FINAL REPORT

Cost and Performance Analysis for Thermal Enhancements at Selected Sites

Prepared for

U.S. AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE

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COST AND PERFORMANCE ANALYSIS FOR THERMAL ENHANCEMENTS AT SELECTED SITES

For

U.S. AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE

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EXECUTIVE SUMMARY

The Air Force Center for Environmental Excellence (AFCEE) contracted with Parsons Infrastructure and Technology Group, Inc. (Parsons) to conduct an evaluation of commercially available thermal enhancement technologies for the remediation of source areas including non-aqueous phase liquids (NAPLs). The intention of this project was to develop a *Cost and Performance Analysis for Thermal Enhancements at Selected Sites* report for AFCEE Remedial Project Managers (RPMs) which identifies positive and negative aspects of thermal technologies and provides guidelines for the appropriate use of thermal technologies. This Report may be used by Air Force RPMs as a tool for aiding the selection process of source remediation technologies.

The first part of the evaluation consisted of accessing environmental databases to identify thermally enhanced source remediation projects in the US. Twenty-seven such projects were identified through the database search. After the projects were identified, an initial web-based questionnaire, requesting general information about each site, was e-mailed by AFCEE to each of the 27 government or consultant Points of Contact (POCs) for each project. Twenty-one of the POCs completed the questionnaires and returned them to AFCEE. Evaluation of the 21 returned questionnaires led to the following conclusions:

- Only one respondent indicated that thermal enhancement was a failure. The other 20 respondents indicated their thermal projects were successful or somewhat successful.
- Of the 20 respondents that felt their projects were successful or somewhat successful (the favorable respondents), four indicated that thermal enhancement had definitely decreased the overall remedial costs; eight stated it had probably decreased overall costs; three indicated that thermal enhancement had definitely increased the overall remedial costs; three responded that the cost impact was

unknown; and two indicated thermal enhancement made no impact to overall costs.

- Of the 20 favorable respondents that felt thermal enhancement was successful or somewhat successful, only 14 of these stated they would use the same technology again.
- Six of the 20 favorable respondents indicated that, knowing the results, they would not use the same thermal technology, and four of these six indicated that, knowing the results, they would have chosen a non-thermal technology.
- Eight of the 20 favorable respondents indicated that, knowing the results, they would have chosen a non-thermal technology.
- Thermal enhancement was selected in decision documents at only 11 of the sites, seven were interim actions, and 16 projects were chosen as technology demonstrations.
- Regulatory encouragement was a factor in the selection of thermal enhancement at 10 of the sites, and vendor marketing was a factor at only five sites.
- Based on the initial questionnaires and from telephone contacts with 17 of the POCs, it is apparent that facility personnel played a substantial role in the selection of thermal enhancement at their respective sites.

Parsons evaluated the 21 questionnaires to reduce the number of sites for further examination from 21 to 11, with the intention of completing more detailed questionnaires and telephone interviews. Only 17 of the 21 responding POCs agreed to provide further support to AFCEE, and six of those 17 would not or could not respond to later requests to complete the more detailed questionnaires and telephone interviews. The 11 remaining projects were selected for more detailed evaluations and telephone interviews.

A second and more detailed questionnaire was e-mailed to each of the remaining 11 POCs requesting site-specific information regarding their project, including their general assessment of the success or failure of their thermal enhancement project. Each POC was interviewed by telephone and, based on the interviews, it became apparent that success of a project did not relate directly to site closure or attainment of predetermined cleanup objectives. In most cases, success meant mass removal was achieved or enhanced as compared to earlier remedial efforts. In some cases, success simply meant that thermal enhancement appeared to be less expensive than long-term groundwater extraction and treatment.

Parsons used the information from the telephone interviews and responses to the second questionnaire provided by the 11 site POCs to identify four sites for detailed evaluation and generation of life cycle cost analyses. The information gathered was summarized into six basic questions:

1) How successful was the project according to the POC?
2) Why was the project considered successful according to the POC?
3) Did the regulators agree that the project was successful?
4) What was the POC's impression of the cost impact?
5) Based on Parsons' evaluation, were the site characteristics favorable to another treatment technology?
6) Based on Parsons' evaluation, did thermal enhancement positively impact overall remedial costs?

Based on the answers to these six questions, Parsons selected the following four sites for detailed evaluations:

- Niagara Falls Air Reserve Station (ARS) Installation Restoration Program (IRP) Site 10, a six phase soil heating project for remediation of trichloroethene (TCE) at a fire training area.
- Savannah River Site (SRS) 321-M, a steam injection project for remediation of TCE and tetrachloroethene (PCE) at a former storage tank.

- Yorktown Fuels Defense Fuel Supply Point (DFSP) Navy Special Fuel Oil (NSFO) Tank Farm, an indirect heating project that used steam recirculation to recover free-phase naval ship fuel oil at a tank farm.
- Fort Richardson Alaska Poleline Road Disposal Area (PRDA), a six phase soil heating project to remediate TCE and 1,1,2,2-PCAfrom a former chemical test kit disposal area.

Parsons visited each site and collected additional information related to the site characterization, thermally enhanced system performance and operation, project cost, and post-treatment analytical data for each site.

Based on the evaluations of the four sites chosen for this project, thermally enhanced source remediation was clearly an appropriate technology at only one site – Poleline Road Disposal Area, Fort Richardson, Alaska. This site was contaminated with recalcitrant compounds (PCE, TCE, and 1,1,2,2-tetrachloroethane) that had migrated to a depth of 38 feet below ground surface (bgs) and the areal extent of contamination was limited in size (two areas of less than one-third acre each). Additionally, pilot testing of air sparging and dual-phase extraction showed limited success, and off-gas treatment of extracted soil vapor was not required, thus reducing the overall remediation costs. Following completion of the Six Phase Soil Heating (SPSH) project, future remedial activities at the PRDA site are now limited to natural attenuation of groundwater. The life cycle cost analysis showed that, at the time frame of this remediation, SPSH was more cost effective than the other remedial technologies that were evaluated in the Corrective Measures Study (CMS).

The evaluations of the projects at Niagara Falls ARS IRP Site 10 and Yorktown Fuels NSFO Tank Farm showed that thermally enhanced source remediation approaches were less effective in terms of cost and removal efficiency than if soils at each site were excavated and treated/disposed.

Evaluation of the steam injection project at SRS 321-M site presents somewhat inconclusive findings. The steam injection project was effective in terms of mass recovery, in meeting soil cleanup objectives for the targeted area of soil, for removing contaminant mass from the clayey layers present at the site, and for temporarily reducing contaminant concentrations in groundwater below the site. However, soil vapor extraction (SVE) without thermal enhancement was also shown to effectively remove contaminant mass from the sandy soil regions and was less costly than the addition of steam to enhance contaminant recovery. The effectiveness of SVE on the clayey layers was not measured, but experience at other sites indicates its effectiveness is reduced in clayey soil, thus reducing its overall effectiveness in achieving remediation of the vadose zone. Remediation of groundwater at the 321-M site was not achieved. However, it should be noted that the plume under the 321-M site is contained within a larger plume and remediation of the plume under the 321-M site would have been only temporary as groundwater flow from the larger plume would have re-contaminated the groundwater under the 321-M site.

Based on the detailed evaluation of these four sites, is appears that while thermally enhanced source remediation has in many cases significantly enhanced the recovery of contaminant mass as compared to non-thermal technologies, implementation of thermal enhancement did not result in the complete closure of any of these four sites. Remediation of the soil unit at PRDA Fort Richardson, AK and of the overburden soil at Niagara Falls ARS Site 10, are considered complete, but additional active groundwater remediation measures are still required at the Niagara Falls site. Additionally, based on the life cycle cost analyses, with the exception of the PRDA site in Alaska and possibly the SRS 321-M site, implementation of thermally enhanced source remediation technologies had significantly higher costs than non-thermal technologies.

Based on all information gathered during this project, it can be concluded that implementation of thermal enhancement did not lead to complete site closure at any of the 21 facilities that were evaluated under this project. Thermally enhanced soil vapor extraction did lead to closure of the soil operable units at Air Force Plant 4, TX and at the PRDA, Fort Richardson, AK, and of the overburden soil at Niagara Falls ARS, NY.

Additionally, thermal enhancement did result in regulatory acceptance of monitored natural attenuation (MNA) at the PRDA site in Alaska, and may have assisted in acceptance of MNA at two additional sites (Edwards Air Force Base [AFB], CA, and Whittier DFSP, AK). However, at both the Edwards AFB site and at Whittier DFSP, MNA would likely have been accepted even in the absence of the thermal enhancement projects. At the two remaining sites at which closure of the soil units were obtained (Air Force Plant 4 and Niagara Falls ARS), active groundwater remediation activities are still required.

Ultimately, it appears that thermal enhancement was effective at achieving closure of the soil units at three of 21 sites, and resulted in regulatory acceptance of MNA, definitively, at only one of those three sites. This translates into closure of soil units at 14 percent of sites, obtaining MNA as the sole remedy at 5 percent of sites, and achieving complete site closure at 0 percent of sites. Although thermal enhancement intuitively seems like a logical approach, results of this study would indicate that Air Force RPMs should approach the technology cautiously, carefully evaluating all remedial alternatives prior to adopting this aggressive and costly technology.

FINAL REPORT
COST AND PERFORMANCE ANALYIS FOR
THERMAL ENHANCEMENTS AT SELECTED SITES

TABLE OF CONTENTS

TABLE OF CONTENTS (CONTINUED)

TABLE OF CONTENTS (CONTINUED)

APPENDICES

LIST OF TABLES

TABLE
NO. TITLE

LIST OF FIGURES

FIGURE
NO. TITLE

LIST OF ACRONYMS

µg/kg	micrograms per kilogram
µg/L	micrograms per liter
A-E	Architect-Engineer
AFB	Air Force Base
AFCEE	Air Force Center for Environmental Excellence
ARS	Air Reserve Station
Battelle	Battelle Science & Technology International
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
BTU	British Thermal Unit
°C	degrees Celsius
CAP	Corrective Action Plan
cfm	cubic foot per minute
cis-DCE	cis-1,2-dichloroethene
cm/sec	centimeters per second
CMS	Corrective Measure Study
COC	contaminant of concern
DAF	dissolved air floatation
DFSP	Defense Fuel Supply Point
DOD	Department of Defense
DOE	Department of Energy
DNAPL	dense non-aqueous phase liquid
DUS	Dynamic Underground Stripping
DWS	DNAPL-water separator
EAB	Enhanced Anaerobic Bioremediation
EPA	Environmental Protection Agency
ERS	Science and Engineering Division
ERT	Electrical Resistance Technology
ESTCP	Environmental Security Technology Certification Program
FRTR	Federal Remedial Technology Roundtable
°F	Fahrenheit
FS	Feasibility Study
ft/day	feet per day
gpm	gallons per minute

LIST OF ACRONYMS (CONTINUED)

HDPE	high-density polyethylene
hp	horse power
HPO	Hydrous Pyrolysis Oxidation
IRA	Interim Remedial Action
IRP	Installation Restoration Program
ITRC	Interstate Technology Regulatory Council
kW	kilowatt
kWH	kilowatt-hour
LNAPL	light non-aqueous phase liquid
LTM	long-term monitoring
MCL	Maximum Contaminant Level
mg/kg	milligrams per kilogram
mg/L	milligrams per liter
MNA	monitored natural attenuation
MVE	vapor extraction well
NAPL	non-aqueous phase liquid
NPDES	National Pollution Elimination Discharge System
NSFO	Navy Special Fuel Oil
NYS	New York State
NYSDEC	New York State Department of Environmental Conservation
O&M	operations and maintenance
Parsons	Parsons Infrastructure and Technology Group, Inc.
PCA	tetrachloroethane
PCE	tetrachloroethene
PID	photoionization detector
POC	Point of Contact
ppm	parts per million
PVC	polyvinyl chloride
PRDA	Poleline Road Disposal Area
psi	pounds per square inch
psig	pounds per square inch gauge
RBC	risk-based criteria
RCRA	Resource Conservation and Recovery Act
ROD	Record of Decision

LIST OF ACRONYMS (CONTINUED)

RPM	Remedial Project Manager
RW	recovery well
scfm	standard cubic feet per minute
SERDP	Strategic Environmental Research Development Program
SPSH	Six Phase Soil Heating
SRS	Savannah River Site
SSTA	Solvent Storage Tank Area
SVE	soil vapor extraction
SVEU	soil vapor extraction unit
SVOC	semi-volatile organic compound
T	trench
TCA	trichloroethane
TCE	trichloroethene
TPH	total petroleum hydrocarbon
US	United States
UST	underground storage tank
VOC	volatile organic compound

1.0 INTRODUCTION

1.1 PROJECT DESCRIPTION AND OBJECTIVES

The Air Force Center for Environmental Excellence (AFCEE) contracted with Parsons Infrastructure and Technology Group, Inc. (Parsons) to conduct an evaluation of commercially available thermal enhancement technologies for the remediation of source areas including non-aqueous phase liquids (NAPLs). Parsons identified 25 Federal (e.g., Department of Defense [DOD], Department of Energy [DOE]) thermal projects and two private sector projects, and gathered preliminary information from each site regarding the thermal technology used, effectiveness for source remediation, and project cost. Using this information, a subset of 11 sites was identified for further evaluation and interviews with the project's Points of Contact (POCs). The list of 11 sites was reduced to four for detailed evaluations and development of life cycle costs for comparison to estimated costs of alternative source remediation technologies. Parsons prepared this *Cost and Performance Analysis for Thermal Enhancements at Selected Sites* report which identifies positive and negative aspects of thermal technologies and provides guidelines for the appropriate use of thermal technologies. This Report may be used by AFCEE Remedial Project Managers (RPMs) as a tool for aiding the selection process of source remediation technologies. The scope of work for this project was described in the 5 June 2003 *Proposal for Architect-Engineering (A-E) Services Support To Evaluate Thermal Enhancement For The Cost-Effective Remediation of Non-Aqueous Phase Liquids (NAPLs)*, prepared by Parsons and submitted to AFCEE as Task Order Number 0021, of Contract No. F41624-03-D-8613.

The objectives identified to support completion of this project are as follows:

- Develop a database containing detailed information on thermally enhanced source remediation projects identified during internet searches.
- Identify four sites with sufficient available data to develop accurate life cycle costs.

- Prepare a report that presents the findings of the project reviews and compares life cycle costs of the four sites to the estimated costs of alternative remedial technologies.

1.2 PROJECT APPROACH

The technical approach for this project was described in the 5 June 2003 *Proposal for Architect-Engineering (A-E) Services Support To Evaluate Thermal Enhancement For The Cost-Effective Remediation of Non-Aqueous Phase Liquids (NAPLs)* (Parsons). The approach was broken down into four basic tasks:

Task 1 – Task order management, including program and project management cost for the project.

Task 2 – Initial site screening to identify potential sites from available internet databases, develop an initial questionnaire requesting information from each potential site, and develop a database to store information generated by the questionnaires.

Task 3 – Selection of 10 sites for further evaluation, including completion of a secondary and more detailed questionnaire and telephone interviews with each project's POC, followed by selection of four of these sites for thorough evaluations, site visits, and development of life cycle cost analyses.

Task 4 – Life cycle reporting including collection of information regarding the project and costs, visits to each site to interview the POCs, analyze the project designs, and audit their performance criteria, followed by development of life cycle costs and comparison to estimated cost of alternative remedial approaches, and preparation of a Cost and Performance Analysis for Thermal Enhancements at Selected Sites Report.

1.3 REPORT ORGANIZATION

This report is organized into seven sections and two appendices:

Section 1.0	Introduction
Section 2.0	Screening and Selection of Thermal Project Sites
Section 3.0	Description of Four Sites Selected for Life Cycle Cost Analysis
Section 4.0	Life-Cycle Cost Analyses of Four Selected Sites
Section 5.0	Pollutant Emissions From Power Generation During Thermal Enhancement Projects
Section 6.0	Summary and Conclusions
Section 7.0	References
Appendix A	Initial Questionnaire
Appendix B	Second Questionnaire and Interview Summaries with Thermal Project POCs

2.0 SCREENING AND SELECTION OF THERMAL PROJECT SITES

2.1 DATABASE REVIEW OF POTENTIAL THERMAL PROJECTS

Parsons began the identification and screening of potential sites in August 2003 by accessing several internet databases for information regarding thermal enhancement projects in the United States (US). The following databases were accessed:

- US Environmental Protection Agency (US EPA) Clu-In website (www.clu-in.org).
- Environmental Security Technology Certification Program (ESTCP) (www.estcp.org).
- Strategic Environmental Research Development Program (SERDP) (www.serdp.org).
- Federal Remedial Technology Roundtable (FRTR) (www.frtr.gov).

The searches concentrated on identification of thermal enhancement projects in the US that were designed for the remediation of petroleum and halogenated hydrocarbon source areas. Using these databases, 25 federal projects and two private sector projects were identified.

Parsons then contacted the POCs for each project as identified on the databases. Most of these POCs were vendor project managers. Parsons contacted the vendor POCs and requested they provide the name and contact information of the government POCs (for the 25 federal sites) or the consultant POC (for the two commercial sites). Several of the vendor POCs did not respond to our request, and several others were no longer with the company and could not be contacted to request their aid in identification of the government POCs. In these instances, Parsons contacted the environmental flight/division of each facility/base to identify the POCs.

Following identification of all 27 government/consultant POCs, Parsons contacted the POCs and requested their support for this project and informed them that AFCEE would contact them directly. The site and POC information was used to develop a secure internet database from which information could be e-mailed directly to the POCs and accessed by AFCEE and other interested parties by use of an internet link, website, and password.

2.2 INITIAL QUESTIONNAIRE

Concurrent with development of the website database, AFCEE and Parsons developed an initial web-based questionnaire designed to gather general information regarding each of the 27 thermal sites. Information related to the type of contaminant, the thermal technology used, scale of the project, relative success of the project, and availability of cost data was requested; and questions related to the regulatory aspects of the project were asked. A copy of this questionnaire is provided in Appendix A.

The initial questionnaire was placed on the secure website, and the link and password information was e-mailed by AFCEE to each POC identified for the 27 project sites. The POCs answered the questions directly on the website, and the information was stored in the database. Twenty-one POCs responded to the request for support and completed the initial questionnaire. Four of the 21 respondents completed the questionnaire but declined to further participate in the AFCEE project. Six respondents, four that declined to further participate and two others, declined to share cost data. Six POCs did not respond to AFCEE's request or complete the initial questionnaire. The answers from the 21 POCs who responded to the initial questionnaire are tabulated and are included in Table 2.1. This table was submitted to AFCEE for review. The table rows in black type indicate the POCs who were willing to further participate in the AFCEE project and to share cost data. The rows in blue type indicate the POCs who, though willing to further participate, were not willing to share cost data. The rows in red type indicate the POCs who were not willing to further participate in this project.

TABLE 2.1
AFCEE THERMAL ENHANCEMENT PROJECTS INITIAL QUESTIONNAIRE SUMMARY

Site Location/Name	P.O.C.	Type Source Area	Technology	Pilot or Full Scale	Project Status	Success or Failure	Extent of Available Cost Data	Impact to Overall Cost	Technology Selected in FS or CMS	Was Project an Interim Action	Was Project a Technology Demonstration	Did Regulators Suggest or Encourage Technology	Was Tech. selected on Vendor Marketing	Knowing results, would you use the same Tech. again	Knowing results, would you use a different Therm technology	Knowing results, would you select a different technology	Are you willing to participate further in this study	Are you willing to share cost data
Edwards AFB	Stephen Watts	CAH in Fuel	Steam	Pilot	Complete	Success	Some Data	Unknown	No	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
Cape Canaveral	Jackie Quinn	CAH	Steam	Pilot	Complete	Somewhat	Extensive Data	Unknown	No	No	Yes	No	No	Yes	No	No	Yes	Yes
Robert Gray AAF	Fred Klinger	Fuel Hydro.	Steam	Pilot	Complete	Success	Some Data	Definitely Decreased	Yes	No	Yes	No	No	Yes	No	No	Yes	Yes
Portsmouth Gaseous Diff.	John Sokol	CAH	Steam	Pilot	Complete	Somewhat	Extensive Data	Increased Cost	No	No	Yes	Yes	Yes	No	Yes	No	Yes	Yes
Ft. Wainright RF Heating	Rielle Markey	Fuel Hydro.	Radio Frequency	Pilot	Complete	Somewhat	Some Data	Increased Cost	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Lowry Landfill	Bill Plaehn	Fuel Hydro.	Electric Resistance	Full-Scale	Complete	Somewhat	Some Data	Definitely Decreased	Yes	No	Yes	Yes	No	Yes	No	No	Yes	Yes
Niagara Falls ANG	Gerry Hromowyk	CAH	Therm Enhance SVE	Full-Scale	Complete	Success	Extensive Data	Probably Decreased	No	Yes	Yes	No	No	Yes	No	Yes	Yes	Yes
North Island NAS	Bill Collins	CAH in Fuel	Steam	Full-Scale	In-Progress	Success	Extensive Data	Probably Decreased	No	Yes	Yes	No	Yes	Yes	No	No	Yes	Yes
Lawrence Livermore	Roger Aines	Fuel Hydro.	Steam	Full-Scale	Complete	Success	Extensive Data	Definitely Decreased	Yes	Yes	Yes	Yes	No	Yes	No	No	Yes	Yes
Rocky Mountain Arsenal	Ronald Versaw	Hexachlorocy.	Electric Resistance	Full-Scale	Complete	Failure	Some Data	Increased Cost	No	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Whittier DESC	Jack Appolloni	Fuel Hydro.	Steam, Air and ER	Full-Scale	Complete	Success	Extensive Data	Increased Cost	Yes	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes
Yorktown DESC	Jennifer Davis	Fuel Hydro.	Steam	Full-Scale	In-Progress	Success	Some Data	Probably Decreased	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes
Mare Island Navy Facility	Christopher Lones	PCBs	Electric Resistance	Full-Scale	Complete	Somewhat	Some Data	No Impact	Yes	No	No	No	No	Yes	Yes	Yes	Yes	Yes
Savannah River (DUS/HPO)	Chris Bergren	CAH	Steam	Full-Scale	Complete	Success	Some Data	Definitely Decreased	No	No	No	Yes	No	Yes	No	No	Yes	Yes
Air Force Plant 4	George Walters	CAH	Electric Resistance	Full-Scale	Complete	Success	Extensive Data	Probably Decreased	Yes	No	No	No	No	Yes	Yes	No	Yes	Yes
Centerville Beach Navy Fac.	Louis Lew	PCBs	In-Situ Therm	Pilot	Complete	Somewhat	Some Data	Probably Decreased	Yes	Yes	Yes	Yes	No	No	No	Yes	Yes	No
Ft. Richardson Pole Line Dis	Scott Kendall	CAH	Electric Resistance	Full-Scale	Complete	Success	Some Data	Probably Decreased	Yes	No	Yes	No	No	Yes	No	Yes	Yes	No
Puget Sound Navy Yard	Rod Gross	Fuel Hydro.	Steam	Full-Scale	Complete	Somewhat	Some Data	Probably Decreased	Yes	No	Yes	Yes	No	Yes	Yes	No	No	No
Leemore NAS	Don Roberts	Fuel Hydro.	Steam	Pilot	Complete	Somewhat	No Data	Probably Decreased	No	No	Yes	No	Yes	No	No	Yes	No	No
Launch Pad 34	Mike Deliz	CAH	Steam	Pilot	Complete	Somewhat	Extensive Data	Unknown	No	No	Yes	No	No	No	No	No	No	No
Kelly AFB	Don Buelter	CAH in Fuel	Electric Resistance	Pilot	Complete	Somewhat	Some Data	No Impact	No	No	Yes	No	No	No	Yes	Yes	No	No

Green font indicates facility is not willing to share cost data.
Red font indicates facility is not willing to participate further with the project.

2.3 SELECTION OF ELEVEN THERMAL PROJECTS FOR FURTHER EVALUATION

2.3.1 Analysis of Initial Questionnaire

Seventeen of the 21 respondents stated that they were willing to further participate in the AFCEE project. Parsons contacted each of those 17 POCs, including the two who declined to share cost data. Each POC was asked to verify their answers to the initial questionnaire, and Parsons assessed their willingness to provide further support for the project (some POCs appeared to be very willing to support the AFCEE project while others were not). The apparent willingness to support AFCEE was one factor in the selection of the 11 projects for which further evaluation was to be conducted.

