond the extent of the wall. The area encompassed by the containment wall and the outline of the various well panels are presented in Figure 4-1. Panel 5, the area of the second SEAR application discussed in this report, is located outside of the wall area to address the DNAPL plume that was identified after wall construction.

The shallow alluvial aquifer where the DNAPL is located is predominantly finer-grain sands and silty-clays overlying sand and gravel that were deposited by the Weber River as it carved into an underlying clay formation that is approximately 200 ft thick or more. The resulting paleochannel, which is V-shaped in cross-section, trends to southwest/northeast in the area of Panel 1. The portion of the paleochannel occupied by ground water is approximately 40 ft wide, and the portion of the paleochannel occupied with DNAPL was approximately 20 ft wide. The water table is present in the lower, sand and gravel portion of the shallow aquifer at an elevation of approximately 4,662 ft asml. The top of the DNAPL layer was historically at approximately 4,652 ft asml. Hydraulic conductivity estimates obtained from grain size analyses and slug tests ranged from approximately 15 to 275 ft per day. Tracer tests indicated a longitudinal dispersivity of approximately 35 ft over an approximately 50-ft distance between injection and extraction points and a bulk hydraulic conductivity at approximately 130 ft per day. A schematic of the cross-section is presented in Figure 4-2.

Characteristics of the paleochannel in the area of Panel 5 were determined in a similar manner as those in the area of Panel 1. The paleochannel in the area of Panel 5 has a similar width and depth as that in the area of Panel 1, but is truncated by landslides of the clay formation. The project team estimates that the total volume of paleochannel in the area of Panel 5 below the water table is approximately 19,000 cubic ft. The alluvial aquifer in this area is comprised of similar material but is slightly more conductive than the area of Panel 1. Bulk hydraulic conductivity estimates from tracer tests suggest hydraulic conductivities ranging from 227.5 to 538 ft per day.

The DNAPL in Operable Unit 2 was characterized by analysis of DNAPL throughout the source area. The DNAPL was found to contain approximately 70% TCE, 10% PCE, 10% 1,1,1-Trichloroethane, and 10% other constituents by weight. The density of the DNAPL is approximately 1.35 g/cm³ with a

viscosity similar to that of water. The interfacial tension between the DNAPL and the water was substantially lower than it would be for pure chlorinated compounds suggesting the surface active agents (surfactants) were disposed of in the area now known as Operable Unit 2 along with the solvents.

The amount of DNAPL in the subsurface was substantially reduced by operation of the SRS. Since 1993 approximately 43,000 gallons of DNAPL were recovered and 15 million gallons of contaminated water was extracted and treated. Prior to the SEAR tests in Panels 1 and 5, the project team estimated approximately 402 gallons of DNAPL present in the aquifer at Panel 1 and 370 gallons of DNAPL present in the aquifer at Panel 5. These estimates, which were primarily based on partitioning interwell tracer tests (PITTs), were considered uncertain by the project team due to the suspected presence of contaminant mass in isolated areas of the heterogeneous formation that were missed by the PITTs.

4.3 TECHNOLOGY DESCRIPTION AND OPERATION: SURFACTANT ENHANCED AQUIFER REMEDIATION

4.3.1 GENERAL TECHNOLOGY DESCRIPTION

SEAR involves flushing the target portion of the DNAPL-impacted aquifer with surfactants to increase the solubility of the DNAPL and to increase the mobility of the DNAPL by reducing the interfacial tension between the DNAPL and ground water. Ground water containing the surfactants and the increased amount of DNAPL is then extracted through a network of wells or trenches for treatment and discharge. Treatment of water with surfactants presents an additional challenge, and is a crucial part of project design.

4.3.2 TECHNOLOGY AS APPLIED DURING THE PROJECT

The SEAR project utilized existing wells and treatment components from the operating SRS, but also included the addition of injection wells, extraction wells, and supplementary treatment components. Ground water modeling was used to help place injection wells and extraction wells to increase the likelihood of addressing DNAPL throughout the panels. Laboratory experiments and data from a previous SEAR experiment (at Panel 2) were used to assist with surfactant selection and formulation, surfactant mobility, and treatment options. The project team incorporated the following into the system design:

- The surfactant formulation would contain between 4% and 7% sodium dihexyl sulfosuccinate.
- Air would be injected along with the surfactant to create foam that would propagate through the subsurface. The foam would help obstruct high permeability areas, diverting surfactant into low permeability portions of the formation.
- Additional solutes (sodium chloride) would be used to reduce the strength of the foam so that it would be consistent with previously studied foam for DNAPL removal.
- Extracted water would be treated with gravity phase separation and steam stripping provided by the SRS, followed by hydrolysis of surfactant compounds under high pH conditions, pH readjustment to be consistent with discharge criteria, and eventual treatment through the activated sludge process at the Base industrial water treatment plant or the nearby publicly owned treatment works. Anti-foaming agent was added to the process water prior to the steam stripper.

The injection system for the SEAR application in Panel 1 included four surfactant/air injection wells, a surfactant-only injection well, a hydrodynamic mixing and delivery system, and reagent tanks for storing brine and surfactant solution. The extraction system included six extraction wells with stainless-steel bottom-loading pneumatic pumps. Distances between injection and extraction wells ranged from approximately 20 to 40 ft. A brine solution was initially added to provide the designed electrolyte

concentration and establish a flow regime. Balanced injection/extraction of surfactant followed. Approximately 42,000 gallons of surfactant solution was injected (with 4% surfactant by weight) at an average flow rate of 10 gpm over the 13-day surfactant injection period. Air was injected to generate foam. The surfactant injection was followed by a 17-day water flood with an average flow rate of 12.5 gpm. Over the course of the application (including the subsequent hot spot application), approximately 320,000 gallons of extracted water was treated.

The injection system for the SEAR application in Panel 5 included six surfactant/air injection wells, a brine-only hydraulic control well, a hydrodynamic mixing and delivery system, and reagent tanks. The extraction system included seven extraction wells with submersible pneumatic pumps. Distances between injection and extraction wells ranged from approximately 20 to 40 ft. Approximately 42,000 gallons of surfactant solution (with 4% surfactant by weight) was injected with an average flow rate of approximately 14.5 gpm. Air was injected to generate foam. The average extraction flow rate was 15.5 gpm. A brine and water flood followed the surfactant injection. Over the course of the application, approximately 478,000 gallons of extracted water were treated.

The project team noted the following operation problems encountered in association with the SEAR applications:

- Various problems associated with the acid addition equipment
- An unexpectedly high frequency of bag filter changes (every 15 to 30 minutes) requiring 24-hour operator attention
- Accumulation in the treatment building of 4-methyl-2-pentanol (an alcohol byproduct of the surfactant destruction by hydrolysis) necessitating the use of respirators and improved ventilation
- Clogging of steam stripper distributor nozzle
- Freezing of the 50% sodium hydroxide solution
- Buildup of carbonate in steam stripper

Many of these types of problems are not unusual for water treatment (particularly during a startup phase); however, the problems may be more pronounced during a short-term, aggressive mass removal program. TCE concentrations in influent were as high as 14,000 mg/L, and effluent concentrations (presumably of total volatile organic compounds) were as high as 1,200 mg/L during a period of operational difficulty, potentially leading to a likely exceedance of the discharge limit.

4.3.3 PERFORMANCE ASSESSMENT – METHODOLOGY

The performance assessment for each of the SEAR applications was comprised of the following components:

- DNAPL mass recovered as determined from integrating the analyses of contaminant concentrations obtained from effluent samples (at extraction wells) collected during SEAR operations
- DNAPL mass recovered during the flood as independently measured by the treatment system at the SRS influent
- DNAPL mass estimated from the analyses of soil samples collected from confirmation borings drilled at each panel at the conclusion of the SEAR application

- Estimates of injectate recovery based on surfactant and IPA analyses conducted during the SEAR application to characterize hydraulic control efficiency

Estimates of DNAPL mass recovery could then be compared to initial estimates prior to the application. Although planned, PITTs were not performed after the SEAR demonstration because they were considered unreliable based on the PITT results conducted prior to the SEAR applications.

4.3.4 PERFORMANCE ASSESSMENT – RESULTS AND CONCLUSIONS

Project-Specific Objective: Remove DNAPL from the target zone

From the effluent at each extraction well in Panel 1, the project team estimates that $1,196 \pm 263$ gallons of DNAPL were removed (including the subsequent hot spot treatment). From the Panel 1 SRS data, the project team estimates that $1,150 \pm 110$ gallons of DNAPL were removed. These estimates, despite the uncertainty (as evidenced by the range provided), are in close agreement and strengthen the confidence in the estimates. They are, however, substantially higher than the initial estimate of 402 gallons estimated by the PITT before the SEAR application. This demonstrates that the pre-test PITT was a poor indication of the amount of DNAPL present in Panel 1. The project team did not specifically state that it intended to remove all DNAPL from the subsurface, and the project team notes that data suggest additional DNAPL is present in the subsurface. The primary evidence for this is that the contaminant concentrations decreased at the same rate as the surfactant concentration as the surfactant flood was replaced with a water flood.

For the Panel 5 application, the project team reports that analysis of the extraction well effluent suggested 371 ± 52 gallons of DNAPL were removed, compared to an initial estimate of 360 gallons of DNAPL present. Analysis of the SRS influent data suggests that 221 ± 41 gallons were removed. Pump tests conducted after the application indicated elevated TCE concentrations suggesting that some DNAPL remained in the aquifer.

The estimates and associated uncertainty of DNAPL removal based on the above data are summarized in the following table from the February 2003 report.

ESTIMATION METHOD ^a	ESTIMATED VOL. RECOVERED (GALS)	UNCERTAINTY (%)	ESTIMATED VOL. RANGE (GALS)	PRE-SEAR PITT ESTIMATE (GALS)
Panel 1 SEAR				
- SEAR Effluent	1,179	18.	967 – 1,391	402 ± 78
- SRS Recovery	1,139	6.3	1,067 – 1,211	
Panel 1 Hot Spot				
- SEAR Effluent	17	17.6	14 – 20	21 ± 14 ^b
- SRS Recovery	11	345	0 – 49	
Panel 5 SEAR				
- SEAR Effluent	371	14.0	319 – 423	360 ± 74
- SRS Recovery	221	18.6	180 – 262	

^a SEAR effluent recovery based on integration of the DNAPL concentration histories and subject to uncertainty associated with relative errors in flow rate and concentration measurements. SRS recovery based on flow measurements of DNAPL transfer from phase separators to solvent storage tank and subject to uncertainty associated with relative errors in flow measurements and DNAPL transfer float assembly

^b A pre-SEAR PITT was not conducted prior to the Panel 1 hot spot treatment, but DNAPL volume was estimated based on contaminant concentration histories measured at the completion of the Panel 1 SEAR

The project team also reported the result of confirmation soil borings made in each of the well panels. For Panel 1, the project team reported that the results from 20 samples collected from various depths in five confirmation soil borings suggested that a large majority of DNAPL had been removed. Of 20 soil

samples collected, only one had concentrations suggestive of DNAPL (407 mg/kg of TCE). The project team estimated that the equivalent of approximately one gallon of DNAPL may be present surrounding this sample. The TCE concentration for all 20 soil samples average approximately 30 mg/kg of TCE, indicating the presence of contaminant mass adsorbed to soil. Based on partitioning between soil and ground water, the site team estimated approximate aqueous phase concentrations of TCE. The average of these aqueous phase concentrations was 93 mg/L. The accuracy of these aqueous TCE concentrations is unclear. The calculations likely did not account for the increased solubility of TCE as a result of the residual surfactant present in the subsurface. The TCE remaining in the subsurface may be preferentially partitioned to the aqueous phase rather than adsorbed to soil, making soil concentrations artificially low and ground water concentrations likely higher than calculated.