Analysis of the answers from all 21 respondents showed some interesting, though somewhat inconsistent, results. Only one respondent indicated that thermal enhancement was a failure. This project was unique in that the contaminant, hexachlorocylco-pentadiene, a pesticide precursor, degraded under heat to produce pure hydrochloric acid, which destroyed the treatment train within 10 days. The other 20 respondents indicated their thermal projects were successful or somewhat successful. However, only four of these 20 respondents indicated that thermal enhancement had definitely decreased the overall remedial costs, and eight stated it had probably decreased overall costs. Of the remaining eight respondents, three indicated that thermal enhancement had definitely increased the overall remedial costs, three responded that the cost impact was unknown, and two indicated thermal enhancement made no impact to overall costs. Of the 20 respondents that felt thermal enhancement was successful or somewhat successful, only 14 of these stated they would use the same technology again. Six of those 20 respondents indicated that, knowing the results, they would not use the same thermal technology, and four of these six indicated that, knowing the results, they would have chosen a non-thermal technology. A total of eight of those 20 respondents (four cited in the previous sentence and four others) indicated that, knowing the results, they would have chosen a non-thermal technology.

There is an apparent inconsistency in the respondent's answers as described in the above paragraph. This conclusion is based on the findings that 20 respondents felt thermal enhancement was successful or somewhat successful, yet only 12 indicated that thermal enhancement had a positive impact to overall remedial costs, and only 12 indicated they would chose the same thermal technology. The definition of success was a key question for the secondary questionnaires and telephone interviews.

Other information made available from the 21 respondents was that thermal enhancement was selected in decision documents at only 11 of the sites. Seven of the thermal projects were interim actions, and 16 projects were chosen for technology demonstrations. Regulatory encouragement was a factor in the selection of thermal enhancement at 10 of the sites, and vendor marketing was a factor at only five sites. One apparent conclusion from these responses, as well as from telephone conversations with 17 of the POCs, is that facility personnel played a substantial role in the selection of thermal enhancement at their respective sites.

Based on analysis of the responses to the initial questionnaires, 17 of the 27 thermal project sites originally identified could be considered for further evaluation. Five of these 17 were not willing to conduct telephone interviews or respond to a second and more thorough questionnaire. One other contact was not the original project POC and was not sufficiently knowledgeable to answer additional questions regarding the thermal project at their site (the original POC was unavailable during the time frame of this AFCEE project). The remaining 11 POCs appeared to be very cooperative and willing to participate further. The selection of the 11 project sites for further evaluation was based on the availability and cooperativeness of the remaining 11 POCs.

2.3.2 Telephone Interviews with Points of Contact

The next step in the selection for sites at which detailed evaluations would be completed was to develop a more thorough questionnaire and conduct telephone interviews with the POCs at the 11 potential sites. Parsons developed the second questionnaire and submitted it to AFCEE and Battelle Science & Technology International (Battelle) for review (Battelle is conducting a related project for ESTCP). The questionnaire requested additional information regarding the scope of the project (pilot or full-scale), details on implementation of the thermal technology, greater detail on what constituted success, and more detail regarding site characteristics and post-implementation sampling. Parsons e-mailed the questionnaires to the 11 POCs and scheduled telephone interviews after the POCs had an opportunity to review them. A copy of the second questionnaire is included in Appendix B. Parsons conducted the interviews from 29 January 2004 through 27 February 2004. Summaries of each interview are also included in Appendix B.

Based on the interviews, it became apparent that success of a project did not relate directly to site closure or attainment of predetermined cleanup objectives. In most cases, success meant mass removal was achieved or enhanced as compared to earlier remedial efforts. In some cases, success simply meant that thermal enhancement appeared to be less expensive than long-term groundwater extraction and treatment, which may be a reasonable measure of success.

Implementation of thermal enhancement did not lead to complete site closure at any of these 11 facilities, primarily due to contaminated groundwater. However, thermal enhancement may have assisted with regulatory acceptance of monitored natural attenuation (MNA) at two sites (Edwards Air Force Base [AFB], CA, and Whittier Defense Fuel Supply Point [DFSP], AK). It should be noted that at Edwards AFB, MNA was approved before the thermal enhancement pilot study was completed. Additionally, at Whittier DFSP, the regulators agreed that thermal enhancement did very little to achieve site remediation, but that source removal was unnecessary as the contamination has not and likely will not migrate off DFSP property. At two other sites, North Island Naval Air Station, CA and Yorktown Fuels DFSP, VA, thermally enhanced remediation is still ongoing, and may lead to site closure within the next 15 to 30 years. Additional, non-thermal remedial actions are underway or are planned to address groundwater at the remaining 7 sites. Thermally enhanced soil vapor extraction did lead to closure of the soils operable units at Air Force Plant 4, TX, Niagara Falls Air Reserve Station (ARS), NY, and the Poleline Road Site, Fort Richardson, AK.

2.4 IDENTIFICATION OF FOUR THERMAL PROJECTS FOR DETAILED EVALUATION

Parsons evaluated the telephone interviews and responses to the second questionnaire to identify four sites for detailed evaluation and generation of life cycle cost analyses. The information gathered can be summarized in six basic questions:

1) How successful was the project according to the POC?
2) Why was the project considered successful according to the POC?
3) Did the regulators agree that the project was successful?
4) What was the POC's impression of the cost impact?
5) Based on Parsons' evaluation, were the site characteristics favorable to another treatment technology?
6) Based on Parsons' evaluation, did thermal enhancement positively impact overall remedial costs?

The responses to these questions are tabulated in Table 2.2. The potential for each of the 11 sites to be considered for detailed evaluation, based on the responses to the six questions, is included in Table 2.2. Four sites were excluded from consideration for detailed evaluation and seven were retained. The bases for a site being excluded or retained are included in Table 2.2. Each of the seven retained sites was ranked in terms of which would provide the most useable information for an overall evaluation of thermal enhancement technology. The Savannah River Site (SRS) was ranked highest based on the opinion that thermal technology may have been a reasonable choice based on the site's specific site conditions (e.g., dense non-aqueous phase liquid [DNAPL] contamination to greater than 160 feet below ground surface [bgs] and groundwater at 145 feet bgs), and the technology appeared to have been effective (greater than 68,000 pounds of tetrachloroethene [PCE] and trichloroethene [TCE] were recovered). Similar

TABLE 2.2

SUMMARY OF SECOND QUESTIONNAIRES AND INVTERVIEWS WITH FACILITY POCS

FACILITY NAME	Savannah River DOE, GA	Fort Richardson, AK	Niagara Falls ANG, NY	Yorktown Fuels DESC, VA	Portsmouth DOE, OH	Whittier DESC, AK	North Island NAS, CA	AF Plant 4, TX	Edwards AFB, CA	Lowry Landfill, CO	Rocky Mountain Arsenal, CO
Should we consider this site for Task 4	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No
Rating to Continue to Task 4	**1**	**2**	**3**	**4**	**5**	**6**	**7**	Not Applicable	Not applicable	Not applicable	Not applicable
Basis for rating	Project is complete, soil RAOs were achieved, and may be the only successful (in terms of cost) application of technology.	Project is complete, heating helped achieve soil RAOs, and evaluation may show increased life cycle costs over dig and haul.	Project is complete, heating helped achieve soil RAOs, and evaluation will likely show increased life cycle costs over SVE or dig/haul.	Probable that technology has had little impact and will probably increase cost vs. other tech. such as bioventing, SVE or dig and haul.	Project was a pilot study only and DOE has tested several technologies, none of which have shown much promise.	Project is complete and evaluation may indicate heat had no impact to site and did increase costs.	Project is on-going and probable that little impact would be made by any technology due to large extent of contamination.	Lockheed not overly willing to share cost data.	Pilot study only, admitted that cost impact was unknown, and source removal was unnecessary due to lack of sensitive receptors.	Client not overly willing to share cost data.	Politically driven site, failure was not cost driven, and system only operated for 10 days before complete system meltdown.
Project Status	Complete	Complete	Complete	On-going	Complete	Complete	On-going	Complete	Complete	Complete	Complete
How successful was project according to POC	Very successful full scale project.	Very successful full scale project.	Very successful full scale project.	Somewhat successful full scale project.	Somewhat successful pilot study.	Very successful full scale project.	Very successful full scale project.	Very successful full scale project.	Very successful pilot study.	Somewhat successful full scale project.	Disastrous pilot study.
Why was project successful according to POC	Recovered 68,000 lb VOCs and met cleanup criteria (asymptotic removal rates)	Goals of mass removal and meeting soil RAOs were achieved.	Total VOC concentrations in soil and GW decreased dramatically.	System recovers 5000 gallons bunker oil per month and has eliminated off-site migration of oil.	Cost over $1M for 50 gallons TCE recovered. Much steam loss due to soil heterogeneity.	Increased fuel recovery from 1 gallon/year with SVE to 15,000 gallons in 21 months with heat and SVE.	Recovered 211,000 lb fuel with heat vs. 80,000 lb with SVE alone.	Cheaper than P&T ($6000/lb vs. $1100/lb). Met soil RAOs.	Met expectation of project. First project in bedrock and removed 2250 lb VOCs and diesel.	Soils met cleanup criteria of 50% overall removal, which should have allowed capping of the pit.	System melted from corrosion within 10 days of start up.
Did regulators agree with success	Agreed that source removal was complete.	Agreed that source area soil met RAOs and GW MNA ok.	Agreed that soil met cleanup criteria but GW did not.	Agreed, good source removal technology.	Agreed that steam injection not appropriate at this site.	Agreed that steam not appropriate for Whittier.	Yes and want system operation to continue.	Yes, agreed soil RAOs were met.	Yes, and agreed full scale wasn't necessary due to lack of receptors	No, EPA changed method for calculating 50% removal.	No, EPA wanted Army to try again with new system.
What was POC's impression of cost impact	Definitely decreased compared to endless P&T.	Probably reduced cost if MNA or TI granted.	Probably reduced costs, but no detail, just gut feel.	Unknown. Total cost likely equal to dig and haul.	Definitely increased cost. Very little return on $1M	Increased life cycle cost due to O&M and little impact.	Definitely reduced cost by increasing mass removal.	Probably reduced cost compared to long-term P&T.	Unknown since did not have to go full scale.	No impact due to large overall site containing 70 disposal pits.	Increased life-cycle costs as Army wanted dig and haul.
In our opinion were site characteristics favorable to another treatment technology	Only other tech likely is ISCO, but probably would not have been effective.	Continued SVE or dig and haul. Probably will monitor site forever anyway.	SVE or dig and haul.	SVE or bioventing.	Unknown. Heterogeneous soil would make SVE difficult.	Bioventing with MNA.	SVE or biovent. Source area is 10 acres and 12' deep with coarse grained lithology.	SVE system was already in place prior to heating, and is still in operation.	MNA, which is what regulators agreed to.	SVE, bioventing, or dig and haul.	Dig and haul probably best solution.
In our opinion, did thermal enhancement impact overall cost	Cost of $4M warranted for 37,000 CY treated ($108/CY). Depth of 160' is very limiting.	Increased cost. Could dig and haul for less than $800 per CY.	Increased cost. Could have implemented SVE or dig and haul for less cost.	Will likely increase cost as system will have to run for more than 15 years.	Increased cost. Site has done pilots and their costs may be greater than ISCO, which is now planned.	Increased cost because Army wanted quick out. Regulators accept that the site will always be contaminated.	Increased cost. Long-term SVE very likely to be less costly.	Increased cost. Cost was $3.1M. Long-term SVE may have been lest costly.	Increased cost and probably would've been unnecessary if AF pushed MNA from beginning.	No. Cleanup of one of 70 pits made no difference to site GW.	Increased cost. Army originally proposed dig and haul. EPA forced an innovative technology.

information was used to rank each of the seven sites, the top four of which were recommended for completion of detailed evaluations.

Upon completion of site evaluations and preparation of Table 2.2, the table and the POC interview summaries were submitted to AFCEE for review. AFCEE agreed with Parsons' evaluation, and directed Parsons to proceed with detailed evaluation of the four highest ranked sites. POCs at each of the four sites were contacted and each agreed to assist with the detailed evaluation, and to provide additional site and cost information. Site visits were then scheduled for each site and were conducted in May and June 2004. Information related to each of the four sites and results of the detailed evaluations and life cycle cost analyses are presented in the following sections.

3.0 DESCRIPTION OF FOUR SITES SELECTED FOR LIFE CYCLE COST ANALYSIS

3.1 INTRODUCTION

Four sites were selected for detailed evaluation and life cycle costs analyses. This section contains descriptions of each site and of the thermal technology used to enhance removal of contaminant source mass. Descriptions of the system's operations, mass removal, post-treatment soil and groundwater sampling results, and project costs are also presented in this section.

3.2 NIAGARA FALLS AIR RESERVE STATION, NIAGARA FALLS, NY

Much of the information related to the Niagara Falls ARS site that is presented in this section was provided in the *Final Interim Remedial Action Report, Site 10: Fire Training Area No. 1, Niagara Falls International Airport Air Reserve Station, Niagara Falls, New York* (Montgomery Watson, 1997).

3.2.1 Site Description

Thermally enhanced soil vapor extraction was implemented at the Niagara Falls ARS, Niagara Falls, NY, Fire Training Area No. 1 in August 1996. This site is identified as Installation Restoration Program (IRP) Site 10. The site was the installation's principle fire training area during the late 1950s and early 1960s. The burn pit was a shallow depression approximately 100 feet in diameter and 2 feet deep, and is located approximately 1,000 feet from the base runway. Cayuga Creek, the main drainage feature of this portion of the base, is located approximately 400 feet south of the former burn pit. A site map of the former burn pit is presented as Figure 3.1 (Montgomery Watson, 1997).

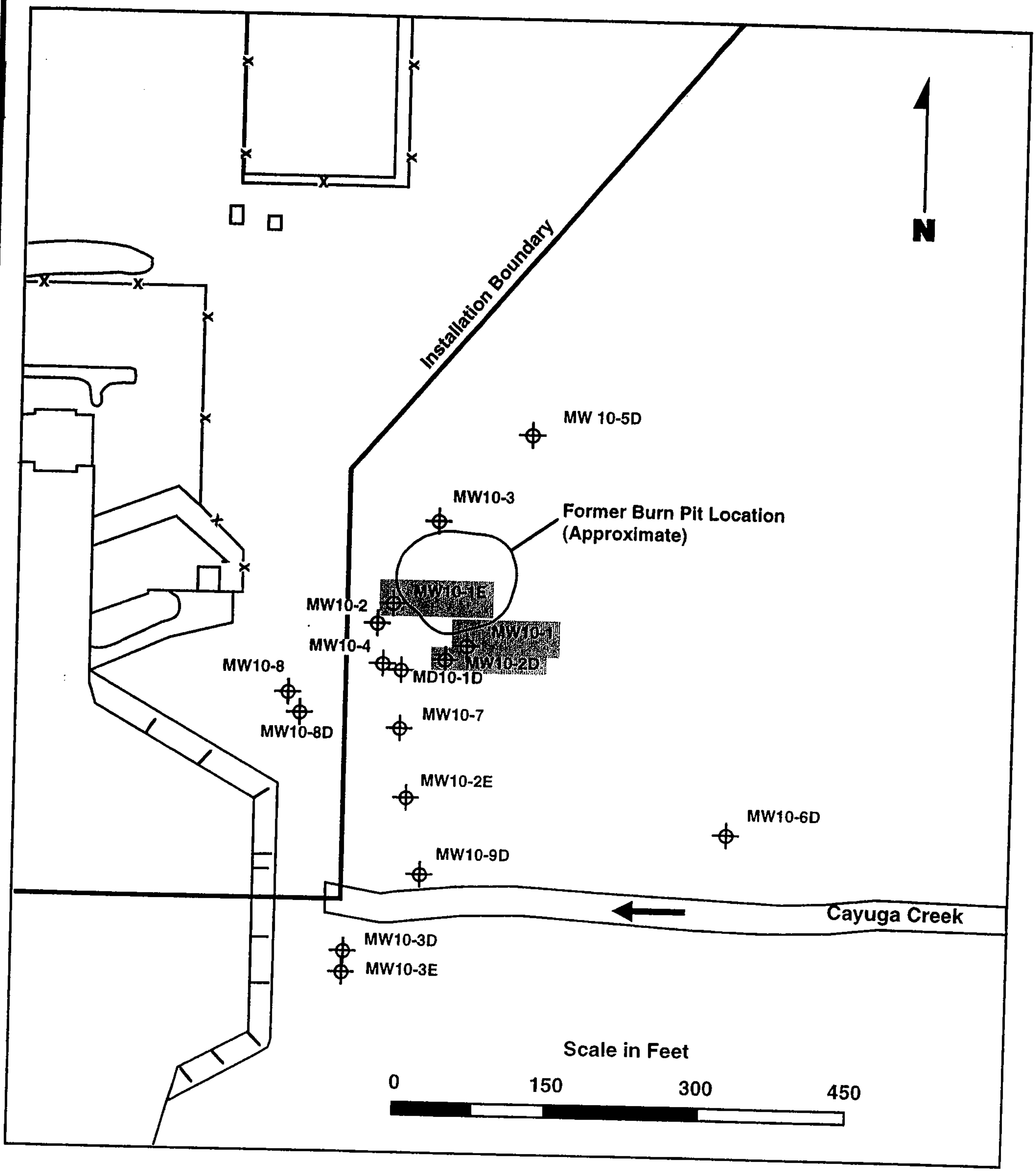
The geology of IRP Site 10 is characterized by a relatively thin overburden of lacustrine sediments and glacial till on top of fractured dolostone bedrock (Montgomery Watson, 1996). The upper overburden consists of a 4- to 8-foot-thick layer of stratified lacustrine clay and silty clay, which sits on top of a 0- to 8-foot-thick layer of glacial till.

The layer of glacial till sits directly on top of the fractured bedrock and is not continuous over the entire site. Groundwater is encountered at approximately 6 feet bgs, and typically flows to the south-southwest toward Cayuga Creek. The overburden and bedrock aquifers appear to be hydraulically connected and have similar hydraulic conductivities. Conductivities averaged 2.8×10^{-4} centimeters per second (cm/sec) in the overburden and 3.7×10^{-5} cm/sec in bedrock. Cayuga Creek can be either a gaining stream or a losing stream depending on seasonal variations in the elevation of the groundwater table. Generally, the creek is a losing stream in the late fall and winter months and becomes a gaining stream during the spring and summer months.

A variety of combustible materials, including oils, solvents, and jet fuel (JP-4) were placed in the burn pit, ignited, and extinguished with fire fighting foam (Montgomery Watson, 1996). Investigations of soil and groundwater quality at IRP Site 10 detected volatile organic compounds (VOCs), with TCE and total xylenes being the primary site contaminants. The burn pit source area covers approximately 0.75 acre and ranges in depth from 6 to 9 feet, the depth at which bedrock is encountered. TCE was found in vadose zone soil samples collected from within the former burn pit at concentrations as high as 14,000 micrograms per kilogram (μg/kg), and concentrations were higher in the deeper samples (4 to 7 feet bgs) than in the shallow samples (0 to 2 feet bgs). Based on the concentrations and distribution of TCE within the former burn pit, the estimated mass of TCE present was 9 kg.

TCE has apparently migrated in NAPL form into the shallow bedrock, and was detected in site groundwater at concentrations as high as 18,000 micrograms per liter (μg/L). Concentrations of TCE exceeded 1,000 μg/L in three of 14 wells at the site. TCE degradation products including cis-1,2-dichloroethene (cis-DCE) and vinyl chloride were also detected in site groundwater. The dissolved phase VOC plume extended approximately 200 feet south of the south boundary of the former fire-training pit. The combination of relatively low permeability soil and the variant gaining/losing stream nature of Cayuga Creek appear to have limited the migration and resultant extent of the dissolved phase plume.

February 1997



Legend

MW10-3 ⌖ Existing Monitoring Well

MW10-1 ⌖ Abandoned Monitoring Well

—x———x— Fence

⬅ Surface water flow direction

Site Map	
Site 10 IRA Report Niagara Falls IAP-ARS	
MONTGOMERY WATSON	Figure 3.1

3.2.2 Thermal Technology Description

3.2.2.1 General Description of Six Phase Soil Heating Technology

Six Phase Soil Heating (SPSH) in conjunction with Soil Vapor Extraction (SVE) were the technologies implemented at IRP Site 10 source area. SPSH is a patented technique that uses low-frequency electricity to heat soils as an enhancement to SVE. Battelle Pacific Northwest Labs, under contract to the US DOE, developed and holds a patent on the SPSH technology, and manages the soil heating electrical power equipment and control systems. SPSH is used primarily to remove VOCs and semi-volatile organic compounds (SVOCs) from relatively impermeable soils where SVE alone is not normally effective. SPSH uses conventional single-phase electric transformers to convert commercial three-phase line power into six single-phase electric outputs. This electrical power is then delivered throughout the soil being treated through galvanized steel electrodes that are inserted vertically into the soil. Electrical current is conducted through the soil, heating it resistively and increasing the contaminant's vapor pressure, thus increasing its potential removal rate. Additionally, the steam produced by heating the soil reportedly steam-strips contaminants *in situ*. The volatilized contaminants and steam are then removed by the SVE system and treated above ground. The only additive to SPSH treatment is water, which must be added to soil surrounding the electrodes during operation. This prevents the soil from drying and becoming non-conductive (Montgomery Watson, 1996).

The basic system components used to implement SPSH include combination subsurface electrodes/vapor extraction vents, an off-gas collection and treatment system (including a vacuum blower, a condenser, and a treatment unit), the SPSH transformers used to condition electric power for application to the soil, and a computer control/data acquisition system. The electrodes/vapor extraction vents are installed in boreholes drilled using standard drilling techniques. The electrodes are placed in the boreholes and the annular space filled with graphite or steel shot (round pellets with diameters of approximately 1 millimeter) to conduct electric power from the electrode into the soil. Off-gas collection is typically accomplished by use of a high permeability gravel layer (plenum), which is placed over the area to be treated. Slotted collection pipes are placed in the plenum and are connected to a vacuum blower. Off-gas treatment is dependent on the type of contaminant (halogenated or non-halogenated) and its concentrations. Activated carbon, thermal oxidizers, catalytic oxidizers, and membrane filters are typical treatment technologies used. The SPSH transformers are trailer-mounted units that convert commercial three-phase power to six separate single-phase outputs with voltages ranging from 0 to 2.4 kilovolts. Each of the single-phase outputs is connected to one of six subsurface electrodes, which are arranged in a hexagonal array. A seventh subsurface electrode is installed in the center of the array and acts as the neutral leg of the electric circuit. Electricity is applied to each of the six outer electrodes and passes through the soil toward the central neutral leg, heating the soil resistively as it passes. The central electrode is also constructed as a vapor extraction well to facilitate the removal of vapor generated deeper within the soil treatment area.

SPSH can be implemented in several hexagonal arrays to treat larger areas of soil contamination. Each array can be as large as 40 feet in diameter, effectively heating a 56-foot-diameter region of soil. The heated region can extend to a depth of up to 200 feet bgs.

3.2.2.2 Description of SPSH Technology Used at Niagara Falls ARS Site 10

The SPSH Interim Remedial Action (IRA) performed in 1996 at IRP Site 10 was designed to treat only the overburden soil with no direct impact on site groundwater. Additionally, the IRA was performed to test the effectiveness of SPSH on clay soils. As such, the arrays used to heat the soil did not extend into the bedrock below the overburden soils. The anticipated effect was to reduce the contaminant mass in the vadose zone, thereby reducing the potential future loading of contamination to groundwater.

Four SPSH arrays were used to conduct the IRA and treat the source area at Niagara Falls ARS IRP Site 10. Each array was 40 feet in diameter and used to treat regions approximately 56 feet in diameter. Together, the four arrays were designed to treat an area of approximately 110 feet by 110 feet with treatment extending to the top of bedrock, or 8 to 10 feet bgs. The total treatment volume was approximately 3,600 cubic yards of overburden soil.

Each array consisted of six positive electrodes arranged in a hexagonal pattern with a neutral electrode in the center of each array. One additional neutral electrode was installed in the center of the treatment area between the four arrays. All the electrodes were constructed of carbon steel pipe with a 5-foot section of stainless steel well screen installed from 1 to 6 feet bgs to allow extraction of soil vapor as well as induction of electrical current into the soil. The system was designed so that soil between the arrays would be heated by a combination of electrical interactions between the arrays and conductive and convective heat transfer. Figure 3.2 (Montgomery Watson, 1997) depicts the array layout at IRP Site 10. A series of grounding rods were installed between the arrays and the transformer system to prevent stray voltages from migrating outside the treatment area.

Maintenance of electrical conductivity at the electrode/soil interface was accomplished by adding water to the graphite material surrounding each positive electrode. A water addition tube was attached to the top of each positive electrode for this purpose. Subsurface temperatures were measured at 2 and 6 feet bgs by thermocouples placed within the treatment area. Subsurface vacuum was monitored by pressure monitoring wells. These pressure monitoring wells were installed to ensure negative air pressure was maintained at the edges of the treatment area. The locations of the temperature and pressure monitoring points are shown on Figure 3.2.

Volatilized contaminants and steam were collected via the vapor extraction system. This system included the four neutral electrode/wells installed in the center of each array, the neutral electrode/well installed in the center of the treatment area, the six positive electrode/wells that formed the perimeter of each of the four arrays (24 vents total), and the gravel layer plenum installed over the treatment area. The plenum was constructed with horizontal and slotted polyvinyl chloride (PVC) pipes covered with a layer of gravel that was placed over the treatment area. The gravel layer was covered with a high-density polyethylene (HDPE) liner that was keyed into the ground surface just beyond the perimeter of the soil treatment area. The liner was covered with sand to form an insulating barrier to prevent excess heat loss from the treatment area. A schematic representation of the plenum is shown on Figure 3.3 (Montgomery Watson, 1997).

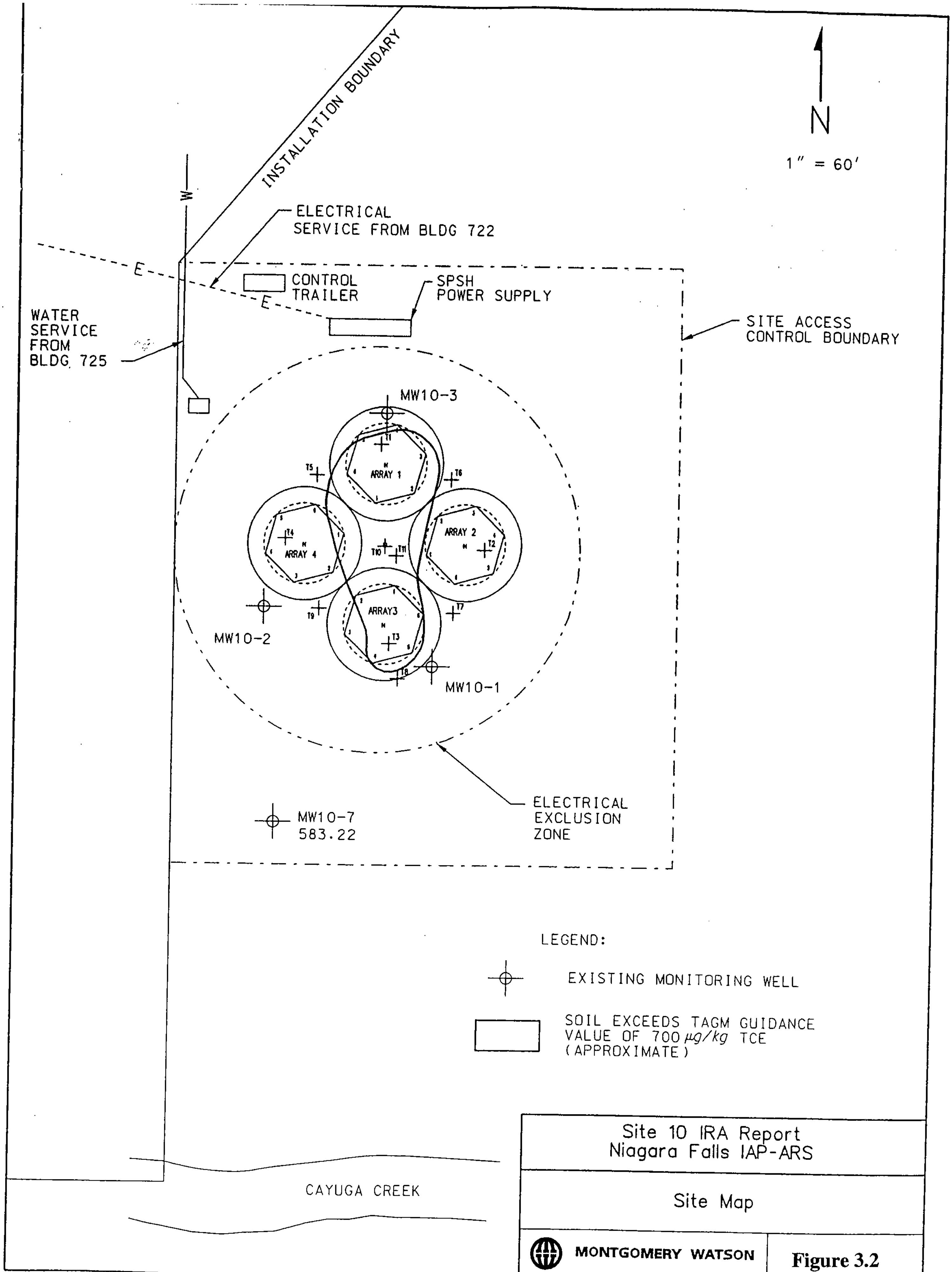
Vapor collected at the electrode/wells was conveyed out of the soil treatment area to a liquid dropout tank to remove free liquids and sediment. The vapor then passed through a heat exchanger/condenser to cool the vapor and remove condensed liquids. A positive displacement blower was used to create the vacuum and extract soil vapor and steam from the subsurface. The blower was located just downstream from the condenser. Extracted soil vapor was then passed through vapor-phase activated carbon for removal of organic contaminants prior to emission of the vapor to the atmosphere. Liquids collected in the condenser were treated through liquid-phase activated carbon prior to discharge to the base sanitary sewer system.

3.2.3 Operation of SPSH System at Niagara Falls ARS Site 10

The soil heating operation began at 1200 hours on 26 August 1996, and the SVE system began operation on 27 August 1996. Soil heating continued until 1200 hours on 25 September 1996. SVE operations continued for an additional 20 days to provide additional contaminant removal and to expedite cooling of the soil. The SVE system was shut down on 15 October 1996.

The total energy input to the treatment area was 336,000 kilowatt-hours (kWH). An estimated 140,000 kWH were spent to heat the soil, and 30,000 kWH were spent evaporating the 11,200 gallons of water in the subsurface that were extracted by the vapor extraction system. Another 30,000 kWH were lost due to conduction from the sides and bottom of the arrays, and 60,000 kWH were lost due to convection off the top surface of the treatment area. An additional 76,000 kWH were spent to evaporate the 7 inches of water that fell on the treatment area during heating operations.

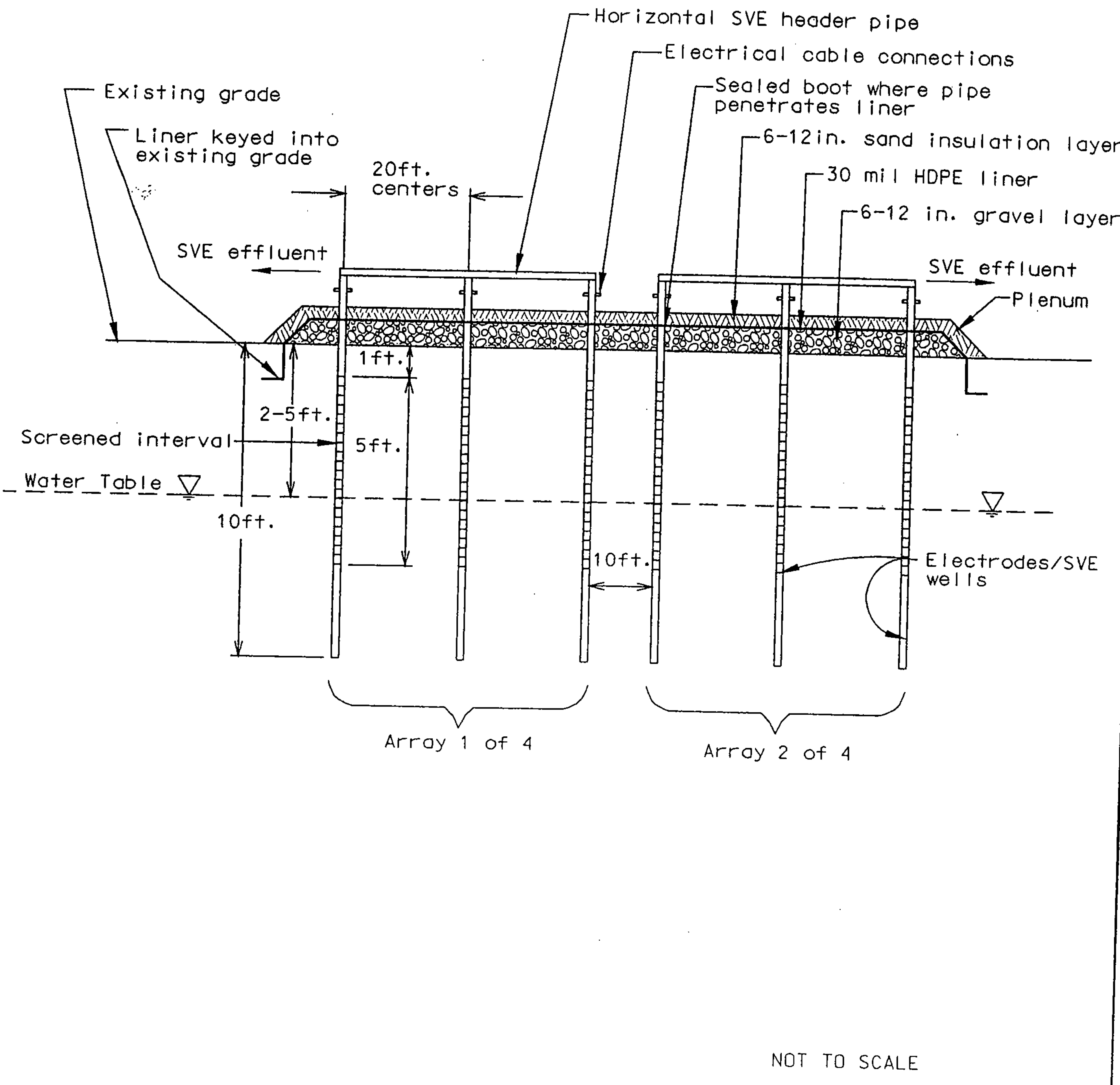
By the end of the first week of heating, steam was being generated, and condensate began to collect in the condenser. After two weeks of heating, the temperatures of soil



Site 10 IRA Report
Niagara Falls IAP-ARS

Site Map

Figure 3.2



Site 10 IRA Report Niagara Falls IAP-ARS	
Soil Heating/Venting System Cross-section	
MONTGOMERY WATSON	**Figure 3.3**

within the arrays at the 2-foot-bgs level had reached an average of 75 degrees Celsius (ºC) and remained relatively stable for the rest of the heating period. Soil temperatures within the arrays at the 6-foot bgs level rose steadily but more slowly, reaching approximately 55 ºC by the end of the 30-day heating period. Temperatures at 2 and 6 feet bgs of soil between the arrays heated more slowly than soil within the arrays, reaching 50 to 60 ºC by the end of the heating period. Soil temperatures outside the treatment area also increased by at least 10 ºC, reaching temperatures ranging from approximately 20 to 50 ºC (Montgomery Watson, 1997). Overall, soil temperatures at 2 and 6 feet bgs within the arrays increased by at least 50 ºC and 40 ºC, respectively. Temperatures of soil between the arrays at 2 and 6 feet bgs also increased by 50 ºC and 40 ºC, respectively.

There was a consistent difference between the heating rate and ultimate temperature of the soil at 2 feet bgs and the soil at 6 feet bgs. Three explanations were cited for this observation (Montgomery Watson 1997), including:

- Quenching due to higher water content in the 6-foot zone than in the 2-foot zone.
- Higher electrical conductivity in the 2-foot region than in the 6-foot region.
- Greater convective loses to soil and groundwater due to the higher water content in the 6-foot zone.

The temperature increase in the soil caused increased volatilization of organic contaminants leading to their extraction by the SVE system and treatment through two carbon adsorbers in series configuration. Vapor was extracted at a relatively stable rate of approximately 250 cubic feet per minute (cfm) for the entire period of SVE operation. The extracted vapor stream was monitored for concentrations of organic contaminants to determine the mass removal achieved during soil heating (discussed in Section 3.2.4), and to measure the loading onto and subsequent contaminant breakthrough of the vapor phase activated carbon adsorbers. Photoionization detector (PID) readings, direct-read colorimetric tubes, and vapor for laboratory analysis were collected at various times during the IRA. Concentrations of TCE and vinyl chloride reached their maximum levels (68 parts per million [ppm] and 64 ppm, respectively) at 23 and 16 days, respectively, into the heating period. Concentrations of TCE and vinyl chloride decreased to 5 ppm and less than 1 ppm, respectively, by 25 September 1996, the day before heating operations were terminated. Concentrations of both compounds had reached non-detectable levels by 4 October 1996, which was 11 days before SVE operations were terminated. The lead carbon adsorber was replaced twice during the treatment period. Four 200-pound activated carbon adsorbers were used to treat the SVE off-gas.

A total of 11,220 gallons of condensed steam was generated during the IRA. The condensate was treated through two liquid-phase carbon adsorbers in series configuration, then stored in a temporary storage tank. The highest dissolved phase concentration of TCE was 260 μg/L, and the carbon adsorbers were observed to satisfactorily treat the condensate. The treated water in the storage tank was sampled, then discharged after sample results indicated the water met discharge requirements for the sanitary sewer system. Two 200-pound carbon adsorbers were used to treat the condensate stream.

3.2.4 Contaminant Mass Removal Estimates

An estimated 131 pounds of the chlorinated ethenes TCE, cis-DCE, trans-1,2-dichloroethene, and vinyl chloride were removed during the IRA. An estimated 10.1 pounds of benzene, toluene, ethylbenzene and xylenes (BTEX) were also removed. These estimates are based on the off-gas sampling conducted during the IRA. The estimated mass of TCE removed was 95.7 pounds, which exceeded the pre-treatment estimate of 19.8 pounds. This discrepancy is most likely due to TCE NAPL that was not found in the pre-characterization study but was discovered at one location (a bedrock trough where free-phase TCE was detected) during the post-treatment sampling. The results of the post-treatment sampling indicated that an estimated 44 pounds of TCE remained at the site. Based on the 95.7 pounds of TCE removed from the site and the 44 pounds of TCE estimated to remain at the site, the initial amount of TCE was approximately 139.7 pounds. The 95.7 pounds of TCE removed during the IRA represents removal of 68.5 percent of the initial amount.

The total mass removal of TCE in the 11,200 gallons of condensate recovered during the IRA was estimated at less than 10 grams. Less than one gram of BTEX compounds was removed from the condensate.

3.2.5 Post-Implementation Sampling/Monitoring Results

3.2.5.1 Soil Sample Results

Soil samples were collected at 14 locations within or near the arrays before the IRA was performed, and the same locations were sampled one month after the IRA was completed. The results of the pre- and post-treatment soil samples collected from within the perimeter of the arrays are summarized in Table 3.1 (Montgomery Watson, 1997). These results showed that the average TCE concentrations declined by 35 percent, or from an average of 1,329 µg/kg to 862 µg/kg. The variability of TCE concentrations, as indicated by the standard deviation of the sample population, decreased even more significantly. Pre-treatment concentrations of TCE exceeded the New York State (NYS) cleanup criterion of 700 µg/kg at three locations within the perimeter of the array. After completion of the IRA, TCE levels still exceed NYS cleanup criteria at those three locations. Additionally, the average of the post-treatment samples was 862 µg/kg, which also exceeded the NYS cleanup criterion.

The results of the post-treatment soil samples were used to estimate the residual TCE mass left at the site after the IRA. Based on these samples, an estimated 44 pounds of TCE remained in site soil, primarily at the soil/bedrock interface. An estimated 80 percent of this residual TCE mass is located at one location, the bedrock trough that was cited in Section 3.2.4.

3.2.5.2 Groundwater Monitoring Results

The SPSH IRA performed in 1996 at IRP Site 10 was not designed to directly treat contaminated groundwater, but to reduce the contaminant mass in the vadose zone, thereby reducing the potential future loading of contamination to groundwater. Although SPSH can be implemented to address contamination in groundwater, this was not possible at IRP Site 10 due to the shallow bedrock. Most of the groundwater at the site occurs either in the bedrock or in the overburden within one foot of bedrock surface. A groundwater extraction trench was installed in June 1998 to address shallow groundwater occurring in bedrock at the site. The trench was installed 150 feet south and

Table 3.1

Soil Sampling Results Before and After Treatment
Site 10 IRA Report
Niagara Falls IAP-ARS
Niagara Falls, New York

Sample Location		T1		T2		T3			T4		T5	
Sample Depth		2-4		4-6		2-4			4-6		4-6	
Parameter	MDL	Pre	Post	Pre	Post	Pre	Pre D	Post	Pre	Post	Pre	Post
Volatile Organic Compounds (μg/kg)												
Tetrachloroethylene	1	ND	ND	ND	2	ND	ND	ND	ND	ND	ND	ND
Trichloroethylene	1	11	5	14	220	140	1	12	97	510	1	10
1,1,1 Trichloroethane	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
trans-1,2 Dichloroethylene	1	ND	ND	43	2	ND	ND	ND	46	20	ND	ND
1,1 Dichloroethylene	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Chloroform	1	3	8	2	4	2	ND	3	ND	2	2	4
Vinyl chloride	2	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
Benzene	1	ND	7	7	ND	5	4	2	3	10	ND	2
Toluene	1	7	14	2	3	3	ND	3	2	4	2	ND
Ethylbenzene	1	ND	ND	12	ND	260	170	56	ND	ND	ND	ND
m,p-Xylene	1	ND	8	ND	ND	34	45	17	ND	2	ND	ND
o-Xylene	1	ND	4	ND	ND	2	ND	ND	ND	ND	ND	ND
MEK (2-Butanone)	1	ND	110	17	13	28	26	ND	ND	ND	ND	ND
Acetone		490	560	770	91	390	250	65	79	12	460	140
Carbon Disulfide	1	3	4	6	6	11	4	1	ND	ND	3	2
Methylene Chloride		140	70	160	48	62	47	140 B	9	110	120	73

B Compound detected in method blank.
MDL Method Detection Limit. MDLs were exceeded in some samples.
ND Not Detected.
* Average of two samples.
Bold indicates levels above TAGM 4046 Guidance Values.

Final: February 1997

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Table 3.1

Soil Sampling Results Before and After Treatment
Site 10 IRA Report
Niagara Falls IAP-ARS
Niagara Falls, New York

Sample Location		**T6**		**T7**		**T8**		**T9**		**T10**	
Sample Depth		**4-6**		**4-6**		**6-8**		**6-8**		**4-6**	
Parameter	**MDL**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Volatile Organic Compounds (μg/kg)											
Tetrachloroethylene	1	9	ND	ND	ND	ND	ND	ND	ND	ND	48
Trichloroethylene	1	**3,000**	7	4	3	6	16	**1,400**	**6,100**	**2,500**	**1,200**
1,1,1 Trichloroethane	1	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
trans-1,2 Dichloroethylene	1	46	1	ND	ND	ND	ND	21	22	32	18
1,1 Dichloroethylene	1	ND	ND	ND	ND	ND	ND	9	14	ND	4
Chloroform	1	ND	2	ND	5	ND	31	1	9	ND	6
Vinyl chloride	2	ND	ND	ND	ND	ND	ND	11	400	ND	ND
Benzene	1	28	ND	ND	ND	ND	ND	11	44	88	57
Toluene	1	ND	3	ND	1	2	ND	4	38	11	12
Ethylbenzene	1	400	ND	ND	ND	1	ND	ND	ND	540	880
m,p-Xylene	1	580	ND	ND	ND	ND	ND	ND	ND	320	370
o-Xylene	1	ND	ND	ND	ND	ND	ND	2	9	ND	25
MEK (2-Butanone)	1	ND	ND	ND	ND	3	ND	ND	ND	ND	ND
Acetone		ND	68	71	73	100	890	140	140	95	130
Carbon Disulfide	1	160	ND	ND	ND	2	ND	ND	ND	ND	3
Methylene Chloride		110	20	47	220 B	36	2,500 B	16	370	180	400

B Compound detected in method blank.
MDL Method Detection Limit. MDLs were exceeded in some samples.
ND Not Detected.
* Average of two samples.
Bold indicates levels above TAGM 4046 Guidance Values.

Final: February 1997
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Table 3.1

Soil Sampling Results Before and After Treatment
Site 10 IRA Report
Niagara Falls IAP-ARS
Niagara Falls, New York

Sample Location		**T11**		**N1**		**N2**		**N3**		**N4**	
Sample Depth		**4-6**		**2-4**		**5-7**		**4-6**		**6-7**	
Parameter	**MDL**	**Pre**	**Post ***	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Volatile Organic Compounds (µg/kg)											
Tetrachloroethylene	1	2	15	ND	ND	30	64	ND	ND	ND	ND
Trichloroethylene	1	**1,900**	**2,400**	1	11	**8,400**	**3,600**	4	9	290	650
1,1,1 Trichloroethane	1	ND	ND	ND	ND	3	ND	ND	ND	ND	ND
trans-1,2 Dichloroethylene	1	24	15	2	1	17	2	12	ND	120	48
1,1 Dichloroethylene	1	ND	1.5	ND	ND	18	2	ND	ND	6	3
Chloroform	1	1	6	2	3	6	7	ND	5	ND	2
Vinyl chloride	2	5	20	ND	ND	18	ND	ND	ND	5	16
Benzene	1	16	25	ND	2	54	18	10	4	24	71
Toluene	1	12	21.5	2	4	180	71	1	5	1	3
Ethylbenzene	1	120	325	ND	ND	200	300	1,000	290	ND	ND
m,p-Xylene	1	29	235	ND	3	710	160	120	42	ND	ND
o-Xylene	1	4	15	ND	2	240	150	ND	ND	ND	ND
MEK (2-Butanone)	1	13	9	ND	ND	ND	69	69	180	ND	ND
Acetone		ND	190	740	19	610	180	360	12	160	51
Carbon Disulfide	1	1	2.5	4	3	5	ND	8	360 B	ND	ND
Methylene Chloride		22	190	140	14	170	160	33	ND	9	110

B Compound detected in method blank.
MDL Method Detection Limit. MDLs were exceeded in some samples.
ND Not Detected.
* Average of two samples.
Bold indicates levels above TAGM 4046 Guidance Values.

downgradient (with respect to groundwater flow) of the center of the former burn pit. Analysis of groundwater data from late 1996 through early 1998 indicates no reduction of contaminant concentrations in groundwater in overburden or upper bedrock wells located within or immediately downgradient of the former burn pit (Ecology and Environment, 2003).

Several wells located between the former burn pit and the extraction trench have shown increasing trends in VOC contaminant levels since June 1998. These trends may be due to the presence of suspected NAPL mass on the bedrock surface that is now migrating south due to the increased hydraulic gradient caused by groundwater pumping at the extraction trench. This NAPL mass may have existed before the IRA or could have collected at low points on the bedrock surface after the IRA. Other wells located near or downgradient of the former burn pits have shown relatively stable contaminant concentrations since 1996 and several others have shown decreasing trends in contaminant concentrations. The overall effect of the IRA on groundwater contaminant concentrations appears to be negligible at this time.