For Panel 5, a total of 22 soil samples were collected at various depths from five confirmation borings. Only one of the samples had TCE concentrations suggestive of DNAPL (4,053 mg/kg). The project team estimated that based on this sample, approximately 4 gallons of DNAPL remain in the subsurface in the area of this sample. The average TCE concentration for the remaining 21 soil samples was approximately 8 mg/kg of TCE, indicating the presence of contamination adsorbed to the soil and dissolved in ground water.

Project-Specific Objective: Conduct a defensible performance assessment of the SEAR application

The site team achieved this goal relative to its project objectives.

Project-Specific Objective: Achieve the most effective use of surfactant through the use of mobility control

The foam surfactant flood appeared to be successful at increasing removal of dissolved phase contamination and free phase contamination. Given the mobilization of free phase DNAPL, it appears that the surfactant was used effectively. However, it is unclear how well the mobility control using foam performed without directly comparing performance to an application without the foam.

Project-Specific Objective: Demonstrate hydraulic control over all injected fluids and DNAPL in the well field

The project team injected isopropyl alcohol along with the surfactant and used this compound as a tracer. The project team reports recovery of approximately 81% of the isopropyl alcohol during the Panel 1 application and recovery of approximately 98% during the Panel 5 application.

The project team did not comment on achieving the goals associated with treatment of the SEAR wastewater stream. It was noted that an exceedance of the discharge criteria may have occurred during a short interval of application, and additional investigation is required to determine if foaming was adequately reduced for processes downstream of the SRS. In addition, the project team anecdotally reports that methyl isobutyl ketone (MIBK) is now evident in the Panel 1 and 5 areas, likely as a result of degradation of the isopropyl alcohol.

4.3.5 ECONOMIC ANALYSIS

The project team reported a total cost of \$1.4 million for the Panel 1 and Panel 5 SEAR applications including characterization, design, and reporting. The project team also anecdotally indicated that the costs for operating the SRS system have increased by \$20,000 to \$50,000 per year as a result of the surfactant floods due to the effects of the remaining constituents in the extracted water. Given the difficulty in treating surfactants in wastewater, substantial capital costs were avoided for this project by using already existing wells and treatment equipment associated with the SRS and the downstream treatment provided by the Base water treatment plant or local publicly-owned treatment works.

4.4 EVALUATION OF TECHNOLOGY

4.4.1 PROJECT SUCCESS RELATIVE TO PROJECT GOALS

The SEAR applications in Panels 1 and 5 generally met the project goals of removing DNAPL. Together, the two tests removed approximately 1,500 gallons of DNAPL, exceeding estimates of DNAPL mass made prior to the applications. Sampling from two different areas (each extraction well and the blended influent to the treatment plant) were used to estimate the amount of DNAPL removed and provided consistent results. Furthermore, confirmation soil sampling results suggested that approximately one in every 20 samples had TCE concentrations above what would be expected if DNAPL were present. Treatment of the effluent was generally achieved as was hydraulic control of the injected fluids. Therefore, the project appears to be a success based on its original stated technical objectives.

4.4.2 PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK

In a financial and regulatory framework, a successful source removal application would likely either reduce the time frame to site cleanup to some finite time (e.g., within 30 years) or substantially reduce life-cycle costs. Despite the substantial DNAPL mass removal, both Panel 1 and Panel 5 have a substantial and unknown TCE mass remaining in the aquifers, with some in the form of DNAPL. Aqueous concentrations are still well over 10 mg/L (approximately 2,000 times the Maximum Contaminant Level), and contamination adsorbed to soil can continue to provide a continuing source of ground water contamination. Nevertheless, DNAPL appears to have largely been removed, and it is possible that the active remediation time frame for these areas may have been shortened to a reasonable time frame (e.g., less than 30 years). Active remediation with SRS continues for mass removal purposes, and the cost of this annual operation has increased as a result of the applications. Therefore, it is unclear how much of a financial benefit there has been in removing the DNAPL at a cost of \$1.4 million and a continuing additional cost of \$20,000 to \$50,000 per year for annual operations and maintenance of the SRS. Additional cost information from the project team and future data regarding site conditions would be needed to estimate the potential financial benefit of the applications.

With respect to contaminant fate and transport, a combination of ground water extraction and the confining nature of the surrounding clay may have successfully prevented migration of contamination during the applications. Additional characterization has not been reported to confirm this. The degradation of isopropyl alcohol to MIBK is concerning; however, given the elevated chlorinated solvent concentrations the MIBK has not substantially degraded the aquifer and may be remediated before the chlorinated solvents are remediated.

4.4.3 CONSIDERATIONS FOR THOSE CONTEMPLATING A TECHNOLOGY APPLICATION AT ANOTHER SITE

These SEAR demonstrations provide the following lessons learned for site teams considering implementing this at their site.

- The technology has demonstrated success in removing mass from an unconsolidated aquifer with permeable media (e.g., a hydraulic conductivity over 100 ft per day). Although substantial mass remains, it appears to be primarily dissolved in ground water or adsorbed to soil. Confirmation soil samples indicated only one in 20 samples with concentrations indicative of DNAPL, but only 42 samples were collected out of a treated volume of approximately 5,000 cubic yards. Based on the contaminant mass removed, this technology provides promise for those site teams looking for DNAPL removal in permeable aquifers where hydrogeologic conditions and engineering controls can be used to prevent migration during the technology application.

- Despite success in removing DNAPL and contaminant mass for both tests, additional active remediation is required, and the SRS continues to operate (with elevated annual costs as a result of the tests). The remaining time frame for active remediation is uncertain, but may be reasonable (e.g., within 30 years) depending on the continued performance of the SRS. Given these results, it is likely that active remediation would be required after an application at a similar site.
- When considering the costs of this SEAR study (\$1.4 million including characterization and technology application), it is important to note that the project team benefited from an already existing infrastructure of the SRS, the Base waste water treatment plant, and the local public-owned treatment works. These or similar resources would not necessarily be available at other sites contemplating this technology. Given the difficulty in treating very high levels of chlorinated solvents and surfactants, these resources or similar resources may add substantially to the cost of the project at other sites.
- A number of technical difficulties that are common with water treatment plants (particularly during the start up phase) occurred during the applications. Due to the aggressive nature and short duration of this source removal technology, the effect of these difficulties is greater because there is often little time to address the issues without affecting the test. In this case, there was likely an exceedance of the discharge criteria. Project teams implementing this or other aggressive technologies may benefit from considering extra redundancies, extra treatment capacity, and extra time for start-up and testing for their treatment systems. This may add to the project costs.
- This project, which involved continued extraction of ground water during the application was relatively successful at providing hydraulic control. This differs from some other technologies or applications of other technologies where ground water extraction is not provided and contaminant migration occurs.
- The use of surfactants or other chemical reagents can lead to the production of other potentially hazardous chemicals. This occurred twice during this project. In one instance, the destruction of the surfactant led to a build-up of 4-methyl-2-pentanol in the treatment plant, necessitating changes in health and safety measures. In addition, the breakdown of isopropyl alcohol is anecdotally leading to the formation of MIBK in the aquifer, creating another potential hazard to address. Given the relative difficulty in treating MIBK with air stripping and granular activated carbon, this (or a similar phenomena) could lead to substantial increases in cost for applications at other sites.
- A site team would benefit by establishing clear goals to be achieved by these technologies and by considering how these goals apply to overall site remediation. In addition, a site team might consider additional active remediation that would probably be required subsequent to the attempt at remediating DNAPL. The project team will likely need to balance the risk of extra expenditures in the short term for the potential reduction in remedy duration.
- The use of PITTs provided a poor indication of the amount of DNAPL present in the subsurface. In one instance, the PITT estimated approximately 400 gallons were present, when over 1,100 gallons were removed. Given this performance, site teams may consider avoiding the use of PITTs for estimating the amount of DNAPL present or to consider the results with skepticism.
- Although the technologies removed substantial mass over a relatively short time period in the hydrogeological setting Operable Unit 2, it is unclear how the technology would perform under other conditions, such as fractured bedrock, ground water with other chemistry, or less permeable sands, silts, and clays. For this reason, site teams moving forward with this technology would benefit by considering the potential performance of the technology in these other settings prior to

conducting a pilot test. The site teams might consider the ability to remove DNAPL, the potential for inducing contaminant migration during a pilot test or full scale application, and the potential for complicating subsequent remediation efforts.

4.5 DOCUMENTS REVIEWED

URS and Intera, 2003 *Panel 1 and 5 Surfactant Enhanced Aquifer Remediation (SEAR) Report, Operable Unit 2, Hill Air Force Base, Utah*, February

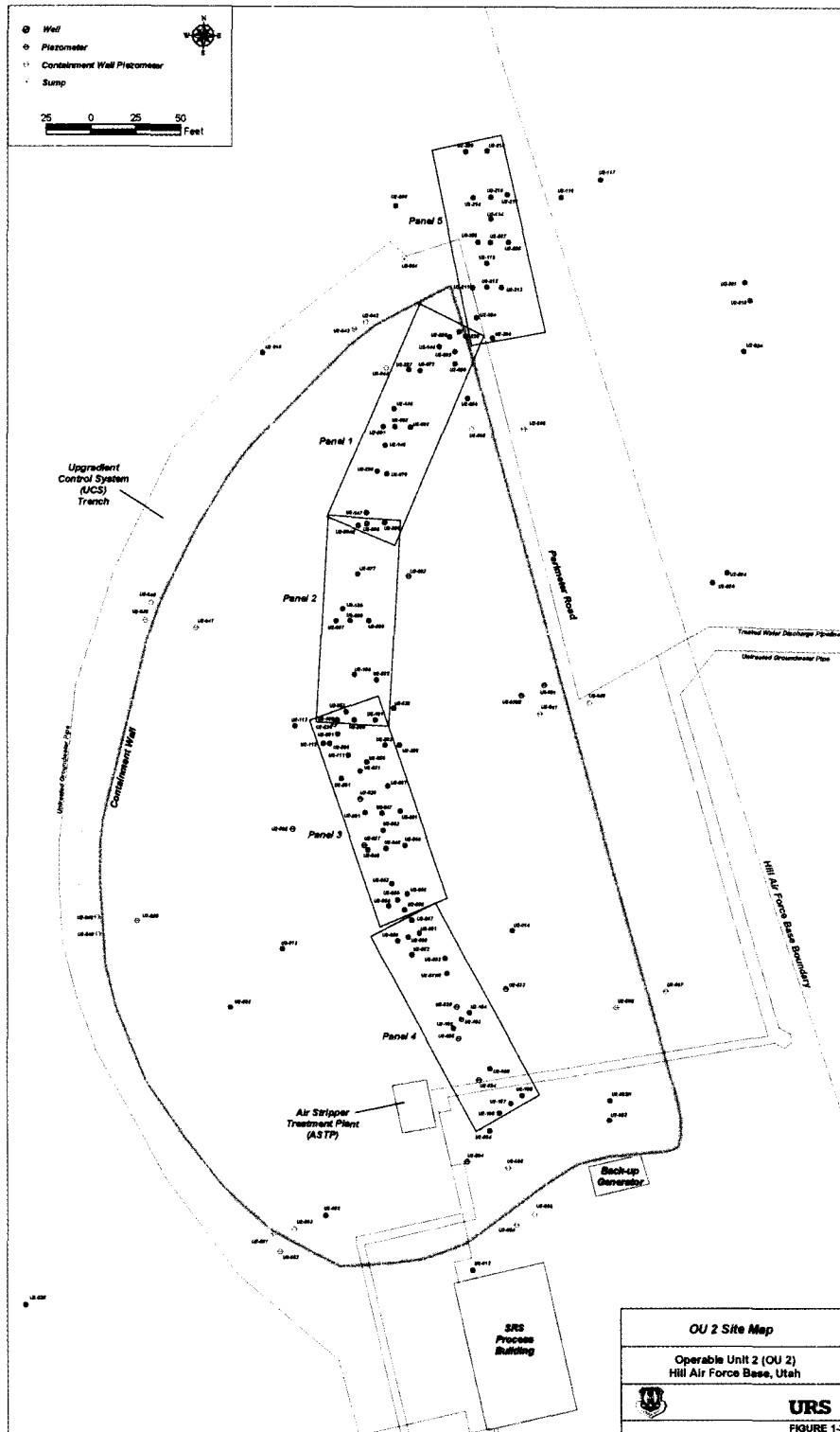


FIGURE 4-1. OPERABLE UNIT 2 WITH LOCATIONS OF PANEL 1 AND PANEL 5 INDICATED (URS, 2003)

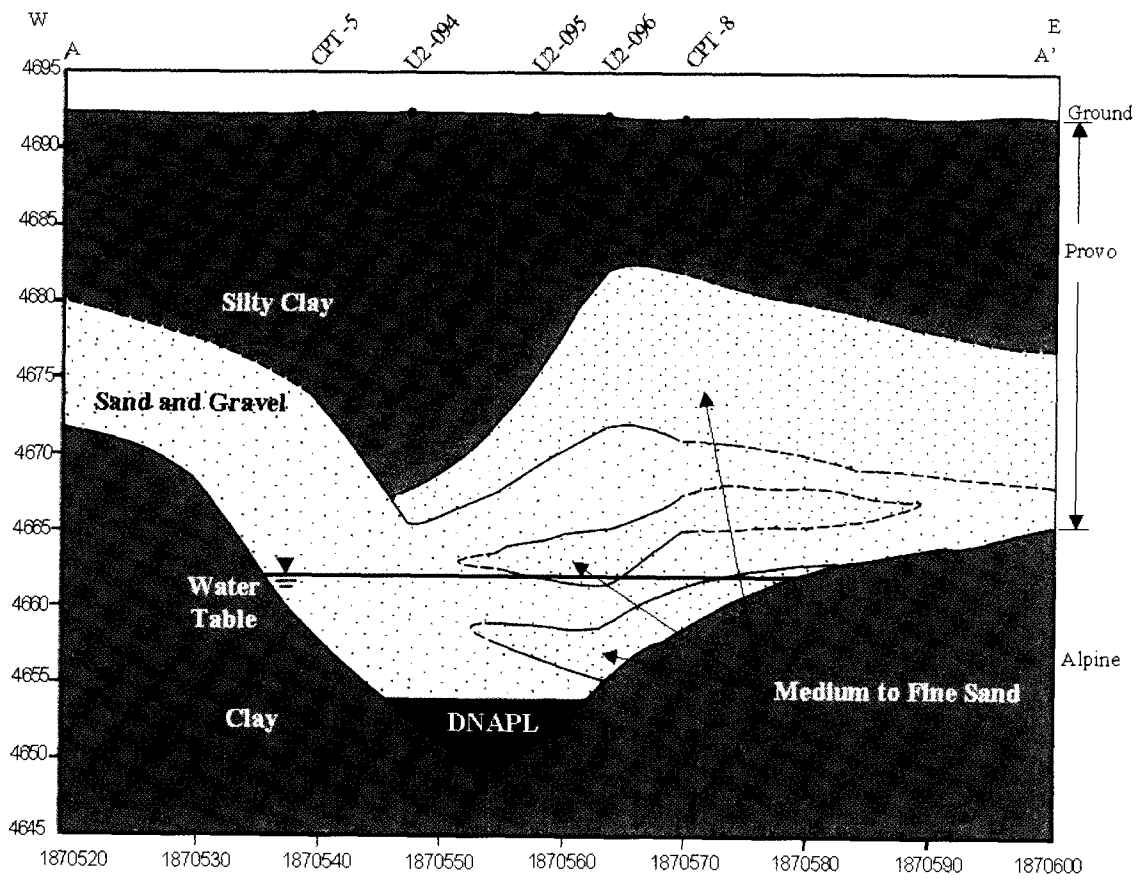


FIGURE 4-2. SCHEMATIC OF OPERABLE UNIT 2 CROSS-SECTION AT PANEL 1 (URS, 2003)

5.0 LORING AIR FORCE BASE, LIMESTONE, MAINE

5.1 PROJECT BACKGROUND

The former Loring Air Force Base (LAFB) is located in Limestone, in northeastern Maine about three miles from the border with Canada. The quarry site (Loring Quarry Site), which comprises an area of about seven acres and includes a wetland, is situated close to the northwestern boundary of the former LAFB. The location of this quarry, which operated from 1947 to 1985, is near a former airfield that contained a jet engine test cell and a “sprawling” Nose Dock Area hangar facility.

The quarry was used by LAFB as a waste repository. Wastes disposed at the quarry included wastes from base activities, industrial and maintenance shops, and construction projects. Drums also were disposed at the quarry. During the 1980s and 1990s, contaminated soil, sediment, and construction debris and 450 drums were removed from the Loring Quarry Site. Later ground water quality testing showed that chlorinated solvents, likely including PCE DNAPL, and fuels were detected in ground water.

In 1990 LAFB was placed on the National Priorities List. The Loring Quarry Site is a CERCLA site. The final Feasibility Study, Proposed Plan, and ROD were completed in 1999. As part of the remediation strategy, \$250,000 was set aside by the U.S. Air Force to evaluate a DNAPL recovery technology that might ultimately be implemented at the Loring Quarry Site. Steam Enhanced Remediation (SER) was selected from responses to an RFP as the DNAPL recovery technology to be studied at the Loring Quarry Site. The SER research team is comprised of:

Maine Department of Environmental Protection (MEDEP)
U.S. Environmental Protection Agency (USEPA)
Office of Research and Development (ORD)
USEPA Region I
Air Force Base Conversion Agency
SteamTech Environmental Services

Table 5-1 is a chronology of the research activities conducted at the Loring Quarry Site. Construction of the system began in August 2002. The extraction system became operational on August 30. Steam injection began September 1, and it was terminated November 19 when funding was no longer available. Extraction was terminated November 26.

The primary document consulted for this report is the SER remediation report for the Loring Site, *Steam Enhanced Remediation Research for DNAPL in Fractured Rock, Loring Air Force Base, Limestone, Maine* (Davis et al. 2005). Unless otherwise cited, this document is the basis for all information about the SER research project presented in this report.

5.2 SITE CHARACTERIZATION

The Loring Quarry Site has undergone an extensive site characterization and review. The site characterization process and results are thoroughly described by Davis et al (2005) in *Steam Enhanced Remediation Research for DNAPL in Fractured Rock, Loring Air Force Base, Limestone, Maine*. Key elements of the site characterization are summarized below.

Geology

Topography at the Loring Quarry Site is typical of quarries, where soil and plants have been removed. Quarrying activities have caused the formation of two tiered benches that are open on the western side. As a result of quarrying, the overburden and shallow, weathered bedrock have been removed. Therefore, a

fractured limestone bedrock sequence, the Carys Mills Formation that typically is not found at the surface, is present in the quarry. The Carys Mills Formation largely consists of interbedded argillaceous, gray limestones and calcareous siltstones. The thickness of these beds is between about 0.75 in and 15 in (Thompson et al. 2004). There are three major structural features in the quarry, an anticline and two faults.

Figure 5-1 shows the geologic conceptual model for the Loring Quarry Site. Three predominant sets of fractures are present in the upper tier, where a zone of DNAPL has been identified — bedding plane fractures, axial plane fractures, and regional joint fractures. The bedding plane fractures are the predominant pathways for ground water flow and contaminant transport. Fractures are more abundant and better connected near the surface. At depths between 55 ft and 70 ft, fractures are typically widely spaced (about 3 ft apart) and fracture apertures are less than 6.6×10^{-4} ft, which is less than $1/10^{\text{th}}$ of an inch. Three types of fractures have been observed in video logs: fractures filled with calcite, fractures in or near calcite-filled fractures, and fractures without calcite deposition (Lane et al. 1996).

Hydrogeology

The Loring Quarry Site is located in the vicinity of a drainage divide. The direction of surface drainage is to the west toward the West Branch of Greenlaw Brook. Drainage from the hangars and taxiways to the east of the quarry drains toward the south and east to the East Branch of Greenlaw Brook. Water is present throughout the year in the lower tier, and drains through a ditch to the Greenlaw Brook wetland.

Ground water is encountered between 20 ft below ground surface (bgs) and 30 ft bgs in the upper tier of the quarry, and ground water flow is typically from the Nose Dock Area east of the quarry to the Greenlaw Brook wetland. The horizontal hydraulic gradient is 0.03, suggesting low hydraulic conductivity, and it increases below the upper tier. Downward vertical hydraulic gradients exist in the zone beneath the upper tier and upgradient of the Quarry. Upward vertical gradients with ground water discharge to Greenlaw Brook have been identified down gradient of the quarry.

Ground water flow is predominantly controlled by the bedding plane set of fractures. Vertical and sub-vertical fractures also significantly influence ground water flow. Calcite-filled fractures significantly reduce the interconnectedness of fractures; in one study 31 of 163 (about 19%) fractures were identified as capable of transmitting ground water (Lane et al. 2006). The fracture porosity has been estimated at about 1% (Lane et al. 1996). At the Loring Quarry Site, the porosity for the weathered rock matrix adjacent to fractures is at least 3% (Thompson et al. 2004). (Analytical results showed significant contamination for some of those rock samples.) The porosity of the matrix at other locations at Loring Air Force Base was measured in 43 rock samples between 0.2% to 2.4%, with 88% of the values below 0.9% (Thompson et al. 2004).

Transmissivity has been estimated between about 2×10^{-7} and 2×10^{-4} ft²/s (2×10^{-8} and 2×10^{-5} m²/s) between the depths of 10 ft bgs to 110 ft bgs. Between 30 ft bgs and 40 ft bgs, many wells were shown to be interconnected due to fracture junctions. The uppermost 65 to 82 ft (20 m to 25 m) is more highly fractured, and the degree of interconnectedness decreases with depth.

Ground water Contamination

Contamination at the Loring Quarry Site is present in ground water in DNAPL and dissolved phases. Tetrachloroethylene (PCE) is the most commonly detected compound, and it has been detected to about 100 ft bgs at a concentration of 27 µg/L. The second most commonly detected compound is trichloroethylene (TCE). Other chlorinated compounds detected at the Loring Quarry Site include cis-1,2-dichloroethylene, trans-1,2-dichloroethylene, chlorobenzene, vinyl chloride, and 1,1-dichloroethane. An estimated zone of residual DNAPL is located in the upper tier of the quarry (Figure 5-2).

Ground water sampling conducted post-SER did not occur at exactly the same depth interval as the pre-SER sampling, because some wells had been grouted for use as an injection or monitoring well. The

maximum pre-SER ground water concentration for PCE was 8,800 µg/L in well EX-3 between 35 and 45 ft bgs. The post-SER ground water concentration at EX-3 at the same depth data was 15,000 µg/L. Post SER ground water data generally showed that after the SER the concentration of PCE fluctuated with no obvious trend, which also occurred in some wells pre-SER. While PCE was the predominant contaminant prior to implementing the SER technology, petroleum hydrocarbons were the predominant contaminant post-SER. The increase in the petroleum hydrocarbon concentrations, indicating mobilization of those contaminants, continued for about 18 months after termination of the SER.

Contaminants have been in the subsurface for 20 years or longer, allowing for processes such as matrix diffusion to occur. Pre-SER analyses of PCE in rock chips show that the maximum concentration of PCE, 72 ppm, in the matrix occurred at about 96 ft bgs. Post SER sampling indicated that generally PCE concentrations were lower in post-SER rock chip samples than in pre-SER rock chip samples. There may be uncertainty in the estimates of contaminant mass in pre-SER and post-SER sampling as a result of 1) the potential difference in sample locations in the fracture distribution and orientation and 2) the sampling methodology. With regard to the sample methodology, rock chips were placed whole into the methanol preservative for one week. This time frame may not have been long enough to extract all of the contaminant mass due to the low permeability of the rock chips.