3.2.6 Thermal Project Cost

The total cost of the SPSH IRA was $688,000. This total included the pre-treatment soil sampling effort; design, installation, and operation of the SPSH and SVE systems; disposal of activated carbon adsorbers; post-treatment soil sampling effort; report preparation; contractor fees; and utility costs. The utility costs included $50,000 for electrical service. The total project costs also included $38,000 in project delay costs incurred by the contractor while the ARS negotiated a Hold Harmless Agreement with the local airport authority.

Excluding the project delay cost, the total cost would be $650,000. Based on an estimated treatment volume of 3,600 cubic yards, the unit cost for the IRA was $180 per cubic yard. On a per pound contaminant removed basis, the unit cost for the IRA was $6,800 per pound of TCE.

3.3 SAVANNAH RIVER SITE 321-M SOLVENT STORAGE TANK AREA, AIKEN, SC

Much of the information related to the SRS presented in this section was provided in the *Cost and Performance Report, Dynamic Underground Stripping-Hydrous Pyrolysis Oxidation at the Savannah River Site 321-M Solvent Storage Tank Area, Aiken, South Carolina* (Westinghouse Savannah River Company, et al. 2003).

3.3.1 Site Description

Dynamic Underground Stripping - Hydrous Pyrolysis Oxidation (DUS/HPO) is the form of thermal remediation that was implemented at the SRS 321-M Solvent Storage Tank Area (SSTA) in September 2000. A 17,000-gallon storage tank was located west of Building 321-M in the A/M area of SRS (Figure 3.4 [figure provided by Mr. James Kupar, Becthel Savannah River, Inc.]) and used to store chlorinated solvents including PCE, TCE, and 1,1,1-trichloroethane (1,1,1-TCA). Numerous undocumented spills and leaks are suspected to have occurred at the 321-M tank site. One significant spill is reported to have released an estimated 1,200 gallons of PCE to the ground surface (Integrated Water Resources, et al., 2004). The tank, associated piping, and part of the rail siding that serviced the tank were removed in 1997 to facilitate investigation and remediation of the site.

Lithology at the site consists of coarse sand and sand to 160 feet bgs. Several horizons of silty to clayey sand are present above 160 feet. A “Green Clay” horizon is located at approximately 160 to 165 feet bgs, and is considered to be an aquitard that underlies the entire 321-M site. Groundwater is encountered at approximately 145 feet bgs.

Previous characterization data revealed high levels of chlorinated solvents (0.2 to 0.3 percent by weight) in soil near the tank, indicating the presence of DNAPL contamination. Surface geophysics was used to delineate the area of DNAPL contamination, and subsequent sampling showed the NAPL composition to be 90 percent PCE and 10 percent TCE. Characterization data suggested that the NAPL contamination was in the form of disconnected ganglia in the saturated zone rather than as a large free-phase layer. The extent of NAPL contamination was generally contained within an area measuring 100 feet by 100 feet extending down to the "Green Clay" layer (160 feet bgs). The mass of NAPL contamination within the 100-foot by 100-foot by 160-foot soil volume was originally estimated at 26,000 pounds. The volume of soil in the treatment area was 59,300 cubic yards.

3.3.2 Thermal Technology Description

3.3.2.1 General Description of DUS/HPO Technology

The DUS/HPO technology combines several processes to remediate soil and groundwater contaminated with fuel and other organic compounds. It is very similar to enhanced SVE, except that it also treats groundwater contamination. DUS/HPO injection and extraction wells are installed so that their screened sections are in both saturated and unsaturated zones. Steam is injected at the periphery of a contaminated area to heat permeable subsurface areas, vaporize volatile compounds bound to the soil, and drive contaminants to centrally located vacuum extraction wells. Electrical heating is used on less permeable clays to vaporize contaminants and drive them into the steam zone (electrical heating was not necessary at the SRS 321-M site). DUS/HPO also uses an underground imaging system called Electrical Resistance Tomography (ERT) that delineates heated areas to ensure total cleanup and process control. HPO is a process whereby air is added to the subsurface in parallel with steam. When steam/air injection is halted, the steam condenses, and contaminated groundwater in the heated zone mixes with this oxygen-rich condensed steam. This enhances natural biodegradation of many compounds by providing nutrients to microorganisms that thrive at high temperatures (called thermophiles). When heated to temperatures near the boiling point of water (thermal treatment technology), DNAPL and dissolved organic contaminants are reportedly rapidly oxidized to form carbon dioxide and non-toxic ions. This remediation method takes advantage of more rapid chemical reactions, which occur at steam temperatures, as well as the large increase in mass transfer rates, which make the contaminants more available for destruction.

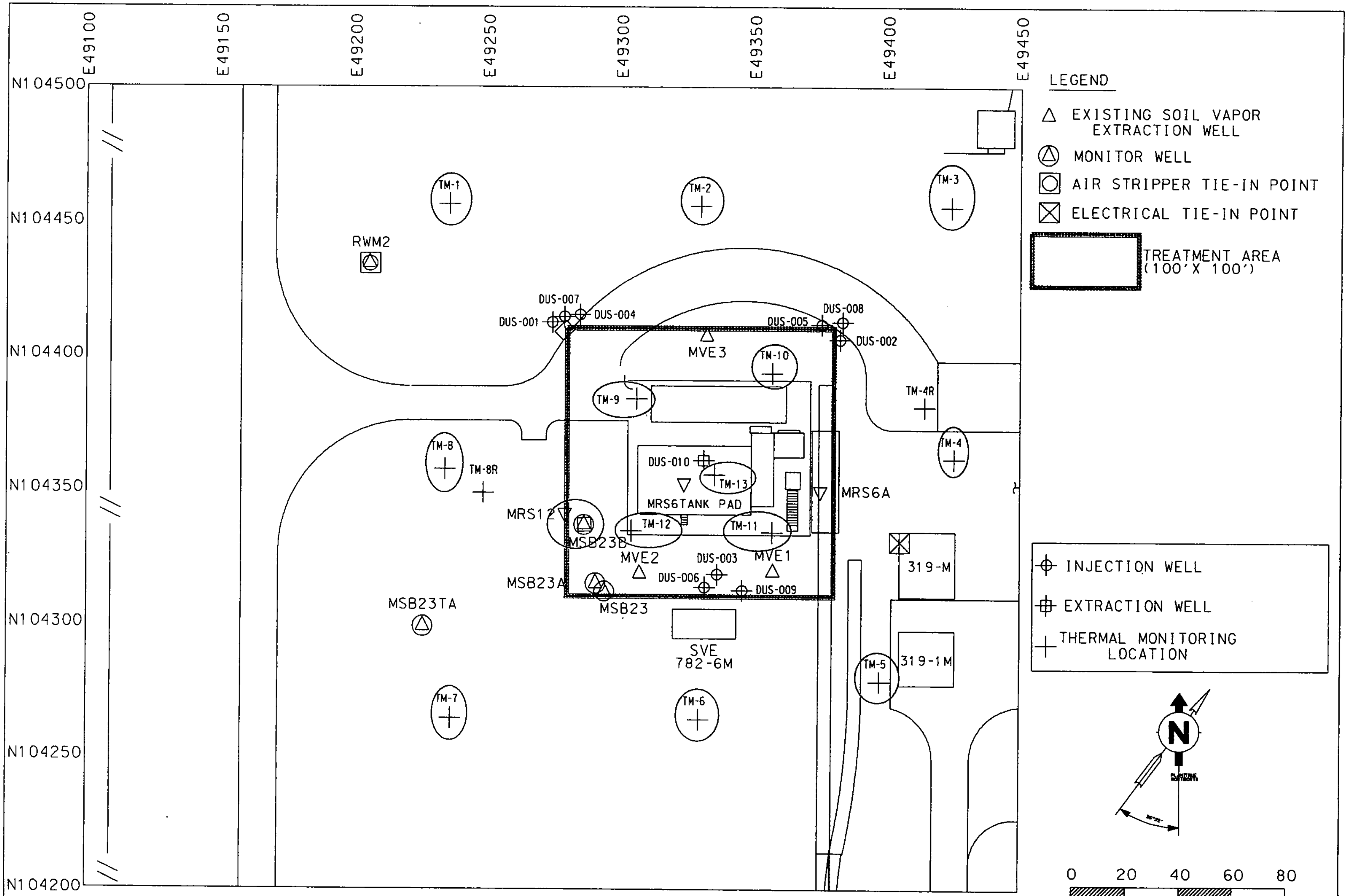


Figure 3.4 Locations of Wells and Thermocouple/ERT Arrays Installed for DUS Remediation

3.3.2.2 Description of DUS/HPO Technology Used at SRS

Figure 3.4 shows a plan view of the DUS/HPO system used at the SSTA site. Three steam injection well clusters were installed around the perimeter of the 100-foot by 100-foot treatment area (at the northwest corner, the northeast corner, and the southern perimeter). Each well cluster consisted of three injection wells with screen intervals at 50 to 70 feet bgs, 110 to 130 feet bgs, and 150 to 160 feet bgs. One dual-phase groundwater and vapor extraction well (DUS-10) was installed in the center of the treatment area with a screen interval from 20 to 160 feet bgs. This well was used to extract both groundwater and vapor from the subsurface. Groundwater was extracted from the well using a high-temperature, electric-submersible pump placed approximately 15 feet below the static groundwater elevation. The extracted groundwater was collected in a tank for subsequent treatment through a facility air stripper followed by discharge to a facility National Pollution Discharge Elimination System (NPDES) outfall.

Vapor extraction was performed using the central DUS-10 well and three existing vadose zone vapor extraction wells (MVE-1, -2, and -3), which were located along the perimeter of the treatment area. SRS's 6M Soil Vapor Extraction Unit (6M-SVEU) was used to extract vapors from the four vapor extraction wells. The vapor flow input to the unit averaged 350 standard cubic feet per minute (scfm). The hot extracted vapors were cooled through a heat exchanger, and condensed liquids were separated from vapors in a knockout tank. The condensate was routed through a DNAPL-water separator (DWS), which separated droplets of DNAPL for collection and removal. Water from the DWS was treated through a facility air stripper prior to discharge to a NPDES outfall. Figure 3.5 (Westinghouse Savannah River Company, et al. 2003) shows the process flow diagram of the DUS/HPO system, with vapor and wastewater treatment. The 6M-SVEU was operated to keep levels of contaminants in the vapor discharge below air emission limits.

Steam for injection into the three well clusters was supplied from other industrial operations at SRS. Facility steam pressure was reduced to 100 pounds per square inch (psi) prior to entering the DUS/HPO system.

Subsurface temperatures were monitored using a series of 14 thermocouple strings, each fitted with up to 24 individual Type-K thermocouples. The thermocouples allowed measurement of subsurface temperatures at approximate 6-foot intervals from 20 feet bgs to 160 feet bgs. In addition to the thermocouples, ERT was used to monitor subsurface temperatures between the thermocouple locations. ERT uses low-frequency electric current injected at one pair of metal electrodes and measuring the voltage at the second metal electrode. The differences in voltage relate to the temperature differentials of the soil.

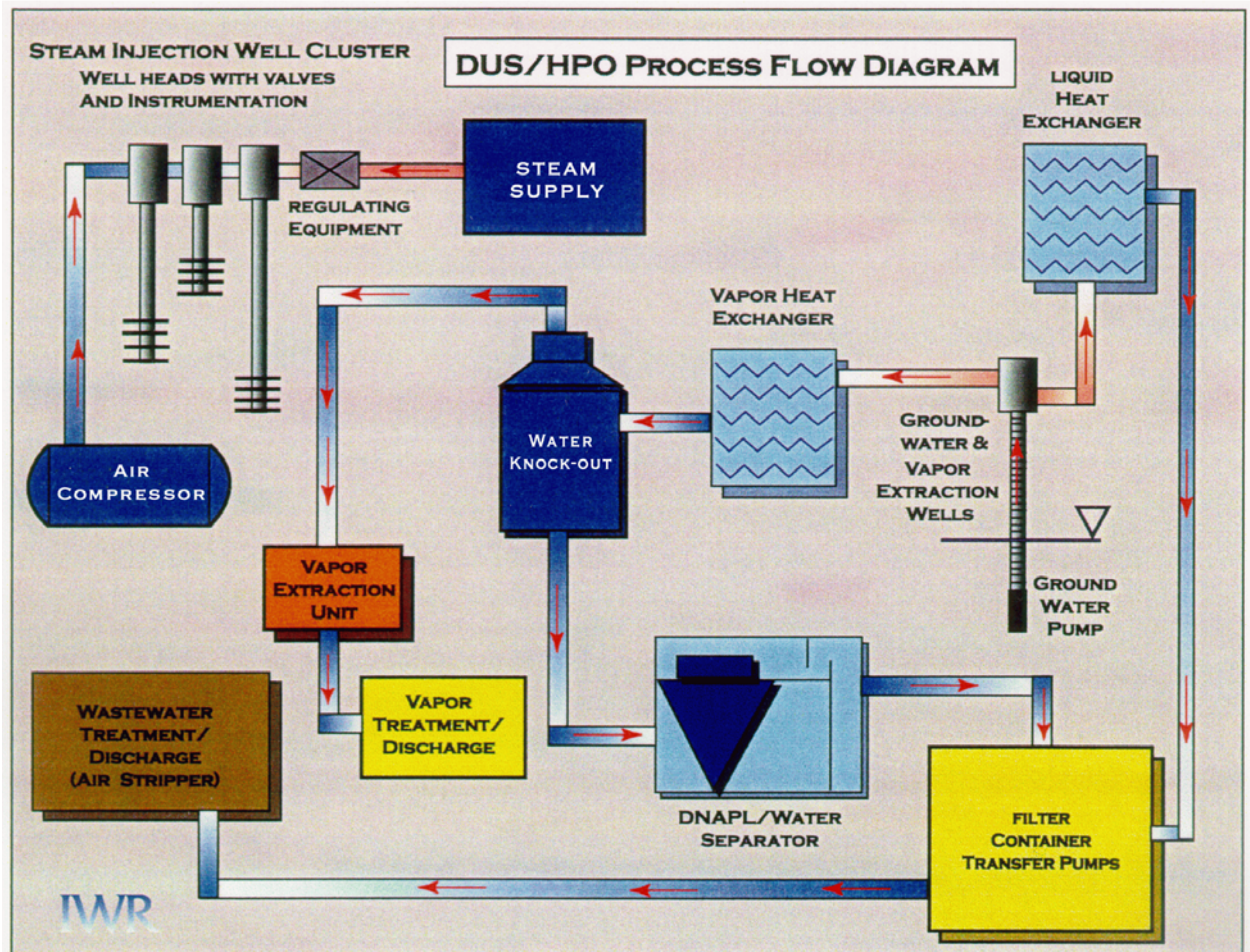
3.3.3 Operation of DUS/HPO System at SRS

Operation of the DUS/HPO system began on 9 September 2000 and continued until 28 September 2001. Over the 1-year operational period, steam injection occurred 36 percent of the time, or for 3,226 hours. The total amount of steam injected was 45,400,000 pounds. The heat content of this steam was 45.4×10^6 British Thermal Units (BTUs). Sustained steam injection periods occurred during November through December 2000, January through March 2001, and April through May 2001. Steam injection continued on a 24-hour basis during these periods.

Initial steam injection to the deep zone was conducted at a pressure of 60 pounds per square inch gauge (psig) and at a temperature of 152 ºC. Injections in the intermediate and upper zones were conducted at 40 and 25 psig, respectively, with temperatures of 143 ºC and 127 ºC, respectively. In addition, initial heating was performed in the saturated zone to create a "hot plate" at the base of the treatment area. This approach helped drive the contaminants in the saturated zone toward the central groundwater and vapor extraction well (DUS-10) and limit the contaminant's potential for dispersal in the subsurface.

The steam injection rate reached a maximum of 20,000 pounds per hour in February 2001 and was held through March 2001. Steam injection was not continuous throughout the project period. Initial steam injection occurred from September through mid-October, then steadily in November and December. Steam injection was renewed in February to mid-March 2001, at which time it was temporarily halted. Steam injection occurred again

Figure 3.5 SRS DUS/HPO Process Flow Diagram



in April and May 2001, then for only several days at a time in June, August, and September 2001. Continuous steam injection was not necessary because after the target source zone temperature of 87 ºC was reached, the soil in the treatment area was able to hold this temperature for several weeks without the need for additional steam.

By December 2000, the average temperature of soil in the treatment area was 87 ºC and the groundwater temperature reached 100 ºC. Steam breakthrough to DUS-10 occurred in late-November, after approximately eight weeks of steam injection. Complete site heat up, based on the boiling point of TCE, was reached in March 2001, 20 weeks after steam injection began. The majority of the steam injection after March 2001 was into the shallow zone, as this area cooled more quickly than the deeper zones.

Air injection into the saturated zone for the purpose of enhancing the HPO process began in December 2000. Air injection took place for 10-hour periods during manned operational periods, and occurred at injection rates of approximately 5 scfm. Subsequent air injection into the saturated zone occurred whenever steam was injected into the deepest well screen intervals. During the later stages of the project, air injection into the deep wells occurred intermittently during periods when steam was injected into the shallow interval.

The SSTA extraction system included groundwater extraction at DUS-10 and vapor extraction at DUS-10, MVE-1, MVE-2, and MVE-3. After steam breakthrough occurred at DUS-10 in November 2000, the groundwater extraction rates averaged approximately 10 gallons per minute (gpm) until December 2000, at which time extraction was discontinued due to the extraction of larger volumes of condensed steam than groundwater.

The average vapor extraction rate from the four vapor wells was 350 sfcm at a vacuum of 5.1 inches of mercury. The condensate load in the vapor averaged 20 gpm after steam breakthrough occurred at DUS-10. Over 2,000,000 gallons of condensate were recovered by the system and treated through the facility air stripper. The non-condensable vapor extraction rate averaged 300 scfm. Treatment of this vapor stream was not required, as the system was operated at a flow rate that ensured emission limits were not exceeded.

The vapor stream was continuously monitored for contaminants using an in-line multi-gas monitor. In addition, samples of the condensate and vapor were collected on a daily basis for laboratory analysis. Concentrations of PCE in the vapor stream increased steadily over the first five months of operation, reaching levels above 1,000 ppm. In March 2001, the emission limits for the project were increased. Less dilution air was introduced into the vapor stream, and PCE concentrations increased to over 5,000 ppm before falling to between 1,000 and 2,000 ppm for the remainder of the project.

3.3.4 Contaminant Mass Removal

Based on the continuous monitoring and daily sampling of the vapor stream, 66,000 pounds of PCE and 2,200 pounds of TCE were removed during the project. Daily removal rates of total contaminants began at 16 pounds per day and reached 1,229 pounds per day in April 2001. The average contaminant mass removal rate for the entire operational period was 190 pounds per day.

The extent to which the HPO process destroyed additional contaminant mass in the subsurface has not been quantified. Estimates based on other DUS/HPO projects and experimental work suggests that the mass of dissolved phase solvent contamination destroyed by HPO could range from 10 to 30 percent of the contaminant mass removed.

The total mass removed, excluding any mass destroyed by HPO, was 68,200 pounds, which exceeded the pre-treatment estimate of 26,000 pounds. Estimation of contaminant mass is difficult, particularly for sites with a deep vadose zone and DNAPL contamination.

The total mass removal of PCE and TCE in the 2,000,000 gallons of groundwater and condensate recovered during the project was estimated at 75 and 10 pounds, respectively.

3.3.5 Post-Implementation Sampling/Monitoring Results

3.3.5.1 Soil Sample Results

Four soil borings were completed in the treatment area following completion of the DUS/HPO project. Post-treatment characterization of soil in the treatment zone (i.e., below approximately 20 feet bgs) indicates that TCE soil concentrations are below 0.01 milligrams per kilogram (mg/kg), with the exception of a single analytical result of 0.1 mg/kg at a depth of 25 feet bgs. PCE soil concentration data from post-treatment characterization indicate concentrations are below 0.1 mg/kg with the exception of two analytical results of 0.5 mg/kg and 10 mg/kg, both at 25 feet bgs. However, as these samples were collected from above the zone of soil remediation that was targeted by the DUS/HPO project (the project targeted soils below 40 feet bgs), these results are not surprising. The post-treatment characterization data also confirmed that high concentrations in shallow (less than 20 feet bgs) clay horizons is likely responsible for the continuing tail of PCE and TCE concentrations measured near the end of the treatment period. The shallow soil was not targeted because of the possibility of soil expansion due to steam injection as well as short-circuiting of injected steam that could cause a health and safety concern.

The unresolved issue that remains is how much residual contamination remains in the treatment zone from the ground surface to approximately 20 feet bgs. This zone is above the depths of both the steam injection and SVE well screens. Although it has not been totally resolved, SRS installed a shallow SVE system in 2003. This system is intended to remove contaminant mass that remains in soil from the ground surface to 40 feet bgs. The system removed approximately 1,100 pounds of PCE and TCE in the first four months of operation.

3.3.5.2 Groundwater Monitoring Results

Post-treatment groundwater sampling has not been completed as of June 2004. This is because all monitoring wells within the treatment area were grouted to the ground surface prior to installation of the DUS/HPO system. Their removal was necessary to prevent short-circuiting of steam that would likely occur if the wells had remained in place. New groundwater monitoring wells have not yet been installed because soil temperatures in the treatment zone remained above 50 ºC until early in 2004. New wells are planned for installation in the summer of 2004.

Although no monitoring wells are currently located within the treatment area, three facility-wide compliance monitoring wells and one area-wide groundwater recovery well are in somewhat close proximity to the treatment area. Data from the compliance wells showed declining or stable levels of dissolved PCE before the DUS/HPO project. These data also show no significant effect on the trends for dissolved PCE concentrations after more that one year post-treatment at the 321-M area. However, data from the area-wide recovery well, RWM-2, which is located approximately 80 feet from the treatment area, may indicate a decrease in PCE and TCE concentrations as a result of the DUS/HPO project. For at least four years previous to the DUS/HPO project, these wells showed relatively consistent levels of both TCE (approximately 12,000 μg/L) and PCE (approximately 12,000 μg/L). Groundwater samples from both wells showed a marked decrease in TCE and PCE concentrations during a sampling event two years after completion of the DUS/HPO project (no sampling was conducted between the end of the DUS/HPO project and October 2003 due to water temperatures in excess of 50 ºC). The concentrations of TCE and PCE during the October 2003 sampling event were approximately 1,500 and 2,500 μg/L, respectively. Although groundwater samples from both wells showed rebound in concentrations to approximately 6,000 μg/L TCE and 8,000 μg/L PCE in the December 2003 sampling event, these values were still below the 12,000 μg/L average concentrations measured before the DUS/HPO project.

3.3.6 Thermal Project Cost

The total cost for this project, including the pre-characterization study and pre-project demolition work was approximately $4,500,000 (Mr. James Kupar, Bechtel Savannah River, Inc., personal communication, May 2004). A rough estimate of pre-project work costs is $250,000, which leaves $4,250,000 for the DUS/HPO project. The costs for steam generation and treatment of vapor, groundwater, and condensate were not included in this cost as these services were provided by existing facilities at SRS, which resulted in significant savings for the DUS/HPO project as these services did not have to be constructed and operated for this project. Based on a treatment area of 10,000 square feet and a depth of 160 feet, the total volume of soil treated was 59,300 cubic yards. The unit costs based on these values, and excluding the cost for steam generation and water/vapor treatment, is $72 per cubic yard. On a per pound of PCE and TCE removed basis, the unit cost for the project was $64 per pound of these two contaminants. If the costs for steam generation and the cost for treatment of vapor, groundwater, and condensate are included, the unit costs would be an estimated $118 per cubic yard of soil treated, or $105 per pound of PCE and TCE removed (see Section 4.3.1 for details on this cost analysis). However, these unit costs are within the range of previously completed soil remediation projects.

The Interstate Technology Regulatory Council (ITRC) reported the cost of this project at $29 per cubic yard, but did not indicate what was included in the cost or how it was calculated (ITRC DNAPL Team, 2002). The ITRC did state that the cost for steam generation and treatment of vapor and dissolved phase contaminants were not included in their estimated unit cost.