5.3 TECHNOLOGY DESCRIPTION AND OPERATION

5.3.1 GENERAL TECHNOLOGY DESCRIPTION

Steam Enhanced Remediation (SER) is a technology that was developed to extract non-aqueous liquids (NAPLs), such as dense non-aqueous phase liquids (DNAPLs), from the subsurface by heating the soil and ground water to a temperature close to the temperature required to boil water. This heating creates a zone of steam that dislocates NAPLs, making them more mobile. This increased mobility improves the ability to extract NAPLs and ground water containing dissolved contaminants. Because steam is injected, a moderate or higher hydraulic conductivity is required for successful injection. In addition, in fractured media, the steam will tend to follow the more permeable fractures and tend to bypass contaminants stored in the matrix.

The more mobile ground water and NAPL is recovered from the subsurface by pumping, and vacuum extraction is used to capture the vapors that were generated during the heating process. After the NAPL and ground water are extracted, the vapors are condensed to the liquid, and the water and NAPL phases are separated. After separation, any significant amount of NAPL can be transported offsite to a recycler, and the water can be treated and discharged. If little contaminant mass is recovered, carbon filtration could be used to treat both the vapor and liquid waste streams.

A form of SER has been successfully used for many years by the petroleum industry for enhanced oil recovery from oil reservoirs to recover additional oil mass. Its use as a remediation technology to retrieve NAPLs from the subsurface first began in the 1980s (Davis et al. 2005). Since then, many lessons have been learned and remediation of contaminated, unconsolidated aquifers has met with some success using this technology.

The SER technology also has been used at a limited number of sites where contamination of fractured rock has occurred. These sites are more challenging to remediate. The depth of contamination at the Loring Quarry Site is at least 70 ft bgs and 55 ft below the water table. The fractures in the limestone at those depths are widely spaced, on about 3 ft spacing, and the fracture aperture, or opening, is very small (6.6×10^{-4} ft or less than 1/10th of an inch). The contaminant source is old (greater than 20 years) and significant matrix diffusion appears to have occurred. This makes remediation of the Loring Quarry Site, as well as other sites like it, more challenging.

5.3.2 PERFORMANCE ASSESSMENT

Two major sets of objectives were developed for the SER research at the Loring Site. The first set is comprised of the USEPA SITE Program objectives (Table 5-2). The second set of objectives is comprised of a group of technology objectives. The group of technology objectives consists of one primary technology objective, seven detailed technology objectives, and four supplemental technology objectives. The primary technology objective is to:

“...determine the feasibility of using SER to significantly remediate ground water contaminated by PCE and other contaminants of concern (COC) in a fractured rock aquifer at the Quarry site on the former Loring AFB.”

The detailed and supplemental technology objectives are summarized in Table 5-3 and Table 5-4, respectively. For a thorough and comprehensive discussion regarding the USEPA SITE Program and the detailed and supplemental technology objectives, refer to the SER remediation report for the Loring Site, *Steam Enhanced Remediation Research for DNAPL in Fractured Rock, Loring Air Force Base, Limestone, Maine* (Davis et al. 2005). Davis et al. systematically and thoroughly analyzed, evaluated, and discussed whether each of the USEPA SITE Program and detailed and supplemental objectives outlined for the Loring Quarry Site SER research project were met. The evaluation provided in this report addresses the primary technology objective quoted above.

5.3.3 ECONOMIC ANALYSIS

The total cost for the SER research at the Loring Site is \$1,543,050. Of the total cost, construction and operation costs are 59.2%; characterization is 24.4%; report preparation, experts, and U.S. Geological Survey radar research were 10.4%, and post-treatment sampling and monitoring were 6%. Cost categories are defined and summarized in Table 5-5.

At \$913,250 the construction and operation costs comprise the bulk of the cost for the SER research program at the Loring Site. For this particular project, the travel distances were large, resulting in high travel costs (\$54,900). A high per diem cost (\$6,300) was also incurred because of the requirement that an employee reside at the site during the construction and operation phase. At other sites where long travel distances can be avoided and residence is not required, significant savings might be realized. The construction and operation costs were mitigated by the provision of in-kind services, such as sample analyses and consulting services, by USEPA. In-kind services may be available from USEPA, other governmental organizations, or universities for implementing the steam enhanced remediation technology at other sites, which could provide a significant reduction in costs.

Unidentified costs can significantly impact the feasibility of a project. At the Loring Site, costs for demobilization of equipment were not included. It is unknown whether any equipment demobilization costs were charged or whether those costs have been included with other costs. It is possible that the cost for construction and operation at the Loring site may be higher than \$913,250.

5.4 EVALUATION OF SER TECHNOLOGY

5.4.1 PROJECT SUCCESS RELATIVE TO PROJECT OBJECTIVES

The overarching objective is to “...determine the feasibility of using SER to significantly remediate ground water contaminated by PCE and other contaminants of concern (COC) in a fractured rock aquifer at the Quarry site on the former Loring AFB.” There are two metrics to define achievement of this objective — removal of contaminant mass from the source zone and performing that reduction of mass at a reasonable cost. At the Loring Quarry site, the total mass of contaminants removed from vapor and ground water was very small (7.36 kg or 16.23 lb), and the amount of DNAPL removed was negligible. The SER technology was implemented at this site to target PCE contamination. Pre-SER ground water concentrations of PCE were low and appear to have fluctuated. These conditions persisted post-SER,

indicating no improvement with regard to PCE contamination. The post-SER rock chip data indicated that PCE concentrations in the matrix were lower post-SER; however, these samples were not necessarily taken from the same structures as the pre-SER data. In addition, the sample methodology may have underestimated the contaminant mass present before and after the SER test. Therefore, the rock chip data is uncertain. The total cost of this project, which is discussed in the "Economic Analysis" section of this report, was more than \$1.5 million. The metrics for success were not met by using SER technology at the Loring Quarry Site.

The factors that caused the SER technology to fail to significantly remove DNAPL or PCE contaminant mass from the subsurface are a result of

- Inadequate site characterization
- Uncertain delineation of the DNAPL source zone
- Low porosity (1%) and permeability of a fracture network with characteristic calcite infilling and a low percentage of active fractures (19%)
- Low matrix porosity (0.8% to about 3%) and permeability
- Matrix diffusion
- Reduction in the number of steam injection wells due to grouting of the fractures during well installation
- Insufficient heating of the matrix due to low porosities and permeabilities and system design issues
- Steam migration out of the treatment zone at the southern boundary
- Insufficient funding to conduct a thorough site characterization and to complete implementation of the SER technology

5.4.2 CONSIDERATIONS FOR THOSE CONTEMPLATING AN APPLICATION AT ANOTHER SITE

Site characterization is a key component to successfully implementing the SER technology. Davis et al (2005) discuss the steps necessary to conduct an effective site characterization for a fractured rock site. The steps they advise are listed below in the advised sequence of steps 1 - 13. The details for each step are described in Davis et al. (2005).

1. Desk study (Use all existing data for conceptual model and remediation design)
2. 2-Dimensional electrical resistivity survey
3. Phase I drilling
4. Phase II drilling
5. Phase III drilling
6. Phase IV drilling
7. Development of all new monitoring wells
8. Ground water sampling and transmissivity profiling

9. Interconnectivity testing of fractures
10. Additional hydraulic testing
11. Final well installation
12. Aquifer recovery
13. Start of remediation operations

In addition to these steps, it is helpful to develop a scope of work for successful technology implementation that is consistent with available funding. Furthermore, because of the challenges related to remediation at fractured rock sites, site teams would benefit from establishing very clear objectives and performance criteria prior to the technology application.

The SER technology is a useful remediation tool under site conditions conducive to optimal implementation at a reasonable cost. This technology is not advised for the Loring Quarry Site, or other geologically complex fractured rock sites such as this one. Other remediation technologies may be more appropriate for this site and could be evaluated independently.

5.5 DOCUMENTS REVIEWED

Davis, E., et al. 2005. Steam Enhanced Remediation Research for DNAPL in Fractured Rock, Loring Air Force Base, Limestone, Maine. EPA/540/R-05/010. August.

Johnson, C.D., et al. 2004. Time-series monitoring in fractured-rock aquifers, in 2004 U.S. EPA/NGWA Fractured Rock Conference: State of the Science and Measuring Success in Remediation. September 13 – 15. Portland, Maine. Proceedings: National Ground Water Association, CD-ROM, 295 – 307.

Lane, J.W., Jr., et al. 1996. Geophysical Characterization of a Fractured-Bedrock Aquifer and Blast-Fractured Contaminant-Recovery Trench. http://water.usgs.gov/ogw/bgas/loring/1996_044.pdf

Thompson, et al. 2004. The Regional Bedrock Structure at Loring Air Force Base, Limestone, Maine; The Unifying Model for the Study of Basewide Groundwater Contamination. U.S. EPA/NGWA Fractured Rock Conference: State of the Science and Measuring Success in Remediation. http://clu-in.org/products/siteprof/2004fracrockconf/cdr_pdfs/indexed/group1/252.pdf.

PHASE	TASK	START	END	DESCRIPTION
Pre-Steam Injection Characterization	Borehole installation and rock chip sampling	5/15/01	6/21/01	All injection (I) and extraction (EX) wells, vertical electrode array (VEA) boreholes VEA-4, VEA-5, VEA-9, and thermocouple (TC) borehole TC-1 were cored and rock chip samples collected. Remaining VEA wells were installed by air hammer.
	Transmissivity testing	6/8/01	6/29/01	All newly installed wells plus existing wells in the target zone were tested on 3.2 meter (10 foot) intervals.
	Geophysical testing	8/7/01	8/9/01	Caliper logs, fluid resistivity, fluid temperature and acoustic televiewer logs were run on all I and EX wells.
	Deep boreholes	11/25/01	12/21/01	Included drilling, casing installation, and hydraulic testing.
	Ground water sampling	12/2/01	12/13/01	Wells within target area sampled
		4/2/02	4/9/02	Wells within target area and deep boreholes sampled
		6/10/02	6/10/02	Deep boreholes sampled
Interconnectivity testing	5/23/02	7/12/02	Field work completed in two phases.	
Steam Injection Operations	Dual-phase extraction	8/30/02	11/01/02	Continuous extraction of liquid and vapor from all wells.
		11/04/02	11/26/02	Continuous extraction restarted after equipment failure.
	Air injection	8/31/02	9/01/02	Air injection into steam wells.
		9/21/02	9/23/02	Air injection resumed while steam system shut down.
		11/19/02	11/26/02	Air injection resumed at end of steam injection.
	Steam injection	9/01/02	9/21/02	Steam injection in wells I-4, I-5, and I-6.
		9/23/02	11/19/02	Steam injection resumed after equipment failure.
10/14/02		11/19/02	Steam injection in wells I-7, I-8, and VEA-5 (I-7 middle interval shut down on 11/9).	
Post-Steam Injection Monitoring	Ground water sampling	5/2/03	5/9/03	Wells within target area and deep wells sampled.
		10/20/03	10/22/03	Wells within target area and deep wells sampled.
		5/17/04	5/20/04	Wells within target area and deep wells sampled.
	Rock chip sampling	7/7/03	7/15/03	Eight drillback locations sampled.

TABLE 5-1. CHRONOLOGY OF REMEDIATION ACTIVITIES AT THE LORING SITE.

EPA SITE Program Objectives

Primary Objectives

- Determine the approximate reduction in contaminant of concern (COC) concentrations that occurs in ground water within the treatment zone as a result of SER treatment.
- Determine the mass removal of COC in all waste streams over the course of the SER treatment period.

Secondary Objectives

- Determine the approximate reduction in COC concentrations in potentially open fracture intervals within the treatment zone as a result of the SER treatment.
- Determine if contamination is mobilized below, downgradient, or to the sides of the treatment zone as a result of the SER treatment.
- Determine if the rock within the treatment zone can be heated to greater than 87°C (the co-boiling point of water and PCE mixture) in the zones containing contaminants.
- Document the ability of the ground water and vapor treatment system to treat the effluent streams and meet any discharge permits.
- Document the operating parameters during evaluation of the SteamTech¹ SER technology.
- Determine the cost of treatment for the SteamTech SER technology based upon the evaluation at LAFB

TABLE 5-2. EPA SITE PROGRAM OBJECTIVES

¹ SteamTech was the vendor selected to perform the work; they are no longer in business.

PRIMARY TECHNOLOGY OBJECTIVE	EXPECTED PERFORMANCE (PRE-TEST)	PERFORMANCE CONFIRMATION METHOD
1. Document the application of steam injection technology and its ability to heat the fractured rock site to temperatures high enough to vaporize any DNAPL present in fractures and matrix	Completion of data collection to allow for assessment	<ol style="list-style-type: none"> 1. Energy balance calculation to estimate volume of rock heated to target temperature. 2. Temperature data from Digitam sensors. 3. ERT data interpretation of heating patterns. 4. Chemical mass recovery trends – effect of the remediation on extracted water and vapor concentrations and NAPL presence.
2. Heat a portion of the target pilot volume from below and from three sides using multiple injection wells and intervals, and measure subsurface temperatures and electrical resistivity.	Target volume raised to target temperature	Direct temperature monitoring and approximation by ERT methods.
3. Identify operational parameters which govern heat-up rates and steam migration.	Collect well-field data on injection and extraction that supports the subsurface monitoring data	<ol style="list-style-type: none"> 1. Determine acceptable injection intervals from core data, geophysics, slug tests, and pulse interference (interconnectivity) testing. 2. Measure steam and air injection pressures and achievable rates. 3. Monitor extraction well data for signs of steam, condensate or air injection effects. 4. Determine potential air injection benefits. 5. Matrix heating: Calculations of thermal conduction time-frames for site heating compared to observed temperatures.
4. Extract liquid and vapors aggressively and recover as much of the NAPL constituents present in the pilot test area as possible within the limitations of the technology, the resources available, and the time frame for operations.	Operate system as designed, with proper adjustments to well-field and process equipment to keep the test and data collection continuous.	<ol style="list-style-type: none"> 1. Monitor mass removal rates for NAPL, water and vapor. 2. Screen and sample individual wells for COC concentrations and headspace PID trends. 3. Inspect extracted fluids for NAPL presence. 4. Evaluate if the system was operated effectively and provided a fair test of the technology at this site. 5. Use collected data to estimate the most appropriate full-scale approach (based on lessons learned), and evaluate how close this test came to showing the mass removal we expect when sufficient time and funds are available.
5. Document removal rates and mass removal by detailed sampling and analyses.	Data collected	<ol style="list-style-type: none"> 1. Determine process stream vapor and liquid phase concentrations. 2. Calculate mass removal rate based on concentrations and flow rate. 3. Screen individual extraction well and analyze to determine trends in recovery rates.
6. Evaluate removal efficiency for PCE and other VOCs identified during sampling by pre- and post-test contaminant characterization.	Data collected by EPA SITE	Use pre- and post-treatment ground water and rock data to evaluate changes in COC concentrations (a SITE objective).
7. Identify potential barriers to full-scale implementation at this site, and at fractured rock sites in general.	Collect data set for discussion	Discussion based on holistic data interpretation, and data from related SER tests in fractures rock.

TABLE 5-3. DETAILED TECHNOLOGY OBJECTIVES FOR THE QUARRY SITE, LORING AIR FORCE BASE.

SUPPLEMENTAL TECHNOLOGY OBJECTIVES	EXPECTED PERFORMANCE (PRE-TEST)	PERFORMANCE CONFIRMATION METHOD
1. Determine the value of borehole tests and interconnectivity tests in determining the best use of each borehole interval for operation.	Make best use of the data during implementation	Discussion based on holistic data review.
2. Study the mechanism and importance of using air co-injection to improve the subsurface remediation.	Collect data for evaluation of potential benefits and downsides	<ol style="list-style-type: none"> 1. Compare steam injection rates with and without air injection. 2. Discuss extraction well responses to air injection following steam. 3. Discuss importance of air injection for reducing VOC condensation, and the risk and impact of spreading VOC-laden air.
3. Develop methods for pressure cycling in fractured rock with extraction hole temperatures below steam temperatures, and assess impacts on mass removal rates.	Use system as built to test pressure cycling options	<ol style="list-style-type: none"> 1. Observe well responses to vacuum adjustments to enhance de-pressurization. 2. Test borehole water level manipulations in support of SER. 3. Discuss options for pressure cycling without steam breakthrough to extraction wells.
4. Study the effect of SER on mass removal rates at temperatures well below boiling, caused by mixing of cold and hot extraction borehole fluids.	Collect data	Discussion based on holistic data interpretation.

TABLE 5-4. SUPPLEMENTAL TECHNOLOGY OBJECTIVES FOR THE QUARRY SITE, LORING AIR FORCE BASE

Project Phase	Item	Cost
Characterization	Drilling	\$168,000
	Transmissivity Testing	17,000
	Borehole Geophysics	15,000
	Rock Chip Sampling	44,000
	Ground water Sampling	12,000
	Deep Monitoring Wells	75,000
	Interconnectivity Testing	44,800
	Subtotal	\$375,800
Construction and Operation	Wages and Payroll Expenses	139,500
	Travel and Per Diem	61,200
	Materials and Supplies	372,700
	Contracted Labor	179,300
	Equipment Rental	32,300
	Utilities, Telephone	31,300
	Freight and Trucking	40,200
	Postage, Shipping	4,600
	Effluent Sampling	52,150
	Subtotal	\$913,250
Post-Treatment Sampling & Monitoring	Drill Back	70,000
	Ground water Sampling	24,000
	Subtotal	\$94,000
Reporting	Report Preparation	30,000
	Subtotal	\$30,000
Miscellaneous	Experts	50,000
	USGS Radar Research	80,000
	Subtotal	\$130,000
TOTAL COST		\$1,543,050

TABLE 5-5. SUMMARY OF COSTS

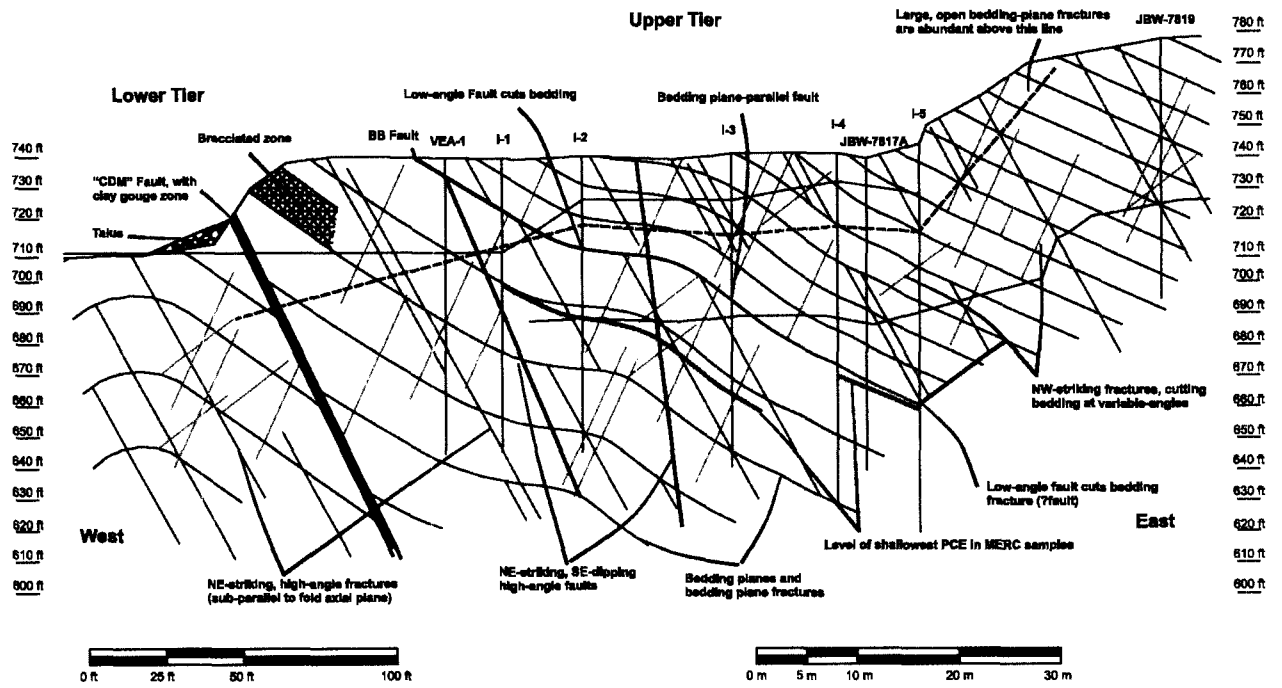


FIGURE 5-1. CONCEPTUAL MODEL OF GEOLOGY FOR THE QUARRY SITE, LORING AIR FORCE BASE

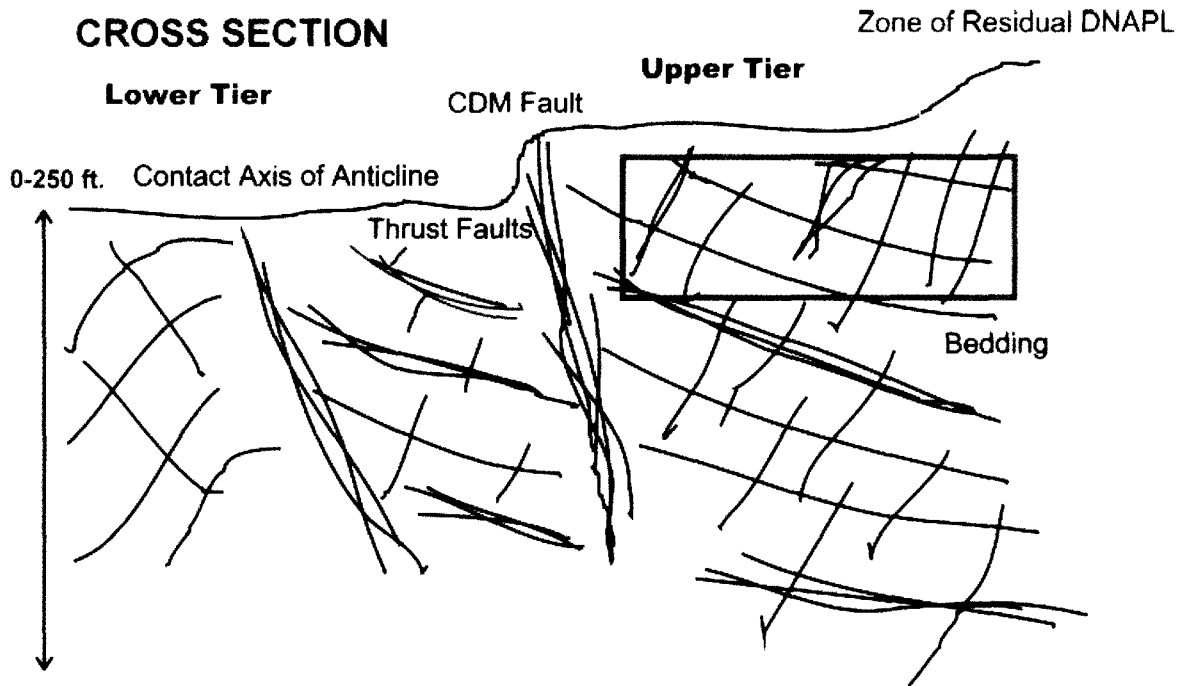


FIGURE 5-2. LOCATION OF THE DNAPL ZONE AT THE QUARRY SITE,
LORING AIR FORCE BASE

6.0 SAGES DRY CLEANERS, JACKSONVILLE, FLORIDA

6.1 PROJECT BACKGROUND

The former Sages Dry Cleaner site (Sages Site) is located at 5800 Fort Caroline Road, Jacksonville, Florida. Dry cleaner operations were conducted at the Sages Site from 1968 to 1973 and, again, from 1979 to 1989 (Mravik et al. 2003). Tetrachloroethylene (PCE) was historically used at this site, resulting in significant releases of PCE in its pure phase as a dense non-aqueous phase liquid (PCE DNAPL). The primary source of the releases is located in an area where a former sump, directly connected to the ground surface, was located (LFR 2000). An area that was just outside the former boiler room door, where sporadic releases of PCE occurred as it was delivered and where used filters were disposed, has been identified as a secondary source (LFR 2000). The Sages Site is a Florida Department of Environmental Protection (FDEP) Dry Cleaner Site Program (DCSP) facility. It was selected as a site for evaluation of source zone remediation technologies, with the possibility that the technologies evaluated at the Sages Site might be implemented at other FDEP DCSP facilities as well.