3.4 YORKTOWN DEFENSE FUEL SUPPLY POINT, YORKTOWN, VA

Much of the information related to the Yorktown DFSP site presented in this section was provided in the *Final Work Plan for Remediation of POL at NSFO Tank Farm, Fleet and Industrial Supply Center, Defense Fuel Supply Point Yorktown, Virginia* (OHM Remediation Services Corp., August 13, 1999).

3.4.1 Site Description

The Yorktown DFSP, an operations unit of the Norfolk Fleet and Industrial Supply Center, is located in central York County in Yorktown, Virginia (Figure 3.6 [OHM Remediation Services Corp., 1999]). The US Coast Guard Reserve Training Center is located immediately northeast of the site, and the Colonial National Historic Park is to the west and north. The Yorktown DFSP facility is a US Navy fuel depot, which presently stores and distributes JP-8 aviation fuel to a number of DOD customers. The Yorktown DFSP facility is an 11-acre site that was activated in 1918 with the construction of eight 90,000-barrel (3,420,000 gallon) capacity, reinforced concrete underground storage tanks (USTs). These USTs were approximately 162 feet square and 17 feet deep, and were used for storage of Navy Special Fuel Oil (NSFO) until 1975. NSFO is a ship fuel, the equivalent of No. 5 heavy fuel oil that is produced by blending No. 6 fuel oil and light petroleum distillates (Perry, 1984). NSFO has a specific gravity similar to water, is a light non-aqueous phase liquid (LNAPL), is very viscous, and requires heating to be pumpable.

In 1998 the eight concrete tanks were cleaned, then demolished, and abandoned in place. The ground cover over the tanks was removed, and the top of each tank crushed and backfilled into the empty tank. The bottom of each tank was perforated using a hydraulic ram, then the upper portions of the tank walls were demolished and backfilled into the tanks. Additional crushed concrete and on-site soils were backfilled into the tanks to allow final grading. The entire NFSO tank farm area was graded to match the original 1918 topography. Figure 3.7 (Field Support Services, Inc. [a division of Shaw Environmental and Infrastructure] 2004) depicts the location of the abandoned USTs.

The shallow subsurface of the site is characterized as coastal sediments consisting of unconsolidated deposits of fine-grained sand, silts, and marine shells. The near-surface geology is characterized by medium- to fine-grained sand with varying amounts of silt and trace amounts of coarse sand and clay. The abandoned USTs and floating NSFO are located within these sediments. Groundwater is encountered at depths ranging from 6 to 26 feet bgs, and flows to the southeast toward a creek located east of the site. The reported hydraulic conductivity of the shallow aquifer is 2.41 feet per day (ft/day), indicating the shallow aquifer has low water transmitting capability.

A floating NAPL plume, up to 12 feet thick in site monitoring wells, has been identified over most of the former tank farm area and extends eastward beyond the tank farm area (Figure 3.7). The estimated volume of NSFO released into the tank farm area is

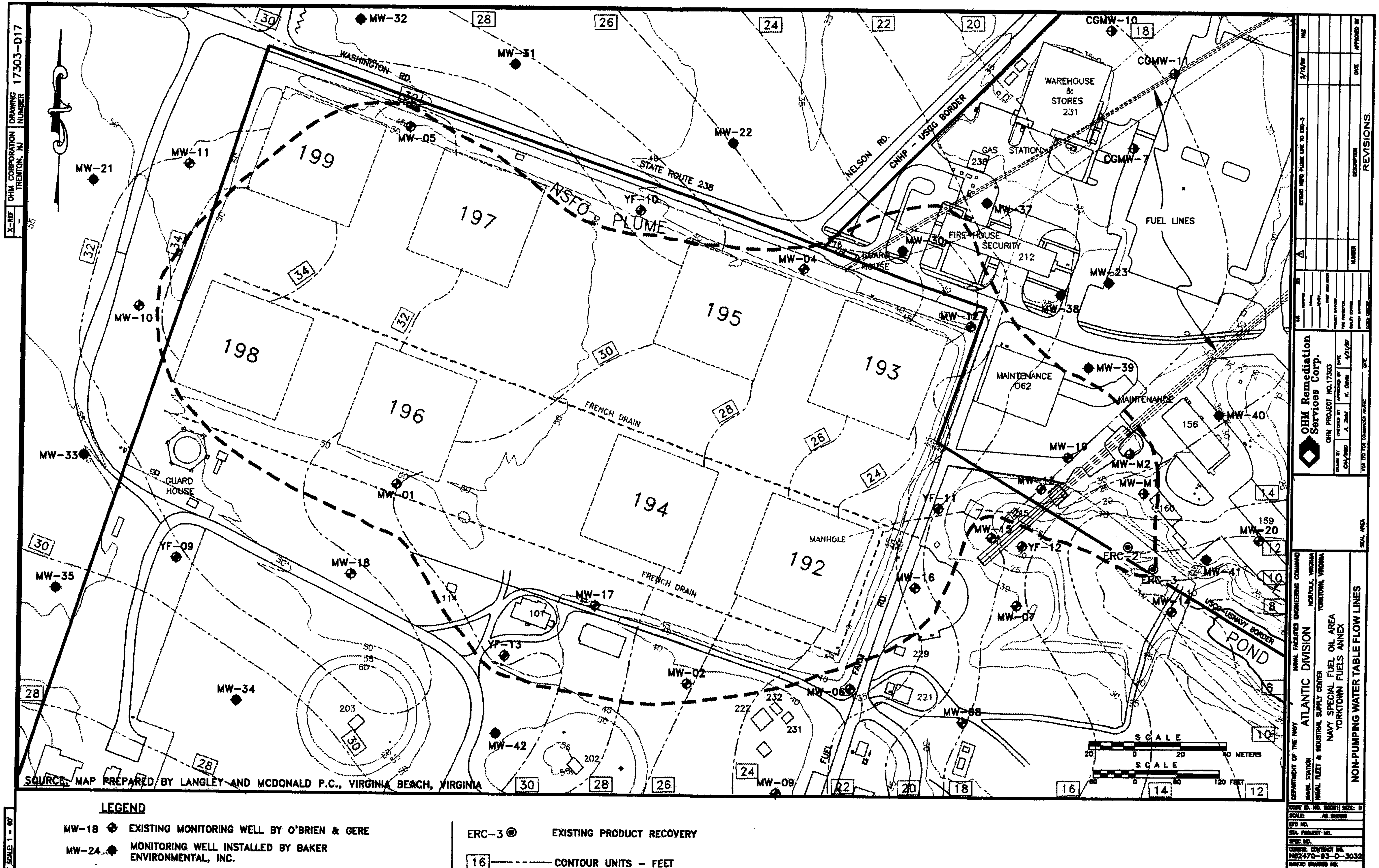
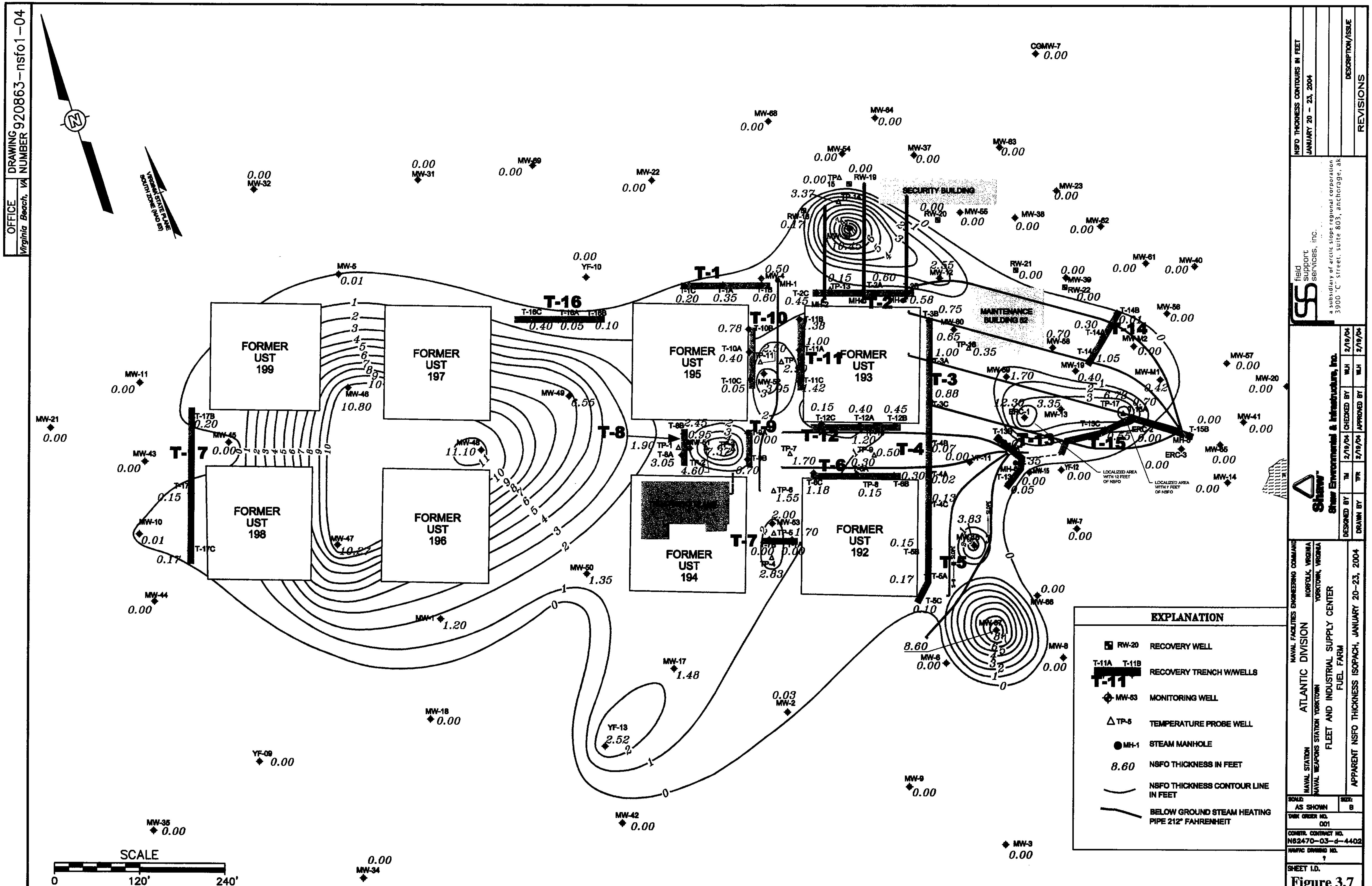

NSFO PLUME
WASHINGTON RD.
STATE ROUTE 238
NELSON RD.
CNHP - USCG BORDER
USCG-USNAVY BORDER
POND
WAREHOUSE & STORES 231
GAS STATION
FIRE HOUSE
SECURITY 212
GUARD HOUSE
MAINTENANCE 062
MAINTENANCE
FUEL LINES
FRENCH DRAIN
MANHOLE
FUEL FARM RD.
SOURCE: MAP PREPARED BY LANGLEY AND MCDONALD P.C., VIRGINIA BEACH, VIRGINIA
LEGEND
MW-18 EXISTING MONITORING WELL BY O'BRIEN & GERE
MW-24 MONITORING WELL INSTALLED BY BAKER ENVIRONMENTAL, INC.
CGMW-7 EXISTING MONITORING WELL INSTALLED BY THE COAST GUARD
ERC-3 EXISTING PRODUCT RECOVERY
16 CONTOUR UNITS - FEET
SCALE
20 0 20 40 METERS
60 0 60 120 FEET
OHM CORPORATION TRENTON, NJ
DRAWING NUMBER 17303-D17
OHM Remediation Services Corp.
OHM PROJECT NO. 17303
REVISIONS
DEPARTMENT OF THE NAVY
NAVAL FACILITIES ENGINEERING COMMAND
ATLANTIC DIVISION
NORFOLK, VIRGINIA
NAVAL STATION
NAVAL FLEET & INDUSTRIAL SUPPLY CENTER
YORKTOWN, VIRGINIA
NAVY SPECIAL FUEL OIL AREA
YORKTOWN FUELS ANNEX
NON-PUMPING WATER TABLE FLOW LINES
N62470-93-D-3032

Figure 3.6



OFFICE Virginia Beach, VA
DRAWING NUMBER 920863-nsfo1-04
VIRGINIA STATE PLANE SOUTH ZONE (NAD 83)
SECURITY BUILDING
MAINTENANCE BUILDING 82
FORMER UST 199
FORMER UST 197
FORMER UST 195
FORMER UST 193
FORMER UST 198
FORMER UST 196
FORMER UST 194
FORMER UST 192
LOCALIZED AREA WITH 12 FEET OF NSFO
LOCALIZED AREA WITH 7 FEET OF NSFO
SCALE
0 120' 240'
EXPLANATION
RW-20 RECOVERY WELL
T-11A T-11B T-11 RECOVERY TRENCH W/WELLS
MW-53 MONITORING WELL
TP-5 TEMPERATURE PROBE WELL
MH-1 STEAM MANHOLE
8.60 NSFO THICKNESS IN FEET
NSFO THICKNESS CONTOUR LINE IN FEET
BELOW GROUND STEAM HEATING PIPE 212° FAHRENHEIT
NSFO THICKNESS CONTOURS IN FEET
JANUARY 20 - 23, 2004
DESCRIPTION/ISSUE
REVISIONS
field support services, inc.
a subsidiary of arctic slope regional corporation
3900 "C" street, suite 803, anchorage, ak
Shaw Shaw Environmental & Infrastructure, Inc.
DESIGNED BY TM 2/10/04
CHECKED BY WJH 2/10/04
DRAWN BY TFR 2/10/04
APPROVED BY WJH 2/10/04
NAVAL FACILITIES ENGINEERING COMMAND
ATLANTIC DIVISION
NAVAL STATION NORFOLK, VIRGINIA
NAVAL WEAPONS STATION YORKTOWN YORKTOWN, VIRGINIA
FLEET AND INDUSTRIAL SUPPLY CENTER FUEL FARM
APPARENT NSFO THICKNESS ISOPACH, JANUARY 20-23, 2004
SCALE: AS SHOWN
SIZE: B
TASK ORDER NO. 001
CONSTR. CONTRACT NO. N62470-03-d-4402
NAVFAC DRAWING NO.
SHEET I.D.
Figure 3.7

3,000,000 gallons. Although NSFO is highly viscous at the average soil temperature at the site, the Yorktown DFSP USTs contained steam heating coils to make the NSFO pumpable. Heat from the USTs was sufficient to warm the soil and groundwater around the tank farm area and enable the NSFO to migrate away from the USTs.

Soil samples have indicated minor concentrations of TCE (<14 μg/kg), benzene (<3 μg/kg), PCE (<80 μg/kg), and total xylenes (<4 μg/kg). Total petroleum hydrocarbons (TPH) have been found at concentrations as high at 36,800 mg/kg. Groundwater samples collected outside the area of the floating NAPL plume have shown non-detectable concentrations of organic compounds, indicating that no dissolved phase plume exists beyond the NAPL plume.

3.4.2 Thermal Technology Description

3.4.2.1 General Description of Steam Recirculation Heating Technology

Steam recirculation technology uses buried pipes to convey steam into the subsurface to heat the soil and mobilize contaminants. This technique can heat volatile and semi-volatile compounds thereby increasing their vapor pressures and making removal by vapor extraction more efficient. The technique can also be used to heat viscous or high-boiling point NAPL to increase its mobility and facilitate its removal via liquid extraction (NAPL-only extraction or combined with groundwater extraction to increase hydraulic gradients toward extraction wells). Depending on the steam pressure used, temperatures well above 100 ºC can be achieved in soil near the recirculation pipes. Recovered vapor and/or groundwater are treated above ground to remove contamination before discharge to the environment. Conveyance of steam in buried pipes can result in greater control of heat input into potentially sensitive areas such as near streams or occupied buildings. It also may enable greater control of contaminant migration as compared to direct steam injection, which can result in surface emission of vapors or uncontrolled migration of contaminant laden steam away from vapor extraction wells.

3.4.2.2 Description of Steam Recirculation Technology Used at Yorktown Fuels Site

Steam recirculation heating combined with NAPL and groundwater extraction has been implemented over a portion of the Yorktown NSFO site (Figure 3.7). Full-scale implementation of the technology will be conducted in a phased approach so that hydraulic control of groundwater migration can be fully realized before heat is applied to the entire site. Additionally, the potential of uncontrolled migration of heated NSFO was to be determined before full-scale application. Based on the positive results of the initial phase in 2000 through mid-2003, implementation of the technology for the remainder of the site was approved in 2003. Construction of the full-scale system began in early 2004, and start-up of the expanded system is planned for late 2004.

Seventeen trenches were constructed for the extraction of mobile NSFO and groundwater (Figure 3.7). The trenches were constructed using single pass trenching techniques, and extended to depths of at least 8 feet below the lowest measured seasonal groundwater table. The trenches were backfilled with high-permeability gravel and were sloped toward vertical multi-phase recovery wells. Both groundwater extraction and NSFO skimmer pumps were installed in the recovery wells. Recovered NSFO and groundwater were conveyed to a central treatment plant, where the NSFO was stored for disposal, and the water was treated for discharge to the York River or for heating and re-injection into upgradient trenches to increase hydraulic gradients and NSFO capture at downgradient trenches.

The trench locations constructed in the initial phase of the remediation were designed to impact the northeast corner of the tank farm and the off-tank farm areas to the east and northeast of site. Much of the tank farm area could not be directly impacted by the trenches due to the presence of the demolished USTs. However, because the floating NAPL plume was well above the bottom of the USTs, the mass of NAPL under the USTs was considered negligible compared to the floating NAPL plume.

Twelve steam recirculation pipes with a combined length of 3,370 feet were installed using directional drilling techniques. Directional drilling was used to minimize disturbance of the soil, which would affect the uniformity of heat transfer into the soil. The steam pipes were installed so that their depths would be approximately 1 foot below the stable groundwater table that would develop during active groundwater extraction. Several thermocouple wells were installed near and between the pipe runs to monitor the groundwater temperatures at the site.

Steam was produced by a packaged boiler system that delivered saturated steam at 116 ºC and an operating pressure of 10 psig. The boiler was sized with an 8 to 1 turndown ratio to allow operation of the boiler at approximately 25 percent capacity, which provided sufficient steam for the initial phase of remediation. The boiler would operate near 100 percent capacity to provide steam for the expanded heating system that will be necessary to treat the entire NSFO plume area. The boiler system is located within the central NSFO and groundwater treatment plant.

The central NSFO and groundwater treatment plant includes a heated tank to hold recovered NSFO and a water treatment system to remove contaminants from recovered groundwater prior to discharge to the York River or re-injection at upgradient recovery trenches. The groundwater treatment system includes dissolved air flotation (DAF) for removal of metals and NSFO, clay adsorbers to remove dissolved hydrocarbons, and bag filters and oil-absorbent bag filters to remove additional sediment and NSFO. For water that is discharged to the York River, additional treatment includes granular activated carbon adsorbers to polish the water and heat exchangers to cool the water prior to discharge. Recovered water that is re-injected into the site subsurface is treated only through the DAF unit, the clay adosrbers, and bag filters, then is heated to approximately 60 ºC prior to re-injection.

3.4.3 Operation of Steam Circulation System at Yorktown Site

NSFO skimming began in April 2000, primarily at the property boundaries adjoining the Coast Guard Reserve Training Center and the Colonial National Historic Park. Skimming-only was implemented early to achieve control of NSFO migration onto those properties prior to initiation of groundwater extraction or steam heating. Groundwater recovery at the 17 extraction trenches began in July 2000. This was implemented so that hydraulic control of groundwater flow could be achieved before steam injection was initiated. Steam heating operations began in May 2001.

Groundwater and NSFO temperatures in the vicinity of the steam heating pipes are elevated relative to the remainder of the site (Field Support Services, Inc. 2004). The groundwater/NSFO temperatures in the vicinity of Trenches T-2 and T-4, located on US Coast Guard property, consistently exceed 100 degrees Fahrenheit (ºF). In most of the remaining Phase I area, the groundwater/NSFO temperature is elevated relative to background. Background temperatures range from the low 60s to low 70s. In March 2004, groundwater/NSFO temperatures in the treatment area ranged from 38.8 ºF to 144.9 ºF. The average temperature for the site in March 2004 was 71.3 ºF.

Groundwater extraction rates range from 480,000 to 580,000 gallons per month, and the average rate has varied little since groundwater extraction began in July 2000. Until 24 November 2002, all recovered groundwater was treated through the central treatment plant and discharged into the York River. Compliance monitoring has shown that all water discharged into the river has met discharge criteria.

On 24 November 2003 an infiltration pilot test was initiated at Trench T-9, located roughly in the center of the Phase I treatment area (Field Support Services, Inc. 2004). Groundwater that had been treated in the central treatment plant was heated to 140 ºF, then injected back into Trench T-9. A 5 gpm infiltration rate was ultimately achieved. Following the successful pilot test, infiltration of heated water became a regular operation that commenced on 7 January 2004. Infiltration rates have ranged from 157,000 to over 220,000 gallons per month since injection of heated water began in January 2004. Data from December 2003 indicated that the groundwater/NSFO temperature had increased by 30 ºF in the vicinity of Trench T-9.

3.4.4 Contaminant Mass Removal

Since system start-up in April 2000, approximately 195,400 gallons of NSFO have been recovered from the site. This includes just over 14,000 gallons that were recovered between July 1997 and April 2000 by hand bailing and vacuum truck pumping.   From

17 April 2000 to 29 July 2000, approximately 4,000 gallons of NSFO were recovered by skimming alone. Between July 2000 and 21 May 2001, over 55,000 gallons of NSFO were recovered by active groundwater extraction combined with NSFO skimming. The average recovery rate of NSFO during the July 2000 to May 2001 time period was approximately 4,600 gallons per month. The recovery rate of NSFO appeared to drop off in March 2001 to an average rate of approximately 1,600 gallons per month. Activation of steam heating in May 2001 increased the recovery rate in June 2001 to almost 4,000 gallons. In the 34 months since heating began, 122,300 gallons of NSFO have been recovered. The average recovery rate since May 2001 was 3,600 gallons per month (Field Support Services, Inc. 2004).

3.4.5 Post-Implementation Sampling/Monitoring Results

3.4.5.1 Soil Sample Results

Because the Yorktown DFSP NSFO remediation project is ongoing, no soil samples have been collected since operation of the NSFO heating and extraction system began.

3.4.5.2 Groundwater Monitoring Results

This project is ongoing, and NSFO NAPL still exists within the treatment area. Due to the presence of NAPL, no groundwater samples have been collected within the treatment area, and no conclusions could be made regarding dissolved phase contamination in groundwater within the active treatment area. However, groundwater samples are collected from immediately outside the NAPL plume on a quarterly basis to the east of the plume, the direction that was downgradient with respect to groundwater flow before groundwater extraction began. These samples have consistently shown non-detectable levels of dissolved petroleum hydrocarbons, indicating that the dissolved plume is contiguous with the NAPL plume (Field Support Services, Inc. 2004).

3.4.6 Thermal Project Cost

The total capital costs for Phase I of the Yorktown DFSP remediation were $7,000,000, which included construction of the extraction trenches ($1,500,000), installation of horizontal steam pipes ($2,000,000), installation of recovery and monitoring wells ($700,000), and construction of the central treatment plant and boiler ($2,800,000). Operations and maintenance (O&M) costs since April 2000 have averaged $1,200,000 per year (Mr. William Hughes, Shaw Environmental & Infrastucture, Inc., personal communication, May 2004).

The total amount expended to date for the Phase I remediation is $12,000,000. It is estimated that it will require another 12 years to reach the remedial action objectives established for the site. The additional O&M cost for these 13 years is estimated at $14,400,000 (this assumes 12 more years at $1.2 MM per year). Based on the total expended to date and the estimated cost to complete, the total cost expended to complete remediation of the Phase I area could be as high as $26,400,000.