The source zone remediation technologies under evaluation are cosolvent flushing and enhanced *in situ* bioremediation. These two technologies, the first for removal of most of the source and the second to facilitate degradation of the remaining contaminant mass to “nonhazardous compounds” (Mravik 2003), are coupled in a “treatment train,” known as Solvent Extraction Residual Biotreatment (SERB). The SERB technology is being evaluated as a tool for complete site restoration (Mravik et al. 2003). This evaluation is a joint effort. Members of the SERB evaluation team include the following:

U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
Ground Water and Ecosystems Restoration Division
Ada, Oklahoma

LFR•Levine Fricke, Inc.
Tallahassee, Florida

University of Florida
Gainesville, Florida

Purdue University
West Lafayette, Indiana

East Central University
Ada, Oklahoma

6.2 SITE CHARACTERIZATION

Geology

The topography across the Sages Site is generally flat, with minor undulation across the western boundary. The Sages Site is underlain by unconsolidated sediments, consisting of very fine sand that contains some silt. The silt content increases with depth. Between 7 ft bgs and 17 ft bgs, the sand is colored dark red to black, and at about 24 ft to 28 ft below ground surface (bgs), nodules of partly indurated sand and silt have been observed. Beneath the very fine sand layer is a thin clay layer, approximately 6 in thick, that is discontinuously present at depths between 33 ft bgs and 37 ft bgs. The clay layer appears to be absent in the southwest corner of the site. A layer of very fine sand to silty sand that is about 5 ft thick is present below the clay layer. Very fine sand is again encountered below that 5 ft layer. An electromagnetic borehole flowmeter survey (Acree 2000) indicated that there is “...significant subsurface heterogeneity...” in the vicinity of the cosolvent flushing area.

Hydrogeology

The water table is typically encountered in the very fine surficial sand at about 8 to 10 ft bgs. The direction of ground water flow in the upper 20 ft of the surficial aquifer is generally to the west, toward the St. Johns River. There appears to be a northwesterly component to the ground water flow direction, which may be due to interaction with the canal situated just west of the Sages Site. Hydraulic conductivity has been measured in slug tests at about 20 ft per day in the upper portion of the surficial aquifer and about 10 ft per day in the lower portion. Electromagnetic borehole flowmeter survey results indicate that (1) the aquifer is “relatively conductive” down to about 26 ft bgs and permeability is lower below that depth and (2) there is a two order of magnitude difference in the vertical distribution of horizontal hydraulic conductivity over 6 in to 2 ft intervals (Acree 2000). The seepage velocity in the upper portion of the aquifer has been calculated to be about 62 ft per year. The horizontal hydraulic gradient is 0.0025 ft/ft in the upper portion of the aquifer. There appears to be a downward vertical gradient at MW515, which is screened between 132 ft bgs and 152 ft bgs. Water is encountered at about 6 ft deeper in this well (14 ft bgs to 17 ft bgs) than in surrounding wells.

Contamination

Source Zone. The area of the Sages Site where it is suspected that PCE has historically been released is a former floor-drain sump that was in direct contact with the subsurface (Jawitz et al 2000). The source zone was characterized twice, before and after the cosolvent flush phase of the treatment train. The methods used to characterize the source zone include extraction of soil cores for examination and analysis, analysis of ground water samples, partitioning interwell tracer tests (PITT), and direct push cone penetrometer.

Using these methods, a PCE DNAPL source zone has been delineated as an area about 24 ft long and about 9 ft wide (Sillan 1999, Jawitz et al. 2000). Analyses of soil samples collected from cores indicate that, at the time the cores were collected, PCE DNAPL was distributed within the source zone in 2 to 3 in thick layers at “relatively high saturation” between 25 and 32 ft bgs (Sillan 1999). The concentration of PCE in soil collected from the interval 25 to 32 ft bgs, which is just above the clay layer identified between 33 ft bgs and 37 ft bgs, ranged from about 3,000 µg/g to greater than 90,000 µg/g.

Groundwater. Volatile organic compounds (VOCs) have been detected in ground water beneath Sages Site, possibly extending off site to below the canal. Ground water sampling results for samples collected on the opposite side of the canal indicated that, as of December 1997, the plume did not extend past the canal (Levine•Fricke•Recon 1997a). However, more recent data indicates that the plume has migrated past the canal (Sillan 2002). VOCs detected at the Sages Site include PCE and its degradation products TCE, cis-1,2-DCE, trans-1,2-dichloroethylene (trans-1,2-DCE), and vinyl chloride. Ground water concentrations of PCE as high as 195,000 µg/L, which is in the range of solubility for PCE (150 mg/L CRC, 200 mg/L Pankow and Cherry 1996) have been detected as deep as 29 ft bgs; 100,000 µg/L at 28 ft bgs to 33 ft bgs; and 81,000 µg/L at 44 ft bgs. Using the rule-of-thumb that an aqueous concentration 1% to 10% of effective solubility may indicate the presence DNAPL, these PCE ground water concentrations suggest the presence of PCE DNAPL as deep as 44 ft bgs. The maximum concentrations of the PCE degradation products are: TCE at 28,000 µg/L in multi-level samplers (MLS), 16,000 µg/L in monitoring wells, and 34,200 µg/L in recovery wells, and cis-1,2-DCE at 8,400 µg/L in MLS, 42,000 µg/L in monitoring wells, and 52,000 µg/L in recovery wells. Some trans-1,2-DCE has been detected in monitoring and recovery wells and drive points, and it has been detected in every injection well. Very little vinyl chloride has been detected; however, the detection limits for vinyl chloride are routinely very high between 100 to 1,000 µg/L. Although Mravik (2003) indicates that ethene has been detected at the Sages Site, there is no data for ethene in the available documents.

6.3 TECHNOLOGY DESCRIPTION AND OPERATION

The objective of the SERB treatment train technology is to achieve “complete site restoration” (Mravik et al. 2003). It is a dual-phase method intended to remove most of the PCE DNAPL mass and to degrade the remaining PCE to harmless compounds (Mravik 2003). The purpose of the first phase, cosolvent flushing, is to remove DNAPL mass. The purpose of the second phase, passive enhanced *in situ* bioremediation, is to take advantage of the presence in the subsurface of a cosolvent that can be a biologically available electron donor for indigenous microorganisms. This cosolvent/electron donor would, theoretically, facilitate reductive dechlorination of the DNAPL mass remaining at the source and down gradient post flush.

Pre-Cosolvent Flush Activities

Preparation for implementing the SERB treatment train included the following (Sillan 1999):

- Estimating the location and extent of PCE DNAPL in the subsurface using soil coring, cone penetrometer with resistivity module, and direct push laser induced fluorescence (LIF)
 - Elliptical distribution about 24 ft long and about 9 ft wide
 - Vertical distribution to a maximum depth of between 26 and 31 ft bgs (in the vicinity of the former sump)
- Modeling to support the well network design (LFR Levine•Fricke 1998)
 - Three 4” diameter PVC injection wells located along the midline of the estimated PCE DNAPL extent and screened between 25 and 32.5 ft bgs (IW-001 through IW-003)
 - Six 4” diameter PVC recovery wells located along the perimeter of the estimated PCE DNAPL extent and screened between 26 and 31 ft bgs (RW-002 through RW-007)
 - Seven multi-level samplers (MLS-1 through MLS-7) located within the estimated PCE DNAPL extent between injection and recovery wells
 - Ten 2” diameter PVC monitoring wells (one located up-gradient, one located to the east, one located to the west, and seven located down-gradient of the estimated PCE DNAPL extent) with nine monitoring wells screened between 26 and 31 ft bgs and one screened between 45 and 50 ft bgs
- Well network installation from June 24 through July 1, 1998 for injection, recovery, and monitoring wells and from July 10 through July 13, 1998 for the multi-level samplers (LFR Levine•Fricke 1998)
- Collection of soil cores to determine subsurface concentrations of PCE
 - PCE DNAPL present in very thin (2 to 3 in), “discontinuous layers at relatively high saturations” (12 to 35% for high concentration layers)
- Partitioning interwell tracer test (PITT) and interfacial tracer test to estimate volume of PCE DNAPL in the source zone
 - Volume estimated from estimated PCE DNAPL extent covered by injection wells, recovery wells, and multi-level samplers is 69 L (Sillan 1999) and 44.4 L (LFR•Levine Fricke 1998).

Cosolvent Flushing Pilot Test

The cosolvent flushing pilot test (CFPT) occurred in 1998, between August 9 and August 15, with completion of post-test tasks on September 10. This CFPT has been described as the “first field-scale demonstration of in-situ alcohol flushing for enhanced remediation of a DNAPL source zone” (Jawitz et al 2000).

Prior to cosolvent flushing of the area of estimated PCE DNAPL extent, the cosolvent flush solution was injected below the PCE DNAPL zone to establish a vertical hydraulic barrier to downward migration of PCE DNAPL during the flush and to provide a mechanism for enhancing the solubility of the PCE DNAPL and recovery of any PCE mass that might have been mobilized downward. During cosolvent flushing, the packer height was first at about 1 ft above the well screen bottom, then the packer height was raised incrementally at about 6 in per hour to a maximum height of about 5.5 ft at IW-001 and IW-002 and about 3 ft at IW-003. At the 70 hour period of cosolvent flushing, the packer was lowered back to the original height about 1 ft above the bottom of the well screen. After 84 hours of cosolvent flushing a water flood of the entire well-screen interval was implemented to drive the cosolvent solution into the bottom of the estimated PCE DNAPL extent.

The injected cosolvent flush solution consisted of 34,000 L of 95% ethanol (EtOH) and 5% water, with a ramped increase in EtOH concentration from 0 to 95% over a 10 hour period (Sillan 1999). The total cosolvent flush solution was estimated by LFR•Levine Fricke (1998) at 9,000 L. In addition to the uncertainty of the total volume of cosolvent flush solution injected (34,000 L or 9,000 L), there is an uncertainty regarding the flow rate for the flush solution. According to the *Field-Scale Evaluation of In Situ Cosolvent Flushing for Enhanced Aquifer Remediation* (Sillan 1999), the combined EtOH and water injection flow rate was 1.1 gpm at IW-001, 1.8 gpm at IW-002, and 1.8 gpm at IW-003 for a total combined injection flow rate of 4.7 gpm. The injection flow rates cited in the *Cosolvent Flushing Pilot Test Report, Former Sages Dry Cleaner* (LFR Levine•Fricke 1998) are 0.8 gpm at IW-001, 1.4 gpm at IW-002, and 0.8 gpm at IW-003, for a total of 3.0 gpm. There is also an internal discrepancy regarding total injection flow rates in LFR Levine•Fricke (1998); although the total of the injection flow rates cited for individual injection wells is 3.0 gpm, the report states that the total injection flow rate was “...4 gallons per minute...” Recovery well pumping rates are also different between Sillan (1999), at a total extraction rate of about 30 gpm, and LFR Levine•Fricke (1998), at a total extraction rate of 8 gpm. After 8 days of cosolvent flushing, nearly all (92%) of the EtOH had been recovered.