Construction of Phase II is estimated at $4,000,000, and the O&M costs for the combined Phase I and Phase II areas is estimated at $1,600,000 per year. The estimated total construction costs for both phases is $11,000,000, and the total O&M cost, assuming 12 more years operation of Phase 1 and 15 years operation of Phase II, are estimated at $22,800,000 (this assumes $1,600,000 per year for 12 years and $1,200,000 per year for three years). If remedial goals are achieved in the expected 15-year time frame, the total remedial costs are estimated at $33,800,000. Assuming a treatment area of 11 acres and an average depth to groundwater of 16 feet, the unit costs for remediation would be $120 per cubic yard of soil.

3.5 POLELINE ROAD DISPOSAL AREA, FORT RICHARDSON, AK

Much of the information related to the Fort Richardson, AK Poleline Road Disposal Area presented in this section was provided in the *Final Interim Remedial Action Report Operable Unit B – Poleline Road* (US Army Corps of Engineers, June 2003).

3.5.1 Site Description

The Poleline Road Disposal Area (PRDA) is located in a wooded area on Fort Richardson, Alaska. The site was used as a chemical disposal area from 1950 to 1972.

During this time, chemical agent identification sets and other military debris were burned and disposed of in four unlined trenches. Standard practice for disposal of the sets consisted of placing a layer of "bleach/lime" in the bottom of a trench, then placing materials that were contaminated with chemical agents on a pallet in the trench (Woodward-Clyde, January 1997). Diesel fuel was then poured on the materials and ignited with a thermal grenade. After burning was complete, a mixture of either bleach or lime, combined with chlorinated solvents, TCE, PCE, and 1,1,2,2-tetrachloroethane (1,1,2,2-PCA) was poured over the burn pile.

Four such trenches were used at PRDA (Figure 3.8 [US Army Corps of Engineers, June 2003]). A removal action was conducted in 1993 and 1994, during which waste material from two of the pits (A-3 and A-4) was excavated, treated off the PRDA site (but on Fort Richardson property), and stockpiled near the soil treatment area. Soil and waste were excavated to a maximum depth of 14 feet, where groundwater was encountered. The removal actions did not address the other two trenches (A-1 and A-2) due to the suspected presence of unexploded ordnance. Additionally, geophysical surveys of trenches A-1 and A-2 indicated these pits contain less significant quantities of buried waste, and therefore less contaminated soil than found in trenches A-3 and A-4.

Soil at the PRDA site consists of very dense glacial sediments and glacial till. These deposits are up to 36 feet thick and consist of unstratified to poorly stratified clays, silts, sands, gravels, and boulders. A basal till lies below the surficial deposits.

Four water-bearing intervals have been identified at the site: a perched zone, a shallow groundwater zone, an intermediate zone, and a deep aquifer. The perched zone is encountered at 4 to 10 feet bgs and is approximately 5 feet thick. The shallow zone is encountered at 20 to 25 feet bgs and is an average of 10 feet thick. Groundwater in the shallow zone flows to the northeast, away from a wetlands area that is located south of the PRDA. The intermediate groundwater zone is encountered at approximately 65 to 95 feet bgs, and the deep aquifer is encountered at 80 to 125 feet bgs. Hydraulic conductivities in all four zones are fairly low, with average values of 0.5 feet per day in all but the intermediate zone. The hydraulic conductivity in the intermediate zone averaged 0.05 feet per day. These low hydraulic conductivities suggest that groundwater flow at the site would be slow and would not significantly disperse dissolved contaminants by advective transport downgradient of the source area.

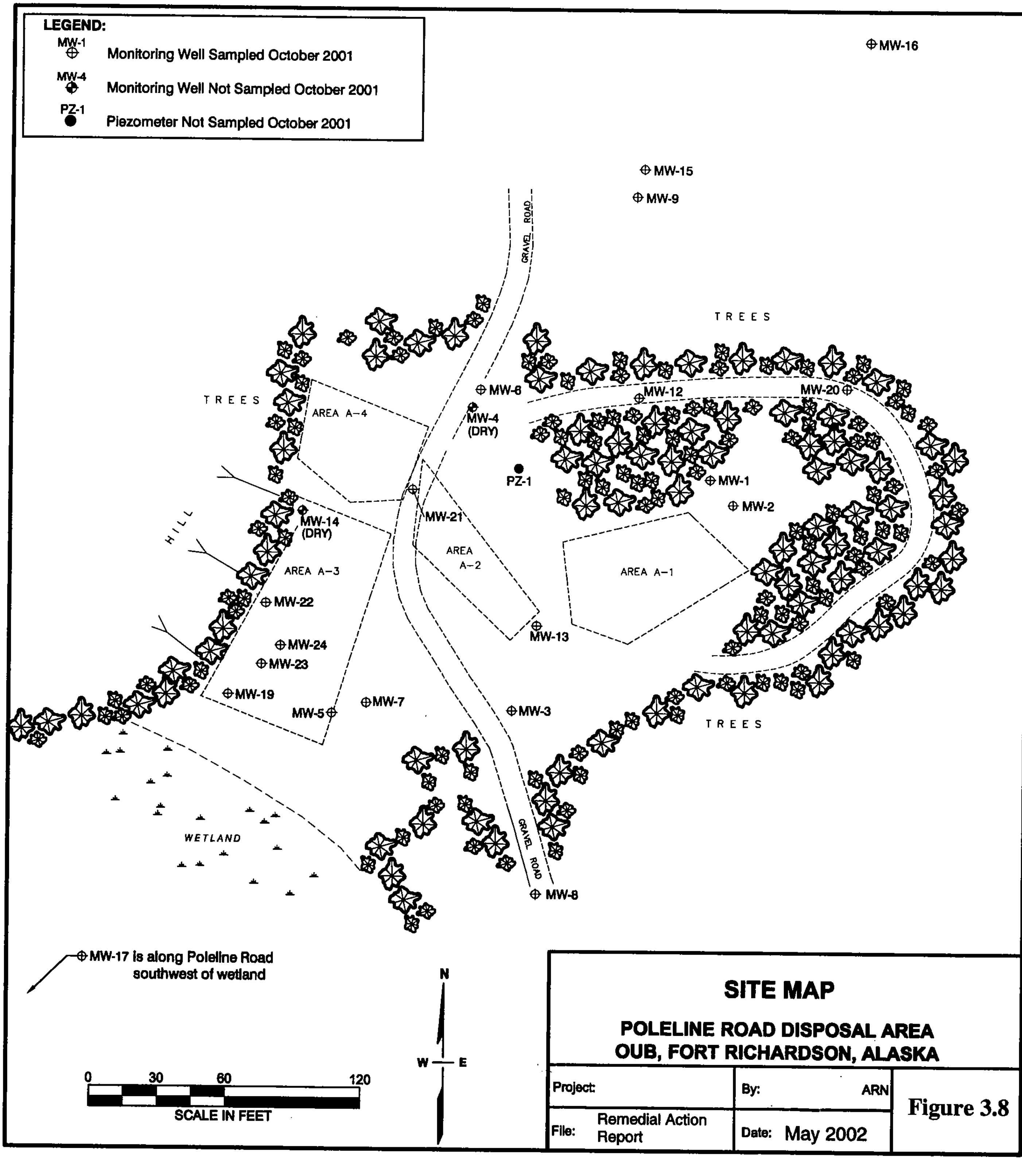
Soil sampling conducted after the wastes were excavated from trenches A-3 and A-4 indicated soil below the extent of excavation were contaminated with high concentrations of 1,1,2,2-PCA (greater than 2,000 mg/kg). TCE was also found at concentrations as high as 0.384 mg/kg. Lesser concentrations of chlorinated hydrocarbon contaminants were detected in soil near trenches A-1 and A-2; however, ordnance breakdown products were not detected. Based on the lower levels of chlorinated hydrocarbons and lack of ordnance breakdown products near trenches A-1 and A-2, it appears that waste contaminated with chemical agents were not disposed in those trenches.

Chlorinated solvent contamination was detected in all four water-bearing zones. TCE concentrations exceeded the state and federal maximum contaminant level (MCL) of 5 μg/L in all four water-bearing zones. 1,1,2,2-PCA was detected in the perched interval at concentrations as high as 1,900 milligrams per liter (mg/L). The concentrations of 1,1,2,2-PCA exceeded its risk based concentration of 52 μg/L in all four water-bearing zones. However, based on the groundwater samples, there was no evidence that contamination had migrated off-site (United States Army Alaska, October 2002). The level of chlorinated hydrocarbons found in groundwater at areas A-3 and A-4 did indicate the presence of a NAPL source for these contaminants.

3.5.2 Thermal Technology Description

3.5.2.1 General Description of SPSH Technology

Six phase soil heating was utilized at the Poleline Road site. A general description of this technology is provided in Section 3.2.2.1 for the Niagara Falls ARS site.



SITE MAP

POLELINE ROAD DISPOSAL AREA
OUB, FORT RICHARDSON, ALASKA

Project:		By:	ARN	**Figure 3.8**
File:	Remedial Action Report	Date:	May 2002	

3.5.2.2 Description of SPSH Technology Used at PRDA Site

SPSH was implemented in two phases at PRDA. In 1997, three arrays (Arrays 1, 2, and 3) were used to treat soil and groundwater in the area near Trench 4. In 1999, three more arrays (Arrays 4, 5, and 6) were used to treat soil and groundwater in the area near Trench 3. SPSH activities were considered to be treatability tests by the Army and US EPA. It was understood that the treatability test would hopefully lead to remediation of portions of the site, but full-scale implementation at one time would have required revision of the Record of Decision (ROD) for the site.

Arrays 1, 2, and 3

Arrays 1 and 2 were each 27 feet in diameter while Array 3 was 40 feet in diameter. The total area treated by the three arrays was 4,700 square feet (Figure 3.9 [US Army Corps of Engineers, June 2003]). The depth of treatment was 8 to 38 feet bgs. The total volume of soil treated was approximately 5,200 cubic yards.

All three arrays were arranged in hexagonal patterns, with six positive electrodes forming the perimeter of the array and one central neutral electrode. All electrodes were constructed of galvanized steel pipe that was slotted from 8.5 to 18.5 feet bgs to allow for the extraction of soil vapor and steam. Each electrode was installed to a total depth of 38 feet and constructed to heat soil from 8 to 38 feet bgs. The annular space between the borehole walls and electrodes was filled with granular graphite. The graphite was electrically conductive, and its granular nature allowed soil vapor and steam to pass freely from the soil to the screened portions of the electrodes. PVC covers were installed over the upper 8 feet of each pipe to isolate the soil interval from ground surface to 8 feet bgs. Drip tubes were installed in the annular space at the top of each electrode so that condensed steam (from the condenser described in the following paragraphs) could be introduced into the graphite backfill to maintain electrical conductivity from the electrode into the surrounding soil.

Power for Arrays 1 and 2 was supplied by a 455 kilowatt (kW) diesel generator, which supplied 480-volt, three-phase power to the six-phase transformer and other equipment on-site. Power for Array 3 was supplied by a 1,200 kW generator. The arrays were operated in a sequential fashion, with only one array operating at a time. The larger Array 3 required more power than the smaller Arrays 1 and 2, thus the need for a larger generator for Array 3.

The six-phase transformer was composed of six single-phase transformers, wired in such a way as to convert the three-phase incoming power into six single-phase outputs. The output from each single-phase transformer was connected to one of the six positive electrodes, and the center electrode was connected to the neutral legs of all six transformers.

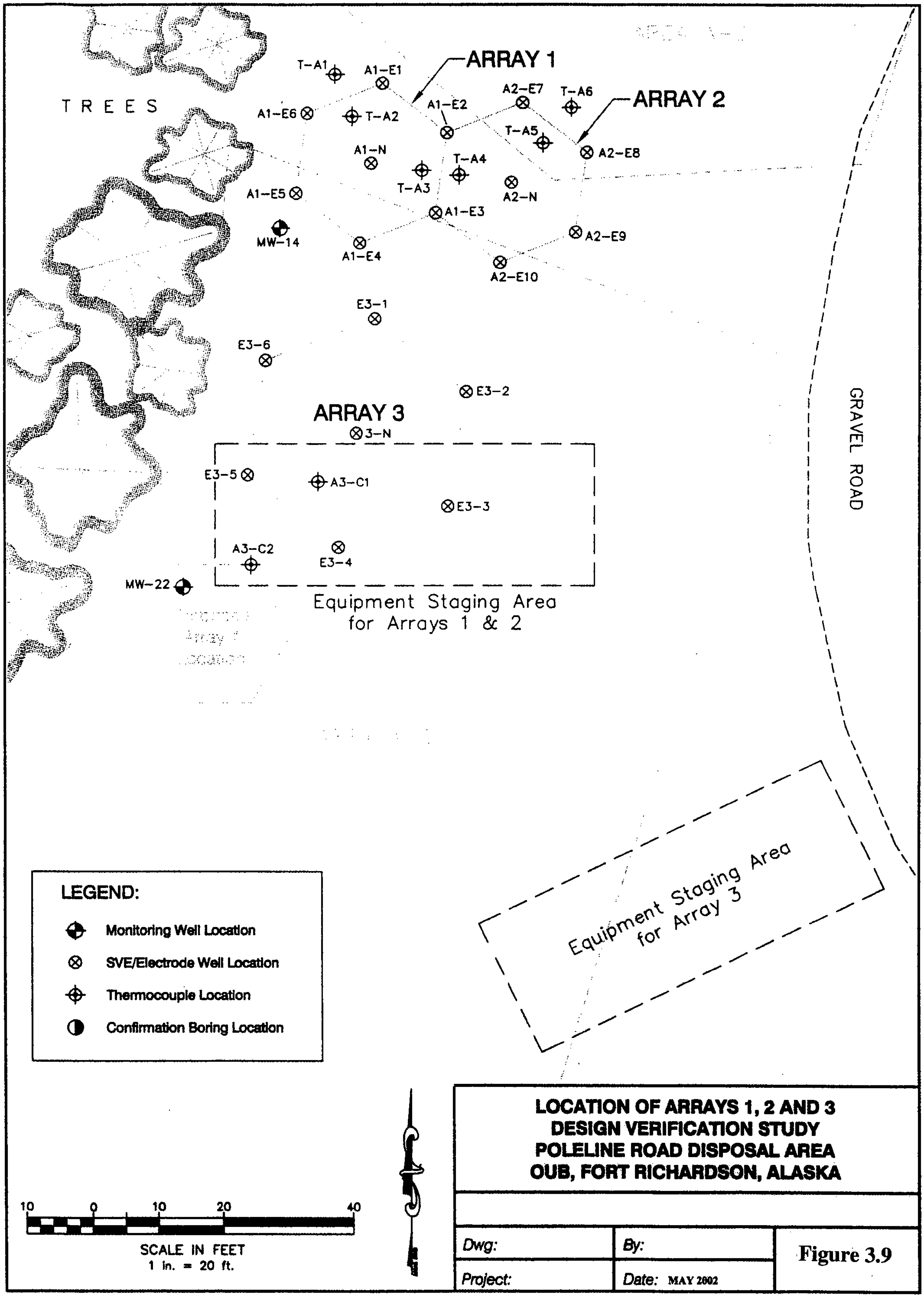
A 20-horse power (hp) positive displacement blower was used to extract soil vapors, which were initially treated through a condensing vapor/liquid separator then a catalytic oxidizer. Condensate from the separator was cooled then treated through a tray-type air stripper to remove VOCs from the water stream. Treated water from the stripper was sampled to ensure discharge parameters were met, then discharged into Area 2 (the area around Trench 2).

The oxidizer was only used to treat the vapor stream generated at Array 1. Stray current from the array made operation of the oxidizer extremely difficult (the stray current affected the oxidizers control system). Additionally, concentrations of organic contaminants in the vapor stream were less than anticipated, which allowed direct discharge of the vapor to the atmosphere.

Soil temperature data was collected from thermocouple borings installed in and around each array. Each thermocouple boring was constructed with individual thermocouples at three depths (either 10, 18, and 28 feet bgs or 24, 30, and 36 feet bgs).

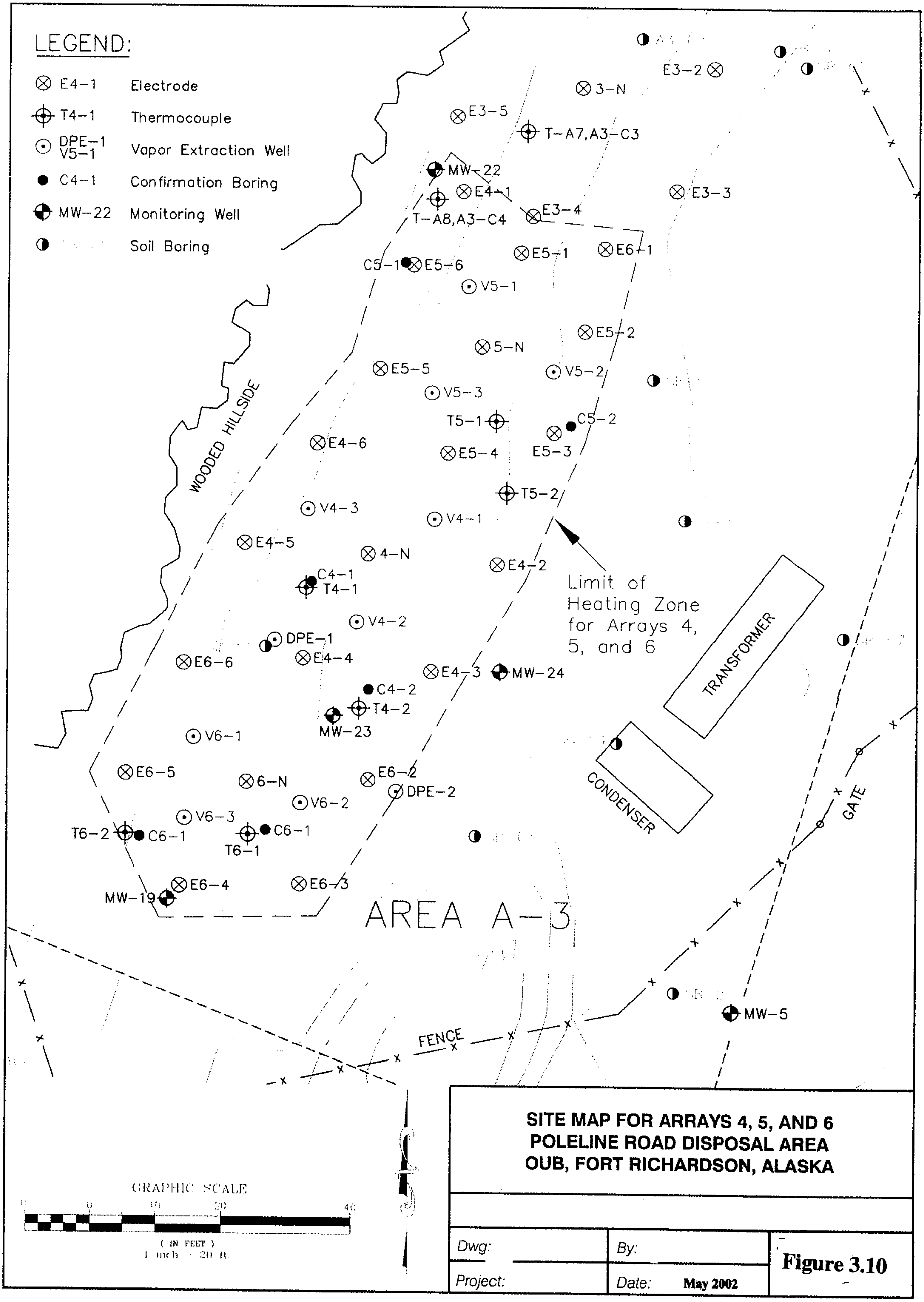
Arrays 4, 5, and 6

Arrays 4, 5, and 6 were arranged differently than the first three arrays. The electrodes were arranged in three rows with seven electrodes in each row (Figure 3.10 [US Army Corps of Engineers, June 2003]). Electrodes were spaced 19 feet apart and offset from adjacent rows by 9.5 feet. Although the electrodes were installed in rows, the overall arrangement formed three individual arrays. An area of 110 feet by 50 feet and 35 feet



LOCATION OF ARRAYS 1, 2 AND 3
DESIGN VERIFICATION STUDY
POLELINE ROAD DISPOSAL AREA
OUB, FORT RICHARDSON, ALASKA

Dwg:	By:	Figure 3.9
Project:	Date: MAY 2002	



SITE MAP FOR ARRAYS 4, 5, AND 6
POLELINE ROAD DISPOSAL AREA
OUB, FORT RICHARDSON, ALASKA

Dwg:	By:	**Figure 3.10**
Project:	Date: **May 2002**	

deep was heated by Arrays 4, 5, and 6. The treatment depth was from 8 to 35 feet bgs. The volume of soil treated was approximately 5,500 cubic yards.

All electrodes were installed to total depths of 35 feet bgs and did not include slotted portions for the extraction of soil vapor and steam (dedicated vapor extraction wells were installed in the interior of each array). Steel shot was used instead of graphite to backfill the annular space between the electrode and borehole wall. The shot was placed around the lower two-thirds of the electrodes, and was separated into three zones, 35 to 26 feet bgs, 25.5 to 18 feet bgs, and 17.5 to 11 feet bgs. Bentonite seals were placed between each zone to separate the steel shot intervals. Epson salt was added to the upper two intervals of steel shot to increase electrical conductivity between the electrodes and the borehole walls. The bentonite seals also minimized vertical migration of the Epson salt. Similar to Arrays 1, 2, and 3, PVC covers were placed over the top 8 feet of all the electrodes installed at Arrays 4, 5, and 6. Drip tubes were installed at the top of the annular space of each electrode to re-hydrate the steel shot/Epson salt backfill in the uppermost intervals. The lower two steel shot intervals were in groundwater and did not need drip tubes to re-hydrate the backfill material.

Power to the electrodes was supplied by the Matanuska Electric Association (local power company) by use of a buried electric cable installed for the treatability study. The use of diesel generators to power Arrays 1, 2, and 3 proved difficult due to the volume of diesel required – over 1,000 gallons per day for Array 3. Additionally, because all three arrays were operated simultaneously during the 1999 project, more power was needed than could be provided by any single generator that was available at Fort Richardson.

The transformer arrangement was the same as that used for Arrays 1, 2, and 3. Six single phase transformers were powered by a 480-volt, 3-phase power source. The only difference was that each single phase transformer was connected to three electrodes, one in each of the three arrays. This differed compared to the 1997 project in which each transformer was connected to only one electrode at a time at Arrays 1, 2, and 3, as these arrays were operated in a sequential fashion.

Three SVE wells were installed in the center of each array. Each well was screened from 8 to 28 feet bgs. Additionally, four temperature monitoring wells were installed within or near each of the three arrays. Individual thermocouples were installed at depths of 12, 25, and 38 feet bgs in each of the 12 temperature monitoring wells.

A 20-hp positive displacement blower was used to extract soil vapors, which were passed through a condensing vapor/liquid separator prior to discharge to the atmosphere. Condensate from the separator was cooled, then treated through a tray-type air stripper to remove VOCs from the water stream. Treated water from the stripper was sampled to ensure discharge parameters were met, then discharged into Area 2 (the area around Trench 2).

3.5.3 Operation of SPSH Systems at PRDA

Arrays 1, 2, and 3

Soil heating at Array 1 began on 11 July 1997 and continued for six weeks until 22 August 1997. Heating at Array 2 began on 24 August 1997 and continued until 9 October 1997. Heating at Array 3 began on 6 November 1997 and continued until 18 December 1997. Each array was heated for six weeks.

Soil from 10 to 24 feet bgs within Array 1 reached 100 ºC in 22 days and maintained this temperature within 5 ºC for the remainder of the heating period. Soil from 24 to 38 feet bgs reached temperatures ranging from over 60 ºC to nearly 100 ºC over the same period. With the exception of soil at 10 feet bgs outside Array 1, all soil within or just outside of this array achieved temperatures of at least 75 ºC during the heating period. Only the soil at 10 feet bgs to the east of Array 1 showed little effect of the heating, with the temperature rising only by approximately 15 ºC. However, since this soil is outside the array, achieving this temperature increase was still positive.

Soil temperatures inside Arrays 2 and 3 achieved similar results. The upper soil intervals reached 100 ºC, and the lower soil intervals achieved temperatures of 80 ºC to 100 ºC. Soil temperatures outside Arrays 2 and 3 increased from 20 ºC to 60 ºC.

Over 100,000 gallons of condensate were generated during the 18 weeks of heating. This water was sent to a tray-type air stripper where about 80,000 gallons evaporated. The remaining 20,000 gallons were used to re-hydrate the graphite backfill and soil around the electrodes. No water was discharged from the system. The condensate was sampled once every two to three days for laboratory analysis. These samples were used to determine the mass of contaminant removed in the liquid stream (which was comprised primarily of condensed steam: no active groundwater extraction was conducted during the heating periods).

Soil vapor was extracted at Arrays 1 and 2 at relatively stable rates of approximately 110 cfm for the entire period of SVE operation. The extracted vapor streams were monitored for concentrations of organic contaminants to determine the mass removal achieved during soil heating (discussed in Section 3.5.4). Vapor samples were collected once every two days for laboratory analysis of site contaminants of concern (COCs). At Array 1, the concentrations of most COCs reached their maximum levels within the first two weeks of heating, approximately the same time as soil temperatures inside the arrays reached 100 ºC. At Array 2, the soil was already warmed by heating at Array 1, and therefore, the concentrations of COCs reached their maximum levels in the first four days of heating. At both arrays the concentrations of all COCs, with the exception of TCE, dropped to less than 10 ppm by the end of the heating periods. Concentrations of TCE were at 82 ppm and 36 ppm at Arrays 1 and 2, respectively, at the end of their heating periods. The off-gas was treated only at Array 1, and only for a limited time at that array. Stray voltages from the array interrupted the control system of the catalytic oxidizer causing frequent shut downs. Additionally, the contaminant concentrations in the vapor stream were lower than anticipated and were low enough that direct discharge of the vapor stream was permissible.

Soil vapor was extracted at Array 3 at a relatively stable rate of approximately 170 cfm for the entire period of SVE operation. Concentrations of most COCs reached their maximum levels within the first three weeks of heating, which, similar to Arrays 1 and 2, was at approximately the same time as soil temperatures inside the array reached 100 ºC. Also similar to Arrays 1 and 2, the concentrations of all COCs, with the exception of TCE, dropped to less than 10 ppm by the end of the heating periods. The concentration of TCE was 20 ppm at Array 3 at the end of its heating period. Off gas from Array 3 was discharged directly to the atmosphere.

Arrays 4, 5, and 6

Soil heating at Arrays 4, 5, and 6 began on 31 July 1999 and continued for nine weeks until 4 October 1999. Operation of the SVE system began on 2 August 1999 and continued until 14 October 1999, 10 days past cessation of soil heating.

Soil temperatures were measured at 12 feet bgs (above groundwater), 23 to 25 feet bgs, and 38 feet bgs. Both lower temperature monitoring intervals were below the groundwater table. Soil from 23 to 25 feet bgs within Arrays 4 and 6 reached 100 ºC after eight weeks of soil heating. Only soil in these middle intervals at Arrays 4 and 6 reached 100 ºC, and no soil in Array 5 reached this temperature. Soil in the upper interval (12 feet bgs) in all three arrays reached approximately 80 ºC while soil in the lower interval (38 feet bgs) in all three arrays reached only approximately 60 ºC. These data suggest that soil below the groundwater table did not heat as efficiently as soil above the groundwater table. This is expected due to the lower conductivity of dryer soil above the groundwater table. Soil at the deepest temperature monitoring interval (38 feet bgs) did not heat as quickly as the shallower saturated soil (25 feet bgs). This observation is most likely due to the deeper interval being near the lowest reaches of the electrodes, and there is greater groundwater recharge (i.e., increased heat sink) available lower in the aquifer. In general, operation of SPSH at Arrays 4, 5, and 6 did not achieve as high of temperatures in soil within the arrays as were achieved for soil within Arrays 1, 2, and 3. Temperatures in soil outside Arrays 4, 5, and 6 were increased from 40 ºC to over 90 ºC.

Almost 80,000 gallons of condensate were generated during the nine week long heating period. Similar to the operation at Arrays 1, 2, and 3, this water was sent to a tray-type air stripper where about 50,000 gallons were evaporated. The remaining 29,000 gallons was used to re-hydrate the steel-shot backfill and soil around the electrodes. No water was discharged from the system. The condensate was sampled once every two to three days for laboratory analysis. These samples were used to determine the mass of contaminant removed in the liquid stream (which was comprised primarily of condensed steam: no active groundwater extraction was conducted during the heating periods).

Soil vapor was extracted at Arrays 4, 5, and 6 at a relatively stable rate of approximately 420 cfm for the entire period of SVE operation. The extracted vapor streams were monitored for concentrations of organic contaminants to determine the mass removal achieved during soil heating (discussed in Section 3.5.4). Vapor samples were collected at a rate of about once every two days for laboratory analysis of site COCs. Because all three arrays were heated at the same time and the vapor stream was sampled only after the condenser, the vapor samples are of the combined flow from all three arrays. No calculations of removal rates from the individual arrays could be made. The concentrations of all COCs reached their maximum levels within the first week of heating even though soil temperatures did not reach their maximum for another six to seven weeks. This observation may be somewhat misleading because vapor extraction occurred only at three extraction wells located in the center of each array, while soil heating was concentrated at the perimeter of the arrays. This differed from the configuration at Arrays 1, 2, and 3, at which all perimeter electrodes also served as vapor extraction wells. At the first three arrays, the maximum soil temperatures corresponded well with the maximum vapor concentrations. Because heating and vapor extraction occurred at the same locations, this is the expected outcome. At arrays 4, 5, and 6, the electrode locations were about 20 feet from the vapor extraction wells, which may have resulted in the observed lag time between maximum vapor concentrations and maximum soil temperatures. Similar to the first three arrays, the concentrations of all COCs, with the exception of TCE, dropped to less than 10 ppm by the end of the heating period. The concentration of TCE was 14 ppm at the end of the heating period. All extracted vapor was discharged directly to the atmosphere.

3.5.4 Contaminant Mass Removal

Based on vapor and condensate monitoring results, the mass of contaminant removed from each array are summarized in Table 3.2 (US Army Corps of Engineers, June 2003).

TABLE 3.2

MASS REMOVAL ESTIMATES AT PRDA SOIL HEATING SITE

	Estimated Pre-treatment Mass (kg)	Estimated Mass Removed in Off-gas (kg)	Estimated Mass Removed in Condensate (kg)	Total Estimated Mass Removed (kg)	Percent Mass Removed
Array 1	506	386	7.6	394	78
Array 2	211	217	2.7	220	104
Array 3	216	138	4.9	143	66
Arrays 4, 5, and 6	998	1385	65	1450	145

Mass removal rates at Arrays 2, 4, 5, and 6 were apparently greater than 100 percent. This discrepancy is most likely due to inaccuracies in estimating the initial contaminant mass, which was based on limited soil sample analytical results.

Mass removal estimates from all arrays shows that approximately twice as much contaminant mass was removed from Arrays 4, 5, and 6 than from Arrays 1, 2, and 3. Approximately 20 percent more soil volume was treated in 1999 and the heating period was 50 percent longer (nine weeks in 1999 compared to six weeks each in 1997). The greater soil volume and longer heating periods would account for the higher mass removal in 1999.

TCE constituted about 80 percent of the contaminant mass in the off gas from all six arrays. 1,1,2,2-PCA and PCE constituted the remaining 15 percent and 5 percent, respectively. Interestingly, the concentrations of 1,1,2,2-PCA in soil were typically three to four times higher that TCE concentrations. More rapid hydrolysis of 1,1,2,2-PCA to TCE under heating conditions may have resulted in higher vapor-phase concentrations of TCE. This reaction is thought to explain the apparent discrepancy.

3.5.5 Post-Implementation Sampling/Monitoring Results

3.5.5.1 Soil Sample Results

The average concentrations of TCE, PCE, and 1,1,2,2-PCA in soil in each array before and after SPSH are shown in Table 3.3 (US Army Corps of Engineers, June 2003). With

3-50

TABLE 3.3

AVERAGE CONCENTRATIONS (MG/KG) OF SITE COCS IN PRE AND POST TREATMENT SOIL SAMPLES

PRDA SOIL HEATING SITE, FORT RICHARDSON, ALASKA

Array ID	Trichloroethene			Tetrachloroethene			1,1,2,2-Tetrachloroethane		
	Before	After	% Removed	Before	After	% Removed	Before	After	% Removed
Array 1	21.53	1.60	93	2.00	0.08	96	82.34	1.17	99
Array 2	31.52	0.81	97	1.23	0.08	94	12.24	0.06	>99
Array 3	7.40	3.21	57	0.33	0.59	- 80	13.10	7.77	41
Array 4	82.5	2.28	97	15.25	0.05	>99	1513.5	0.03	>99
Array 5	11.12	1.87	83	3.22	0.09	97	124.8	0.08	>99
Array 6	26.92	8.48	68	0.60	0.12	80	70.04	0.03	>99

the exception of the results for PCE from Array 3, all arrays showed positive reductions in contaminant concentrations. Reductions of greater than 99 percent were seen for contaminants in several arrays. Although there were indications of PCE concentration increases at Array 3, these increases were not of concern to regulators, as the pre- and post-treatment concentrations were below the risk based concentrations (RBC) developed for PRDA.

The removal of TCE, PCE, and 1,1,2,2-PCA from the soils in Arrays 1 and 2 ranged from 93 to greater than 99 percent. This removal rate was achieved after six weeks of treatment. The percent of contaminants removed from Array 3 was approximately 50 percent for TCE and 1,1,2,2-PCA. The concentrations of PCE in soil at Array 3 increased but were still below the RBC. The removal of TCE, PCE, and 1,1,2,2-PCA from the soils at Arrays 4, 5, and 6 ranged from 68 to greater than 99 percent. However, many samples that were collected after treatment at these arrays still had TCE concentrations above the RBC.

3.5.5.2 Groundwater Monitoring Results

Groundwater sampling from monitoring wells located within the treatment area showed marked decreases in contaminant concentrations after completion of the SPSH projects, and these concentrations have remained below pre-treatment levels (e.g., no rebound has been indicated). Five wells located in the treatment area and screened in the shallow aquifer showed reductions in TCE concentrations from an average of 8,370 μg/L in November 1997 to an average of 1,930 μg/L in October 2000. Reductions in 1,1,2,2-PCA concentrations were from an average of 22,480 μg/L in November 1997 to an average of 3,770 μg/L in October 2000. Contaminants in groundwater at PRDA are showing decreasing trends in concentrations in almost all monitoring wells at the site (CH2MHill, 2004). All wells located within the treatment area are showing decreasing trends. Two wells, one located adjacent to the former disposal trench number 2 (which was not excavated or treated by SPSH) and one located approximately 300 feet downgradient of Arrays 1, 2, and 3 may be showing increasing trends in TCE and 1,1,2,2-PCA concentrations. However, because the groundwater flow rate is estimated to be less than 50 feet per year, contamination at the downgradient well may be the result of contaminant migration that occurred before the 1997 SPSH activities at Arrays 1, 2, and 3.

3.5.6 Thermal Project Cost

The total cost for the 1997 and 1999 SPSH projects was approximately $1,900,000 (Mr. Scott Kendall, USACE, personal communication, June 2004). This total does not consider power generation or performance monitoring costs, which include approximately $80,000 for diesel fuel for the first three arrays; approximately $70,000 for electric utility costs for Arrays 4, 5, and 6; and approximately $200,000 for performance monitoring. Inclusion of these costs brings the total cost to $2,250,000. The volume of soil treated during both SPSH projects was approximately 10,700 cubic yards, and the total mass of contaminant removed was approximately 2,200 pounds. Based on these numbers, the unit cost for the SPSH projects was $210 per cubic yard or $1,020 per pound of contaminant removed.

4.0 LIFE CYCLE COST ANALYSES OF FOUR SELECTED SITES

4.1 INTRODUCTION

Life cycle costs were estimated for each site based on actual costs incurred at each site (provided by the POC for each site) and on the estimated costs for long-term monitoring (LTM) provided in the Feasibility Study (FS) or Corrective Measures Study (CMS) completed for the sites (LTM costs for the SRS site were based on Parsons' experience at sites with similar monitoring networks and COCs). For sites at which remediation, exclusive of LTM, is not complete, additional estimated remediation costs were provided by the POCs. The range of unit costs for soil remediation at previously completed projects was provided by the US EPA Clu-In website. This section presents the results of the life cycle cost analyses for each of the four sites. Many of the costs are presented as estimates since LTM is ongoing at all four sites studied. This section also includes discussion of other potential technologies that were not identified in the decision documents.

4.2 NIAGARA FALLS AIR RESERVE STATION NIAGARA FALLS, NY

4.2.1 Comparison of Actual Costs to Other Remedial Approaches Discussed in the Decision Documents

The Resource Conservation and Recovery Act (RCRA) CMS for Sites 3, 10, and 13, Niagara Falls IAP-ARS, Niagara Falls, New York (Ecology and Environment, 1995) identified six alternatives for remediation of IRP Site 10. These alternatives included:

- Alternative 1 – No Action and Natural Attenuation (30 years O&M).
- Alternative 2 – Institutional Actions and Natural Attenuation (30 years O&M).
- Alternative 3 – Groundwater Extraction by Trenches, On-site Treatment of Extracted Groundwater, and Discharge of Treated Water to Cayuga Creek (30 years O&M).

- Alternative 4 – Soil Vapor Extraction, Groundwater Extraction by Trenches, On-site Treatment of Extracted Groundwater, and Discharge of Treated Water to Cayuga Creek (five years O&M).
- Alternative 5 – Excavation and Off-site Disposal of Contaminated Soil, Groundwater Extraction by Trenches, On-site Treatment of Extracted Groundwater, and Discharge of Treated Water to Cayuga Creek (five years O&M).
- Alternative 6 – Excavation and Off-site Disposal of Contaminated Soil, Groundwater Extraction by Trenches, and Discharge to Cayuga Creek (five years O&M).

The following costs were estimated for the alternatives:

- Alternative 1 – $725,131
- Alternative 2 - $734,131
- Alternative 3 - $1,038,055
- Alternative 4 - $679,599
- Alternative 5 - $696,641
- Alternative 6 - $635,545

Annual groundwater monitoring costs were estimated at $23,004 per year. No discount or escalation factors were used in development of the estimated costs.

The New York State Department of Environmental Conservation (NYSDEC) and the US Air Force initially agreed that Alternative 6 was the most appropriate approach for remediation of IRP Site 10. Niagara Falls ARS holds RCRA Part B hazardous waste permit under which remedial actions are regulated. Their Part B permit was modified to incorporate the recommended alternative, then was modified again to allow thermally enhanced soil vapor extraction (in 1996, SPSH was a new technology, and the US Air

Force was interested in a technology demonstration; this interest and the flexibility of the Part B permit drove the selection of thermally enhanced SVE over the alternative that was recommended in the CMS).

The actual cost incurred to conduct the SPSH project in 1996 was $688,000. However, this cost did not include annual groundwater monitoring or any actions to address site groundwater (Alternative 6 did include groundwater extraction). For comparison to the alternatives listed in the CMS, five years of LTM must be added to the costs actually incurred for SPSH. Assuming the same cost for annual groundwater monitoring, as was assumed in the CMS cost estimates ($23,004), and monitoring for five years, the total LTM costs are estimated at $115,020 (this assumes no discount or escalation factors were used in the calculation). Adding the cost for five years of annual monitoring to the actual capital costs incurred results in a total estimated cost for SPSH of $803,020. This cost is approximately 26 percent higher than the estimated cost for Alternative 6 (excavation, off-site disposal, groundwater extraction, and discharge), and as previously stated, did not include any measures to address contaminated groundwater associated with the site (such measures were included in Alternative 6).

Following completion of the SPSH project, TCE levels in soil at IRP Site 10 exceeded NYS cleanup criteria at three sample locations within the treatment area, and the average of the post-treatment samples also exceeded the NYSDEC cleanup criterion. However, the NYSDEC agreed that cleanup of the overburden soil was complete (Mr. Gerald Hromowyk, personal communication, February, 2004). Additionally, NYSDEC stated that groundwater remediation was not complete, and Niagara Falls ARS was required to implement groundwater extraction and treatment to address the groundwater contamination.

In 1998, Niagara Falls ARS constructed a groundwater interceptor trench, and in 2002, installed two groundwater extraction wells to address contaminated groundwater at the site. Extracted groundwater is treated through a bubbler-type stripper, then through activated carbon. The total cost of the extraction and treatment system was $584,000. Annual O&M costs of the extraction and treatment system are approximately $100,000.

Based on the capital costs of the SPSH ($688,000) and groundwater extraction and treatment system ($584,000), the total capital costs incurred at IRP Site 10 are approximately $1,272,000. The LTM costs from 1996 through 2003 were approximately $161,000, and the O&M costs since 1998 were approximately $500,000. The total cost of all remedial actions taken at IRP Site 10 since selection of SPSH in 1996 is approximately $1,933,000, which is significantly higher than any of the alternatives listed in the CMS, including those that included five years of LTM and O&M costs. Additionally, this cost of $1,933,000 does not include the estimated $100,000 annual O&M cost for the groundwater extraction and treatment system for operation after the first five years. If this system operates for 15 more years, the O&M costs could add an additional $1,500,000 to the $1,933,000 that has already been spent, which could bring the total remedial costs to $3,400,000.

Based on the cost estimates included in the 1996 CMS, the total cost for excavation of soil to bedrock and its off-site disposal, installation of a groundwater extraction system, and discharge of extracted groundwater to Cayuga Creek was $635,545, which included five years of LTM and O&M. Comparison of this cost to the total cost expended for SPSH and subsequent groundwater extraction and treatment over a five year period, $1,933,000, shows that excavation of the overburden soils would have been less expensive than SPSH. However, it should also be noted that excavation and off-site disposal would not have relieved the Air Force of the potential liability associated with off-site disposal. The Air Force would have remained responsible for the contamination associated with the disposed soil even had the soil been properly disposed in a permitted landfill. The cost of this “potential liability” could exceed the overall cost of the remedial actions conducted at Niagara Falls ANG, but this potential cost can not be determined.

4.2.2 Other Remedial Approaches That May be Applicable to Niagara Falls ARS IRP Site 10

Based on the shallow nature of soil contamination, typically from 0 to less than 8 feet bgs, the small areal extent of soil contamination, and the close proximity of a permitted land disposal facility (Model City Landfill, approximately five miles from the site), it appears that excavation and disposal would have been a more cost effective option for remediation of soil at IRP Site 10. Excavation of soil down to bedrock, typically encountered at less than 8 feet bgs, would likely have removed more contaminant mass than did the SPSH project. While neither soil excavation of SPSH would have directly addressed groundwater contamination, the high probability that additional contaminant mass would have been removed by excavation would also likely have reduced the overall time frame necessary to achieve remediation of site groundwater.

Because just over $1,100,000 has been spent to address groundwater contamination since the completion of the SPSH project, and another $1,500,000 may be spent to achieve groundwater remedial action objectives, the removal of additional mass may have facilitated reaching groundwater remedial action objectives at a lower life cycle cost.

4.3 SAVANNAH RIVER SITE, AIKEN, SC

4.3.1 Comparison of Actual Costs to Other Remedial Approaches Discussed in the Decision Documents

Savannah River Site holds a RCRA Part B permit, and the remedial actions carried out at the 321-M site were conducted under this permit. SRS modified their Part B permit by preparation of a Corrective Action Plan (CAP) for the Central Sector of the SRS. The 321-M site is included in the Central Sector. Under the CAP, SRS was allowed to conduct numerous pilot studies of innovative technologies and conduct a full-scale test of the technology that showed to be the most appropriate for a given site. The 321-M site is a relatively small site that is similar in soil type, depth to groundwater, and contaminant type to the much larger Area M Settling Basin. A focus of the Central Sector CAP was to identify a technology that proved effective at the smaller 321-M site that could be implemented at the larger Area M Settling Basin. This approach was the basis for testing and implementing a remedial technology at the 321-M site.

Several technologies were tested at the larger M-Area, including groundwater extraction and treatment, SVE, SVE enhanced with six-phase heating, *in situ* chemical oxidation, and soil washing. SVE was able to remove PCE from the vadose zone, but the estimated time frame to achieve cleanup of the soil operable unit was estimated at greater than 30 years. Additionally, SVE would have had no direct effect on contaminated groundwater. The other technologies that were tested proved to be ineffective at the -M-area. SRS then chose to test DUS/HPO at the 321-M site based on reported successful results at a creosote site in California. SRS planned to use the results of the DUS/HPO project to allow its implementation at a much larger PCE site at SRS, the M-Area settling basin.

The process of testing and implementing the most effective technologies used at SRS did not include preparation of a CMS or FS. Because no FS or CMS was completed, a comparative cost analysis for alternative remedial approaches was not generated, and the actual costs of DUS/HPO can not be readily compared to the costs of other approaches.

The total cost of the DUS/HPO project at the 321-M site was $4,250,000. This cost did not include the capital or O&M costs for steam generation and treatment of vapor, groundwater, and condensate as these services were provided by existing facilities at SRS. A rough estimate for the construction of a boiler and treatment plant would be approximately $2,000,000 (based on the construction cost of the treatment plant and boiler at the Yorktown NSFO site, which was somewhat larger and cost $2,800,000). O&M costs for one year of operation of the DUS/HPO project would be approximately $750,000, which is also based on the O&M costs of the somewhat larger Yorktown NSFO project. Using these estimated costs and the actual cost incurred at the 321-M site, the overall construction and operation costs for the DUS/HPO project are estimated at $7,000,000. Based on a volume of soil of 59,300 cubic yards, the unit cost for the entire DUS/HPO project is estimated at $118 per cubic yard. This unit cost is within the range of previously completed soil remediation projects. Based on cleanup of the soil operable unit alone, it appears that DUS/HPO was a reasonable technology in terms of effectiveness and cost.

However, the DUS/HPO project targeted soil from 40 to 160 feet bgs, and soil above 40 feet bgs still contained significant contamination. To complete remediation of the vadose zone soils at the 321-M site, SRS installed an SVE system, which removed over

1,100 pounds of contamination in the first four months of operation. The cost of the shallow SVE system, including the installation and first four months of operation, was approximately $200,000 and was not included in the cost analysis provided in the previous paragraph. Because no off-gas treatment is required for the shallow SVE system, the O&M costs for the system are low as they include only electric utility, monthly vapor sampling, and reporting costs. These costs would amount to approximately $50,000 per year. If cleanup is achieved in 30 years, the total cost of shallow SVE system may amount to $1,700,000 ($200,000 plus 30 years O&M at an annual cost of $50,000). Addition of this cost to the total estimated cost of the DUS/HPO project ($7,000,000) increases the total costs at the 321-M site to $8,700,000. The unit cost based on this total and the volume of soil treated is $147 per cubic yard, which is still within the range for previously completed soil remediation projects, and well within the range for sites with soil contamination at depths of over 160 feet.

Additionally, the impact of the DUS/HPO project on-site groundwater is not clear. A large plume of contaminated groundwater exists at the Central Sector, and groundwater at the 321-M site co-mingles with this larger plume. SRS has not subtracted the cost of groundwater extraction and treatment for the 321-M site from the costs for the larger plume. The cost for treatment of groundwater at the 321-M site is likely insignificant when compared to treatment of the large plume. However, if groundwater treatment was required based solely on contamination emanating from the 321-M site, the costs would likely be in excess of $1,000,000 due to the depth to groundwater and slow dissolution from the sorbed phase of the site contaminants.

4.3.2 Other Remedial Approaches That May be Applicable to SRS Site 321-M

SRS tested several innovative and proven technologies at the M-Area. Of these, only SVE and DUS/HPO were shown to remove significant quantities of contaminants from the soil. DUS/HPO also positively affected groundwater contamination. However, this affect will likely be only temporary, as groundwater at the 321-M site is within a much larger plume, and the area impacted by DUS/HPO will be re-contaminated, as contaminated groundwater migrates within the larger plume. While SVE was shown to be effective, significant contaminant mass was found to reside in discontinuous and multiple clay layers, and removal of contaminants from these layers would likely have required a lengthy operational period.