The total volume of PCE DNAPL extracted from the area of the estimated PCE DNAPL extent swept by the recovery wells during the CFPT is cited as 41.5 L (LFR Levine•Fricke 1998) and as 42.02 L (Sillan 1999). Using soil cores, Sillan (1999) estimated the volume of PCE DNAPL in that area between 15 and 40 L. The PITT estimate of PCE DNAPL in that area was cited as 44.4 L by LFR Levine•Fricke (1998) and as 69.1 L by Sillan (1999). The following table summarizes PCE DNAPL recovery as presented by Sillan (1999) and Levine•Fricke (1998).

WELL	LFR LEVINE FRICKE 1998			SILLAN 1999		
	PITT- PRE	COSOLVENT	PITT-POST	PITT-PRE	COSOLVENT	PITT-POST
	PCE DNAPL PRESENT (L)	PCE DNAPL RECOVERED (L)	PCE DNAPL PRESENT (L)	PCE DNAPL PRESENT (L)	PCE DNAPL RECOVERED (L)	PCE DNAPL PRESENT (L)
RW-2	3.2		1.5	4.9	1	2.8
RW-3	11.6		2.2	18.1	10.6	4.1
RW-4	4.6		2.6	7.1	3.7	4.9
RW-5	4.1		1.9	6.4	0.02	3.6
RW-6	7.2		2.5	11.3	12.2	4.6

RW-7	13.7		3.2	21.3	14.5	5.9
Total	44.4	41.5	13.9	69.1	42.02	25.9
Cosolvent Injection Volume (L)		9,000			34,000	

Wastewater from the CFPT was treated using the Akzo Nobel Macro Porous Polymer Extraction System (MPPE) with a published removal efficiency of 99.9999%. PCE is removed from the MPP by steam stripping, condensed, and separated into the pure phase. The volume of PCE recovered from the MPPE system at the Sages Site was between 30 L and 40 L (Sillan 1999). The MPPE system was the primary treatment technology for wastewater generated during the CFPT, and an air-stripping tower was used as a secondary, polishing wastewater treatment technology. The volume of wastewater that was generated by the cosolvent flushing pilot study and the post-study tracer test and treated by the MPPE system was about 160,000 gal (LFR Levine•Fricke 1998, Sillan 1999).

Post-Cosolvent Flush Activities

Post cosolvent flush activities designed to estimate the amount of PCE DNAPL remaining after the flush through the area of the estimated PCE DNAPL extent, included additional soil coring and a post-flush PITT. The results from the soil cores indicate that about 14 L of PCE DNAPL remained post-flush in stringers over the initial depth distribution between 24 and 31 ft bgs. These results also indicated that at about 33 ft bgs, a depth not previously sampled, a PCE concentration in soil of 15,000 µg/g indicated the presence of PCE DNAPL at that depth. The results from the PITT indicated that about 26 L remained. Based on the results from the soil cores and the PITT, removal effectiveness was calculated to be between 61% and 63%.

Passive, Enhanced in situ Bioremediation

The purpose of the second phase of the SERB treatment train technology, passive enhanced *in situ* bioremediation, is to stimulate the indigenous microorganisms to completely degrade PCE to ethane in a source zone, as well as down gradient in a plume. This, theoretically, would be accomplished by supplementing the microorganisms with an electron donor. In this case, the electron donor is the EtOH that remains in the subsurface after the cosolvent flush.

No information has been provided regarding the date at which the passive, enhanced in situ bioremediation phase began. However, this phase appears to have begun concurrently with or soon after the cosolvent flushing pilot program, lasting nearly four years afterward (Mravik 2003). The concentrations of PCE and its degradation products — TCE, cis-1,2-DCE, trans-1,2-DCE, vinyl chloride, and ethene — were measured for at least 42 months after completion of the cosolvent flushing pilot test. Although other parameters, such as sulfate, chloride, acetate, methane, and hydrogen gas, were quantified and evaluated, it is the concentrations of PCE degradation products over time that are the primary indicators of the occurrence of reductive dechlorination.

Microcosm studies were conducted to determine whether native microorganisms capable of mediating the reductive dechlorination of PCE were present at the Sages Site. Native aquifer material from the Sages Site used in this microcosm study was collected prior to the cosolvent flush. The results of the microcosm study showed that the microorganism necessary to mediate degradation of PCE — *Dehalococcoides ethenogenes* — was present in aquifer materials at the Sages Site, and it was able to completely degrade PCE in the laboratory.

The analytical results through mid-2002 for ground water samples from monitoring wells that were collected for this phase of the SERB treatment train indicate that degradation of PCE is occurring at the Sages Site. The degradation however, may be only partial and stalling, with cis-1,2-DCE accumulating. Mravik (2003) indicates that ethene has been detected in ground water since six months post-flush, but

that data has not been provided for examination. These results are discussed in greater detail below, in the Performance Assessment section.

6.3.1 PERFORMANCE ASSESSMENT

Cosolvent Flushing

There is disagreement between Sillan (1999) and LFR•Levine Fricke (1998) regarding the cosolvent solution injection rate, volume of cosolvent solution injected, the volume of PCE DNAPL estimated by the pre-flush tracer tests, and the volume of PCE DNAPL estimated by the post-flush tracer test. These discrepancies create uncertainties that prevent, at this time, a full evaluation of the effectiveness of the cosolvent flushing phase of the SERB technology and the quantification of the amount of PCE DNAPL removed from the subsurface. However, certain observations can be made:

- A comparison between the results of (1) the pre-flush and post-flush tracer tests and (2) the pre-flush tracer tests and the cosolvent flushing indicate that some quantity of PCE DNAPL appears to have been removed from the subsurface.
- The results from the post-flush soil coring and tracer test indicated that a significant quantity of PCE DNAPL remained in the subsurface over the same depths at which PCE DNAPL was originally estimated.
- There was no appreciable change in the PCE ground water concentration in the estimated source zone extent after the cosolvent flush.
- The post-flush soil coring went to a greater depth, about 33 ft bgs, than in the pre-flush coring. Results from the soil sample analysis showed that the concentration of PCE at that depth, which was about 15,000 µg/g, indicated the presence of PCE DNAPL at a depth greater than the originally estimated PCE DNAPL vertical extent. This PCE DNAPL may have been present prior to cosolvent flushing. An alternative is that it may have been mobilized from above during the flush, which might be an indication that the vertical hydraulic barrier was breached.
- The results from analyses of soil samples collected from cores indicate that the PCE DNAPL distribution is in thin, discontinuous stringers about 2 to 3 in thick between 25 and 32 ft bgs.
- In order to reach the thin, discontinuous stringers of DNAPL, a large volume of the aquifer needs to be flushed to get to these very thin layers, which requires a large volume of cosolvent. This not only increases costs, but it also increases dilution in the recovery wells (Sillan 1999).
- The recovery well and multi-level sampler (MLS) data showed that (1) the recovery well data is flux-averaged and may underestimate ground water concentrations of PCE and (2) the MLS data is a point measurement where dilution from significant volumes of injection fluid may be less likely. Data from the MLS could provide a better estimate of PCE DNAPL volume.
- The SERB technology, as implemented at this site, did not target residual PCE DNAPL at depths above or below the estimated primary zone of DNAPL. Any remaining PCE DNAPL mass would continue to be a source of contamination, and, as a result, source removal objectives would likely not be met.

Passive, Enhanced in situ Biodegradation

Ground water quality data for PCE, PCE degradation products, and EtOH has been summarized from 1997 through mid-2002 for ground water samples collected from injection, recovery wells, and monitoring wells. Observations from these data include:

- Over time the extent of EtOH was reduced and EtOH concentrations in ground water decreased in the source zone.
- Within two months to two years after the cosolvent flush, EtOH arrived at down-gradient monitoring wells and the EtOH concentrations increased over time at those locations.
- Soon after the cosolvent flush, EtOH appeared in MW505, the monitoring well directly north of the estimated PCE DNAPL extent. Ground water flow to this well would be perpendicular to the known westerly flow direction. If this data is real, it appears that the presence of EtOH in this well is due to a breach of hydraulic containment during the cosolvent flush.
- Reduction of the concentration of PCE in the estimated source zone extent did not occur until about one year post-flush, and the reduction is due not to mass removal during the flush, but to reductive dechlorination.
- For wells where EtOH is present, degradation of PCE to TCE and c-1,2-DCE appears to be occurring significantly, with very high concentrations (up to about 50,000 µg/L) of cis-1,2-DCE being generated. It is unclear whether degradation to vinyl chloride is occurring because detection limits for most of these analyses were very high (250 to 1,000 µg/L). It is unclear whether vinyl chloride is degrading to ethene because no ground water quality data for ethene analyses have been provided.

6.3.2 ECONOMIC ANALYSIS

The total cost for the cosolvent flushing pilot test was approximately \$440,000. The design (\$46,000 or 10% of total cost) and construction costs (\$159,700 or 36% of the total cost) were lowest, and the operation costs were the highest (\$234,200 or 53% of the total cost). Reductions in cost could be achieved by making the following adjustments in implementation of the technology (Sillan 1999):

- After an initial high capital cost, reduce the future site-by-site construction cost by 20% by using a trailer-mounted injection and extraction system.
- Recycle EtOH through the MPPE system to reduce costs of waste stream disposal. Initial capital costs would be high, but use on a site-by-site basis could reduce future costs
- Improve well system design and optimize injection and recovery strategy to reduce wastewater volume for disposal and amount of EtOH required.
- Modify the sampling protocol from one focused on research to one focused on a more typical site characterization.
- Lessons learned from the design phase can be applied to future projects, conceivably reducing design costs by 50%.

In addition Sillan 1999 suggests the potential use of 2-in diameter injection wells rather than 4-in diameter injection wells to reduce costs by about 20% due to lower materials and soil disposal costs (smaller cores produce less soil for disposal). However, the use of smaller injection wells could lead to a reduction in performance due to the smaller screened area for injection.

Eliminating the tracer test could reduce costs by \$150,000 and implementing the cost reductions described above, which could reduce costs by another \$150,000, could result in the following costs for future projects (Sillan 1999):

- \$1,200 to \$1,500 per ton for 75 to 125 tons of soil

- \$900 to \$1,250 per ton for 150 to 200 tons of soil
- \$800 to \$1,000 per ton for 250 to 350 tons of soil

No information was provided for the cost of the passive, enhanced *in situ* bioremediation phase of the SERB treatment train technology.

6.4 EVALUATION OF SERB TREATMENT TRAIN TECHNOLOGY

The purpose of this study at the Sages Site was to accomplish the following objectives:

- Evaluate the feasibility and effectiveness of cosolvent flushing remedial technology at the Site for other FDEP Drycleaning Solvent Cleanup Program (DSCP) sites.
- Remove PCE DNAPL from the subsurface.
- Completely dechlorinate PCE by supplementing indigenous microorganisms with an electron donor, in this case EtOH, for a passive enhancement of reductive dechlorination.

6.4.1 PROJECT SUCCESS RELATIVE TO PROJECT GOALS

The metrics for success in meeting the goals of the SERB Treatment Train are (1) significant reduction of PCE DNAPL mass in the source zone and in the plume and (2) complete reductive dechlorination of PCE to harmless daughter products. It appears that the metrics for success are being partially met. While quantification of the amount of mass that can be removed from the source zone is not possible at this time, this study indicates that at least some mass removal can be attributed to cosolvent flushing. The lack of data for vinyl chloride and ethene limits an assessment of whether complete dechlorination is occurring at the Sages Site; however, PCE appears to be at least partially degrading at this site.

The ground water concentration of PCE in the estimated source zone extent after the cosolvent flush essentially did not change from pre-flush values. A reduction in PCE concentration in the source zone did not significantly change until about one year post flush. This reduction in concentration was not due to the mass removal phase of the project, but to the microbially-facilitated reductive dechlorination in the passive, enhanced bioremediation phase. The concentration of PCE in the estimated source zone extent is still very high (26,000 µg/L), at a level that indicates that PCE DNAPL remains in the subsurface. The Sages Site research team believes that "...the PCE plume response resulting from the co-solvent flood will require years or decades for realization..." (USEPA 2003).

6.4.2 PROJECT/TECHNOLOGY SUCCESS WITHIN A FINANCIAL AND REGULATORY FRAMEWORK AND CONSIDERATIONS FOR APPLYING THE TECHNOLOGY AT ANOTHER SITE

The reviewed data suggest that implementation of the SERB treatment technology at the Sages Site was successful at removing a significant amount of the estimated contaminant mass through the cosolvent flush and that some reduction in PCE mass was achieved through reductive dechlorination. However, the SERB treatment technology has not yet been shown to be an effective technology for successful aquifer restoration at the Sages Site. It appears that the remedy will need to operate for several more years or longer to achieve restoration. As such, it is difficult to determine the effectiveness of the technology at this point. Items that were either not addressed or had significant uncertainty in the reviewed documents are as follows:

- Actual cosolvent solution injection flow rates and volumes used for cosolvent flush
- Volume of PCE DNAPL prior to the test, after the test, and removed by the test

- The presence of ethene from the degradation of vinyl chloride to determine whether complete dechlorination of PCE is occurring
- Distribution of DNAPL in the subsurface as indicated by recovery well (The multi-level samplers may provide better data with regard to delineating DNAPL distribution.)

Effective implementation of the SERB treatment technology is highly dependent on subsurface conditions. On a site-by-site basis, subsurface conditions can be highly variable, including factors such as the presence of indigenous microbial populations capable of degrading the target contaminant and a sufficiently permeable subsurface to allow for remedial fluid dispersal and recovery. Therefore, it is advisable to evaluate the use of the SERB treatment technology on a site-by-site basis to determine whether it is an effective choice for other sites.

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7.0 CONCLUSIONS

7.1 SUMMARY OF PROJECT RESULTS

Most of the technologies were successful at removing substantial contaminant mass from the subsurface. The results for each of the projects and technologies tested are summarized in the following table. As reflected in the footnotes to the table, several of the reported values are subject to uncertainty.

PROJECT/TECHNOLOGY	CONTAMINATION PRESENT BEFORE DEMONSTRATION (MASS OR VOLUME)	CONTAMINATION REMOVED FROM TARGET AREA (MASS OR VOLUME)	PERCENTAGE OF MASS RECOVERY (%)	PROJECT COST
Launch Complex 34 - units	kg	kg		
Resistive heating	11,313	1,101 ¹	90% ¹	\$612,742 ²
Steam injection/extraction	10,435	1,546 ¹	85% ¹	\$1,256,275 ²
Dover National Test Site - units	L	L		
Cosolvent flushing	~83 ³	~53 ³	64% ³	N/A
AS/SVE	~64 ³	~57 ³	90% ³	N/A
SEAR	~70 ³	~45 ³	65% ³	N/A
Cosolvent mobilization	~57 ³	~44 ³	78% ³	N/A
Complex sugar flushing	~70 ³	~33 ³	48% ³	N/A
Operable Unit 2, - units	gal	gal		
Hill Air Force Base	~800 ⁴	~1,500	99% ⁵	\$1.4 million ⁶
Loring Air Force Base - units	kg	kg		
Steam enhanced remediation	unknown	~7	negligible	\$1.5 million
Sages Dry Cleaner - units	L	L		
Cosolvent flushing	44 - 69 ⁷	~40	58 - 91% ⁷	\$440,000

¹ Mass removed from target area may reflect mass that migrated from the target area during application. For the resistive heating application, only 19% of the mass removed could be accounted for in the vapor recovery system.

² Costs reflect the cost of the technology only (i.e., excludes cost of additional characterization and assessment).

³ Values reflect averages or middle of range reported by project team (calculated from liters using 1.6 g/mL for density of PCE)

⁴ Contamination from all three SEAR applications in Panels 1 and 5. Contamination present was determined by PITTs, which were later determined to be inaccurate based on the amount of mass removed.

⁵ Mass recovery percentage is based on estimated mass remaining in aquifer based on limited soil sampling. Actual mass recovery percentage may be much lower.

⁶ Cost reflects total cost of studies, application, and assessments, but does not include substantial savings that resulted from using existing infrastructure.

⁷ Contaminant volume estimates before and after cosolvent flushing are subject to uncertainty.

7.2 COMMON LESSONS LEARNED

Specific lessons learned from each of the projects are included at the end of the Sections 2 through 6 of this report. Common lessons learned from the projects are as follows:

- All of the DNAPL technologies discussed have the potential to remove substantial mass from the subsurface, including several demonstrations that report approximately 90% or more mass recovery. In all cases, however, DNAPL remained in the subsurface (albeit in much reduced quantities) and soil and dissolved concentrations were sufficiently high to merit additional active remediation. Site teams may consider the likelihood that substantial contamination will remain in the subsurface after application of one of these technologies at another site.

- Technology performance was heavily dependent on site-specific planning and on site-specific setting. For example, the SEAR application at Panels 1 and 5 in Operable Unit 2 at Hill Air Force Base entailed substantial planning, including laboratory analysis, field studies, and numerical modeling. In addition, target areas were relatively permeable with hydraulic conductivities exceeding 100 ft per day. Contaminant mass removal from this demonstration was successful (although an unknown amount of contaminant mass remains in the subsurface). Contrastingly, the steam injection/extraction demonstration at Loring Air Force Base was conducted in a fractured bedrock environment that the site team knew had very limited porosity. The contaminant mass removal from this technology was limited.
- Hydrogeological parameters appear to have played a large role in technology performance. The following table summarizes the site-specific hydrogeological factors that appear to have substantially impacted the performance of each technology. Application of these technologies at other sites under different hydrogeologic conditions, such as a higher or lower hydraulic conductivity, may significantly alter the performance of these technologies.

TEST SITE AND TECHNOLOGY(IES)	HYDROGEOLOGICAL FACTORS THAT INFLUENCED TEST PERFORMANCE
Launch Complex 34, Cape Canaveral, Florida <ul style="list-style-type: none"> • Resistive heating • Steam injection/extraction 	<ul style="list-style-type: none"> • The relatively permeable Upper Sand unit likely facilitated recovery of contaminant vapors. • The relatively shallow test area (40 ft of saturated thickness) likely assisted with heating the vertical interval from the bottom of the test cell to the vapor recovery system.
Dover National Test Site, Dover Air Force Base <ul style="list-style-type: none"> • Cosolvent flushing • AS/SVE • SEAR • Cosolvent mobilization • Complex sugar flushing 	<ul style="list-style-type: none"> • The hydraulically isolated test cells likely facilitated technology implementation and allowed for recirculation of remedial fluids. • The relatively permeable formation with a hydraulic conductivity of 8 ft per day to 34 ft per day likely improved dispersal of the injected remedial fluids and DNAPL recovery. • The absence of a confining layer enabled vapor recovery for the AS/SVE test.
Operable Unit 2, Hill Air Force Base <ul style="list-style-type: none"> • SEAR 	<ul style="list-style-type: none"> • The high permeability of the formation with a hydraulic conductivity over 100 ft per day likely improved dispersal of the injected remedial fluids and recovery of DNAPL. • The clay formation surrounding the paleochannel, where the technology was tested, likely helped contain DNAPL and the injected remedial fluids.
Quarry Site, Loring Air Force Base <ul style="list-style-type: none"> • Steam enhanced remediation 	<ul style="list-style-type: none"> • The low primary and secondary porosity of the fractured rock formation (on the order of 3% and 1%, respectively) significantly reduced the delivery of steam (heat) to the subsurface and had a significant negative affect on technology performance.
Sages Dry Cleaner <ul style="list-style-type: none"> • Cosolvent flushing • Passive, enhanced bioremediation 	<ul style="list-style-type: none"> • DNAPL in thin “stringers” complicated DNAPL removal. • The relatively permeable formation (10 ft per day to 20 ft per day) likely improved dispersal of the injected remedial fluids.

- Because none of the demonstrations had results that eliminated the need for further active remediation, it would be difficult to determine the financial benefit of these technology applications had they been conducted for the purpose of reducing life-cycle remediation costs.
- In addition to an uncertain amount of additional active remediation required, other factors also contribute to complicating the application of the financial information from these demonstrations to other sites. For example, the SEAR application at Operable Unit 2 at Hill Air Force utilized existing infrastructure that would generally not be available at other sites considering use of this technology. Also, the tests conducted at the Dover National Test Site benefited from recycling

treated water with elevated PCE concentrations because the test cells were hydraulically isolated from the surrounding aquifer. Recycling this water at another site would likely either require additional treatment than that used during the demonstration or additional cost for isolating the target area to be treated. Data suggests that the resistive heating application at Launch Complex 34 released substantial TCE vapor to the atmosphere and that TCE may have migrated from the test plot in the subsurface. A more comprehensive ground water and vapor recovery system that would have limited this contaminant release would likely have added substantially to the costs provided.

- Several of the technology demonstrations may have had negative impacts on the environment or on future remedial activities. For example, the resistive heating application at Launch Complex 34 resulted in unwanted contaminant migration (to the atmosphere and within the subsurface). Four of the five technologies implemented at the Dover National Test Site left residual reagents in the aquifer (e.g., surfactants or cosolvents) that may complicate future ground water treatment by air stripping or granular activated carbon. The SEAR application at Hill Air Force base resulted in the production of MIBK, in the test area, potentially creating a new environmental hazard. In addition, the application has increased annual operations and maintenance costs for the ongoing treatment system by \$20,000 to \$50,000 per year.

7.3 LESSONS LEARNED FOR FUTURE DEMONSTRATION PROJECTS

The DNAPL removal demonstration projects described in this report and in other documents have proven the ability of the technologies to remove substantial contaminant mass in many cases. Therefore, there is questionable value in additional demonstrations of the same technologies with the sole purpose of quantifying mass removal. There is substantial value, however, to conducting demonstrations of these technologies to provide more comprehensive information regarding the ability of the technologies to reduce life-cycle costs or reduce the time to closure within a reasonable time frame (e.g., 30 years). For this reason, the remediation community would benefit from considering the following:

- Project demonstrations could develop and attempt to achieve more refined remedial objectives than to remove contaminant mass. Such demonstrations would more closely mimic the conditions that most remedial site managers face. To accomplish this, future demonstration project managers might consider working with the site regulator to determine a set of achievable site conditions that would eliminate the need for further active remediation. Similarly, project managers and engineers could determine a set of achievable site conditions that would substantially reduce operations and maintenance costs for future remedial efforts. The demonstration projects could then continue until the identified sets of conditions have either been met or until an unacceptable amount of money has been spent and an acceptable (and potentially lower-cost) long-term remedy has been put in place. It is recognized that these demonstrations would likely occur over several years, potentially with multiple applications of mass removal technologies and/or actual implementation of subsequent source control measures.
- Involving site regulators in demonstration projects can also be helpful in that the site regulators can help the project team determine the measures that would need to be taken to prevent unintentional spreading or release of contamination or to address the results of unintentional spreading or release of contamination.
- Project demonstrations could be conducted in the types of settings and with the type of infrastructure that would be found at the typical site. For example, further demonstrations in hydraulically isolated test cells have reduced value (unless the isolation is a component of the technology being tested) because the cell isolation affords the demonstration team advantages that are not generally available at other sites. Similarly, the use of existing infrastructure such as an existing pump and treat system or wastewater treatment plant may be an advantage that is not

necessarily available at other sites. It is recognized that using this infrastructure allows the demonstration to be conducted for a more reasonable price; therefore, if such infrastructure is used, it may be appropriate to provide realistic cost estimates for providing that infrastructure or a similar level of treatment at another site.



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