The total cost of the DUS/HPO project was estimated at $7,000,000. An additional $1,700,000 may be spent to complete remediation of the shallow soil (from 0 to 40 feet bgs). If SVE was utilized as the remedial technology, the total costs may have been less, particularly when considering that the manpower to operate the SVE system would already have been on-site to operate the site-wide groundwater extraction and treatment system. The 321-M site had dimensions of 100 feet by 100 feet by 160 feet. Using a conservative radius of influence for SVE of 25 feet, 16 vapor extraction wells would likely have been required to address the entire area of the site. A rough cost for installation of a 4-inch well to 160 feet is $30,000 per well, totaling $480,000 for 16 wells. A 25-hp positive displacement blower system with a knockout tank, condensate discharge pump, control panel, and system piping would cost, conservatively, $100,000. Off-gas treatment would likely not be required, as it was not required during the DUS/HPO project. Utility costs for the blower would be approximately $30,000 per year (25 kWH at $0.12 per kW times 8,760 hours per year). Labor costs would include weekly site visits (one day each), monthly maintenance visits (two days per month), and reporting and management (two days per month). Assuming a labor cost of $50.00 per hour for the weekly site and monthly maintenance visits, and $125.00 per hour for reporting and management, the annual labor costs would amount to $54,400 per year. Monthly vapor samples would cost approximately $4,000 per year. Capital costs would total $580,000, and annual O&M costs would total $88,400. Assuming a 30 year operational period, the total cost of an SVE system would be estimated at $3,232,000. Based on a 30-year remediation period, implementation of SVE would cost approximately 35 percent of the combined costs of the DUS/HPO project and shallow SVE system. However, the effectiveness of SVE without thermal enhancement on the clayey layers at the 321-M site would be reduced as compared to the sandy layers, which may result in an operational period of more than 30 years.

4.4 YORKTOWN FUELS DESC, YORKTOWN, VA

4.4.1 Comparison of Actual Costs to Other Remedial Approaches Discussed in the Decision Documents

The Final Corrective Action Plan with Supplemental Site Characterization, Fleet and Industrial Supply Center, Yorktown Defense Fuel Supply Point Yorktown, Virginia (Baker Environmental, 1996), identified six alternatives for remediation of the tank farm site. These alternatives included:

- Alternative 1 – Natural Attenuation.
- Alternative 2 – Product Recovery in Trenches or Wells without Heat Enhancement.
- Alternative 3 – Product Recovery in Trenches or Wells with Steam Injection (Heat) Enhancement.
- Alternative 4 – Excavation and Off-Site Treatment (Incineration)/Disposal.
- Alternative 5 – Excavation and On-Site Treatment (Incineration), and On-Site Disposal of Treated Soil/Ash.
- Alternative 6 – Excavation and Off-Site Treatment (Incineration) at Tank Farm and Product Recovery in Trenches or Wells with Steam Injection at Wormley Pond Area.

The following costs were estimated for the six alternatives:

- Alternative 1 ($250,000 plus LTM).
- Alternative 2 ($10,000,000 plus LTM).
- Alternative 3 ($12,500,000 plus LTM).
- Alternative 4 ($25,100,000).

- Alternative 5 ($13,200,000).
- Alternative 6 ($18,000,000 plus LTM).

Although LTM costs were not included in the estimates for Alternatives 1, 2, 3, and 6, these alternatives would require annual groundwater monitoring for 30 years. Assuming 36 wells would be monitored under Alternatives 1, 2, and 3, and the groundwater would be sampled for VOCs, SVOCs, and metals, the annual cost of monitoring and reporting would be approximately $50,000 (no discount or escalation factor would be assumed for the 30 year period). Alternative 6 would require that only 12 wells be sampled, as groundwater monitoring would be limited to the Wormley Pond Area. The annual cost for LTM, including reporting, for Alternative 6 would be approximately $20,000. No LTM costs were included for Alternatives 4 and 5 other than four quarters of monitoring after completion of soil excavation. Addition of LTM costs to the alternatives listed above results in the following total estimated costs.

- Alternative 1 - $1,750,000
- Alternative 2 - $11,500,000
- Alternative 3 - $14,000,000
- Alternative 4 - $25,100,000
- Alternative 5 - $13,200,000
- Alternative 6 - $18,600,000

Alternative 3 – Product Recovery with Steam Injection Enhancement, was initially selected by US EPA and US Navy. However, prior to implementation, US EPA and the National Park Service raised concerns about the potential of NSFO mobilization caused by steam injection. To alleviate this concern, the Navy amended the CAP to include steam recirculation (in pipes, no direct injection of steam) and to implement the remediation in a phased approach that would allow time to observe the potential for NSFO migration inside Navy property before implementing the technology near the adjoining Park Service property. The estimated cost of the steam circulation approach was not significantly different than the cost of direct steam injection. The higher cost of horizontal boring was offset by the number of vertical wells that would have been necessary for the direct steam injection approach.

The total capital costs for Phase I of the Yorktown DFSP remediation were $7,000,000, and the total expended to date for the Phase I remediation is $12,000,000 (includes 4 years O&M at $1,200,000 per year). Construction of Phase II is estimated at $4,000,000, and the O&M costs for the combined Phase I and Phase II areas are estimated at $1,600,000 per year. The total O&M cost, assuming 12 more years operation of Phase I and 15 years operation of Phase II, is estimated at $22,800,000 (this assumes $1,600,000 per year for 12 years and $1,200,000 per year for three years). If remedial goals are achieved in the expected 15-year time frame, the total remedial cost is estimated at $38,800,000. This total estimated cost, which is partly based on the actual construction and O&M costs that have been incurred during Phase I, is significantly higher than the costs that were estimated for Alternative 3 in the CAP. Additionally, the total estimated cost for steam recirculation is significantly higher than the cost of any of the alternatives listed in the CAP.

The cost for Alternative 5 - Excavation and On-Site Incineration – included in the CAP was based on the excavation of 125,000 cubic yards of soil. The unit cost for Alternative 5 would be $106 per cubic yard. This unit cost appears to be within the range of cost for previously completed excavation and on-site incineration projects. The addition of a 50 percent contingency added to the cost for Alternative 5 would raise the total estimated cost to $19,800,000. Comparison of the estimated cost for excavation and on-site incineration, including the contingency, to the total estimated cost for steam recirculation indicates that excavation and on-site incineration may have been a more cost effective approach for remediation of the Yorktown NSFO site.

4.4.2 Other Remedial Approaches That May be Applicable to Yorktown Fuels NSFO Site

Based on the site conditions of shallow soil contamination, a relatively immobile contaminant, and lack of a dissolved contaminant plume, excavation and treatment or thermally enhanced NAPL recovery are the most appropriate technologies for achieving cleanup of the Yorktown Fuels NSFO site. As was stated in the preceding section, soil excavation with on-site thermal treatment and on-site backfilling of treated soil was likely a more cost effective approach for cleanup of the site.

4.5 FORT RICHARDSON POLELINE ROAD, FORT RICHARDSON, AK

4.5.1 Comparison of Actual Costs to Other Remedial Approaches Discussed in the Decision Documents

The Final Feasibility Study Report for Operable Unit B Poleline Road Disposal Area Fort Richardson, AK (Woodward-Clyde, 1997) identified six alternatives for remediation of the PRDA. These alternatives included:

- Alternative 1 – No Action.
- Alternative 2 – Natural Attenuation including site-wide institutional controls and groundwater monitoring.
- Alternative 3 – Containment using a synthetic liner and soil cover cap with a bentonite slurry wall to 25 feet bgs around the hot zone, institutional controls, and groundwater monitoring.
- Alternative 4 – Interception trench, air stripping, and soil vapor extraction. A series of drainage trenches would intercept groundwater that would be collected and treated via an air stripper. Soil vapor extraction would be used to remediate soil above the lowered groundwater table.
- Alternative 5 – Air sparging and soil vapor extraction of the hot spot combined with natural attenuation. Groundwater in the hot spot would be treated using air sparging, and soil above the water table would be treated using soil vapor extraction. Groundwater would be monitored for natural attenuation parameters and VOCs.
- Alternative 6 – Soil vapor extraction of the hot spot. Dual-phase extraction would be used to extract soil vapor and groundwater, both of which would be treated

above ground. Site-wide institutional controls and groundwater monitoring would be implemented.

The following costs were estimated for the alternatives:

- Alternative 1 - $0
- Alternative 2 - $1,300,000
- Alternative 3 - $2,500,000
- Alternative 4 - $7,500,000
- Alternative 5 - $5,500,000
- Alternative 6 - $4,000,000

With the exception of Alternative 1 (No Action), all alternatives included annual groundwater sampling and analysis of 17 wells for VOCs and natural attenuation parameters and O&M costs for 30 years. Annual groundwater monitoring costs were estimated at $29,070 per year. No discount or escalation factors were used in development of the estimated costs.

US EPA and the US Army agreed that Alternative 6 was the most appropriate approach for remediation of the PRDA, and this alternative was incorporated into the ROD. The FS estimated cost of the alternative was $4,000,000. Originally, the alternative did not include thermal enhancement. However, the ROD did incorporate completion of treatability studies using innovative technologies that had potential to enhance the selected remedy. The ROD also allowed implementation of innovative technologies if the initial remedy proved ineffective. Based on this language in the ROD, Fort Richardson conducted the two SPSH treatability studies to evaluate its potential to enhance SVE. Based on the results of the study, and on the post-treatment soil samples that showed greater than 90 percent mass removal, US EPA agreed that remediation of the source area was complete and that MNA was acceptable for remediation of the dissolved phase plume.

The actual cost incurred to conduct the SPSH projects in 1997 and 1999 was \$2,200,000. Assuming the same cost for annual groundwater monitoring (\$29,070) and a 30-year time frame, the total LTM costs are estimated to be \$872,100 (this also assumes no discount or escalation factors were used). The costs developed in the FS assumed a 35 percent contingency on capital and O&M costs. Application of the contingency to the estimated LTM costs brings those costs to \$1,180,000 (no contingency would be added to the capital costs of the SPSH projects as the \$2,200,000 was the actual costs incurred). Adding the long-term monitoring costs to the actual capital costs incurred results in a total estimated cost for SPSH of \$3,380,000.

Based on the FS-estimated cost for Alternative 6 (\$4,000,000) and the life cycle cost estimate for SPSH which included the actual construction costs and estimated LTM costs (\$3,380,000)and implementation of SPSH will, over a 30-year remedial period, be less expensive than the ROD-selected alternative. Because US EPA has agreed that remediation of the source area is complete and the remedy was less costly than the ROD-selected alternative, it appears that, overall, SPSH was an appropriate technology for use at the PRDA.

4.5.2 Other Remedial Approaches That May be Applicable to Fort Richardson PRDA

Based on the depth to groundwater (4 to 10 feet in the perched zone and 20 to 25 feet in the shallow zone) and the depth of contamination at the PRDA (38 feet), excavation of contaminated soil would not have been feasible. Fort Richardson had tested air sparging and soil vapor extraction with groundwater depression at the PRDA, with limited success. Dual-phase extraction may have been viable, but the long-term cost of groundwater treatment would have made the technology more costly than SPSH. A possible technology that was not available in 1997 is enhanced anaerobic biodegradation (EAB). This technology uses carbon addition to first stimulate aerobic biodegradation leading to oxygen depletion and the development of anaerobic conditions in groundwater. Once anaerobic conditions are achieved, indigenous microbes can often times utilize chlorinated hydrocarbons as an alternative electron acceptor, which results in the reductive dechlorination of the chlorinated hydrocarbons to less chlorinated or non-chlorinated by-products. At the PRDA, carbon addition would likely be best accomplished by construction of a mulch wall downgradient of the source area. The wall could be installed by a single-pass trencher to simultaneously cut a trench, backfill it with a mixture of sand and bark mulch, and install a horizontal pipe for the introduction of fresh carbon substrate if the source area contamination outlasts the mulch. Current technology allows use of a single pass trencher to depths of up to 35 feet. At the PRDA site, contamination exists to a depth of 38 feet. Therefore, a 3 to 5 foot deep bench would be excavated for the trencher to work in and reach the required 38 foot depth. A rough cost for construction of the mulch wall would be $1,000,000, which includes $250,000 for mobilization of specialized construction equipment and $750,000 for construction of the wall. The addition of 30 years of LTM, at an estimated cost of $872,000, would bring the total cost of a mulch wall to just under $2,000,000. This technology has been successfully implemented at several DOD sites and, if available in 1997, may have been an option at the PRDA.

5.0 POLLUTANT EMISSIONS FROM POWER GENERATION DURING THERMAL ENHANCEMENT PROJECTS

One additional aspect of thermal enhancement projects is the emission of pollutants during the generation of the electric power and/or the steam that is necessary to heat the subsurface soils (this aspect also applies to any remediation project that utilizes electricity or steam). The emission of pollutants from power/steam generation may become a consideration of the overall effects of site remediation. Combustion of fossil fuels is the predominant means of generating electric power, which is used for the SPSH projects, and steam, which is used for steam injection and recirculation projects. Fossil fuel combustion releases air pollutants, including nitrogen oxides, sulfur dioxide, and heavy metals including mercury. The emission of these pollutants can be estimated and compared to the mass of pollutants recovered during the thermal enhancement projects. This comparison could be used in the overall evaluation of the efficiency of thermal enhancement technologies.

For this report, only the four sites that were evaluated in detail will be considered for this comparison of pollutant emissions versus contaminant recoveries. Sufficient data to allow the calculations were collected from only these four sites. Additionally, the comparison will only utilize the pollutants generated during the combustion of fossil fuels to generate electricity or steam. Indirect pollutant emission from power plant/steam generator construction and maintenance will not be considered. The rates of pollutant emissions per unit fossil fuel combusted were provided in the report, *Estimating Future Air Pollution from New Electric Power Generation* (Commission for Environmental Cooperation of North America, June 2002). This report includes a compilation of US EPA, Environment Canada, and industry data regarding the production rates of air pollutants during fossil fuel combustion. Some of the production rates are estimates or are average rates and should not be considered definitive.

The pollutant production rates provided in the aforementioned report are tabulated on Table 5.1 (Commission for Environmental Cooperation of North America, June 2002).

This table includes pollutant production rates for only the fossil fuels used to generate electricity/steam for the four projects at which detailed evaluations were completed. The fuels used for each site are listed below:

- Niagara Falls ARS – No fossil fuel used. Power for the City of Niagara Falls is generated at the Robert F. Moses Hydroelectric Power Plant located on the Niagara River in Niagara Falls, New York.
- Savannah River Site 321-M Site – Steam was provided by a central steam plant that is fired with natural gas.
- Yorktown Fuels DFSP NSFO Tank Farm – Steam is generated by a packaged boiler system that is fired by natural gas. However, Yorktown Fuels DFSP did not provide the natural gas utilization rate, and therefore, calculation of pollutant emissions can not be made.
- Fort Richardson PRDA Site – Diesel fired generators were used for Arrays 1, 2, and 3, and the Matanuska Electric Association, which operates a fuel oil fired steam turbine power plant, provided power for Arrays 4, 5, and 6.

TABLE 5.1

AIR POLLUTANT PRODUCTION RATES PER UNIT OF FOSSIL FUEL

Fossil Fuel	Nitrogen Oxide	Sulfur Dioxide	Mercury
Natural Gas	320 lb/10^6ft^3	0.598 lb/10^6ft^3	2.6 x 10^{-4} lb/10^6ft^3
Fuel Oil	5.64 kg/m^3 (0.047 lb/gal)	68 kg/m^3 (0.566 lb/gal)	1.13 x 10^{-7} lb/gal
Diesel Fuel	2.88 kg/m^3 (0.024 lb/gal)	8.52 kg/m^3 (0.071 lb/gal)	3.9 x 10^{-7} lb/gal

The volumes of natural gas, fuel oil, and diesel that were combusted must be known in order to determine the mass of pollutants emitted during electricity/steam generation. SRS provided the energy input to the SPSH system, 45.4 x 10^6 BTUs. The energy content of natural gas (1,000 BTUs per cubic foot [naturalgas.com]) must be used to convert the energy input into the volume of natural gas combusted. Fort Richardson provided the volume of diesel used to power the SPSH at Arrays 1, 2, and 3. To calculate the volume of fuel oil used at the Matanuska Electric Association plant, the energy input, 700,000 kWH, must be converted to BTUs (3413 BTUs per kWH) then to a volume by use of the energy content of fuel oil (140,000 BTUs per gallon [engineeringtoolbox.com]).

Savannah River Site reported the total energy input to the SPSH site was 45.4×10^6 BTUs. Assuming an average efficiency for steam boilers of 35 percent, an estimated 1.30×10^8 BTUs (45.4×10^6 divided by 0.35) of natural gas were consumed to generate the energy that was input into the 321-M site. Using the energy content of natural gas, 1,000 BTUs per cubic foot, the amount of natural gas used to generate steam for the SRS SPSH project was 1.30×10^5 cubic feet (1.30×10^8 BTUs divided by 1,000 BTUs per cubic foot). Based on the values provided in Table 5.1, the mass of pollutants emitted during the combustion of 1.30×10^5 cubic feet of natural gas were:

- Nitrogen Oxides: 41.6 pounds (1.30×10^5 multiplied by 320 lb $NOx/10^6 ft^3$)
- Sulfur dioxide: 0.078 pound (1.30×10^5 multiplied by 0.598 $SO_2 lb/10^6 ft^3$)
- Mercury: 0.000034 pound (1.30×10^5 multiplied by 2.6×10^{-4} lb $Hg/10^6 ft^3$)

These values assume that there is no emission controls equipment in operation on the stack of the steam plant.

The first SPSH project (Arrays 1, 2, and 3) at Fort Richardson PRDA used an estimated 70,000 gallons of diesel fuel. The second SPSH project (Arrays 4, 5, and 6) used a total of 700,000 kWH, which equates to 2.39×10^9 BTUs (700,000 kWH multiplied by 3413 BTUs per kWH). Using the energy content of fuel oil of 140,000 BTUs per gallon, approximately 34,000 gallons of fuel oil, assuming 100 percent efficiency, would be consumed to generate 700,000 kWH. Assuming an average efficiency of 35 percent for fuel oil fired steam turbine power plants, the total volume of fuel oil needed to produce 700,000 kWH of electricity would be approximately 97,000 gallons (34,000 gallons divided by 0.35). Using the estimated volumes of diesel fuel and fuel oil, 70,000 gallons and 97,000 gallons, respectively, and the pollutant unit production rates listed in Table 5.1, the following estimated masses of pollutants were released during the SPSH projects at Fort Richardson PRDA:

- Nitrogen Oxides: 6,239 pounds (70,000 gallons multiplied by 0.024 lb/gal plus 97,000 gallons multiplied by 0.047 lb/gal)
- Sulfur dioxide: 59,872 pounds (70,000 gallons multiplied by 0.071 lb/gal plus 97,000 gallons multiplied by 0.566 lb/gal)
- Mercury: 0.0383 pound (70,000 gallons multiplied by 3.9 x 10^{-7} lb/gal plus 97,000 gallons multiplied by 1.13 x 10^{-7} lb/gal)

These values assume there is no pollution control equipment located either on the diesel generators or at the Matanuska Electric Association plant.

Based on the calculations provided above, the pollutant emission rates during the SRS 321-M SPSH project were minimal. The pollutant emission rates of nitrogen oxides and sulfur dioxide during the Fort Richardson PRDA were significant. The use of diesel fueled generators and fuel oil fired steam turbine electric power plants produced greater masses of pollutants than did the natural gas fired steam generator. The use of diesel generators and/or fuel oil fired electric power plants may become a consideration for future site remediation projects.

6.0 SUMMARY AND CONCLUSIONS

6.1 SUMMARY OF PROJECT ACTIVITIES

6.1.1 Site Selection

Parsons utilized internet databases to identify 25 federal and two private sector thermal enhancement projects. The government or consultant POC for each project was identified, and 21 of these answered an initial questionnaire regarding their project. Seventeen of the 21 POCs agreed to participate further with the project. Parsons then contacted those 17 POCs, of which 11 agreed to conduct telephone interviews and provide more detailed information regarding their respective projects. Using information from the questionnaires and interviews, Parsons selected four projects for site visits and detailed evaluations. Parsons visited each of the four sites and gathered additional detailed information regarding the technology selection process, implementation and operation of the selected technology, the cost of each project, and the results of any post-project soil and groundwater sampling.

6.1.2 Pollutant Emissions from Power/Steam Generation

The emission of pollutants during the generation of the electric power and/or the steam that is necessary for remediation of a site may become a consideration of the overall effects of site remediation. Combustion of fossil fuels for power generation releases air pollutants, including nitrogen oxides, sulfur dioxide, and heavy metals including mercury. As was shown in Section 5, the combustion of natural gas to generate the steam for the DUS/HPO project at SRS emitted 41.6 pounds of nitrogen oxides, 0.078 pound of sulfur dioxide, and 0.000034 pound of mercury. The combustion of diesel fuel and heavy fuel oil during the Fort Richardson PRDA projects emitted 6,239 pounds of nitrogen oxides, 59,872 pounds of sulfur dioxide, and 0.0383 pound of mercury. Based on these estimated values, it is readily apparent that combustion of natural gas produces significantly less air pollutants than the combustion of fuel oils. A comparison of the relative detrimental effects of air pollutants released versus soil and/or groundwater pollutants recovered may be useful in determining the overall net positive effect of a site remediation. This type of comparison was outside the scope of this project.

6.2 CONCLUSIONS

Evaluation of the responses from the 21 POCs that returned the initial questionnaires led to the findings listed below:

- Only one respondent indicated that thermal enhancement was a failure. The other 20 respondents indicated their thermal projects were successful or somewhat successful.
- Of the 20 respondents that felt their projects were successful or somewhat successful (the favorable respondents), four indicated that thermal enhancement had definitely decreased the overall remedial costs, eight stated it had probably decreased overall costs, three indicated that thermal enhancement had definitely increased the overall remedial costs, three responded that the cost impact was unknown, and two indicated thermal enhancement made no impact to overall costs.
- Of the 20 favorable respondents, only 14 of these stated they would use the same technology again.
- Six of the 20 favorable respondents indicated that, knowing the results, they would not use the same thermal technology, and four of these six indicated that, knowing the results, they would have chosen a non-thermal technology.
- A total of eight of the 20 favorable respondents indicated that, knowing the results, they would have chosen a non-thermal technology.
- Thermal enhancement was selected in decision documents at only 11 of the sites, seven were interim actions, and 16 projects were chosen as technology demonstrations.
- Regulatory encouragement was a factor in the selection of thermal enhancement at only 10 of the sites, and vendor marketing was a factor at only five sites.

Based on the responses in the 21 initial questionnaires, from the telephone contacts with the 17 POCs that initially agreed to participate further, and from the interviews with 11 POCs, almost one-half of the POCs (10 of 21) indicated that they would have either chosen a different thermal technology (2 POCs) or would have chosen a non-thermal technology (8 POCs). Only three of the 21 respondents indicated that the project was both successful and had definitely decreased remedial costs. One of these three, the SRS 321-M site still requires active remedial actions to cleanup groundwater and residual soil contamination, and based on the life cycle costs analysis (Section 4 of this report), thermal enhancement may not have been a cost effective alternative. Of the eight respondents that indicated thermal enhancement probably decreased cost, only one site, the PRDA site in Alaska, could definitively show that the costs were less than other remedial technologies (this conclusion is based on the life cycle cost analyses performed in Section 4 of this report and on the basis that life cycle cost analyses were not conducted for all eight of these sites). At two of those eight sites, Yorktown DFSP and Niagara Falls ARS, it is apparent that the cost of thermal enhancement was or will be considerably higher than the cost of other remedial approaches (also based on the aforementioned life cycle cost analyses).

Based on the evaluations of the four sites chosen for this project, thermally enhanced source remediation was clearly an appropriate technology at only one site – Poleline Road Disposal Area, Fort Richardson, Alaska. This site was contaminated with recalcitrant compounds (PCE, TCE, and 1,1,2,2-PCA) that had migrated to a depth of 38 feet bgs, and the areal extent of contamination was limited in size (two areas of less than one-third acre each). Additionally, pilot testing of air sparging and dual-phase extraction showed limited success, and off-gas treatment of extracted soil vapor was not required, thus reducing the overall remediation costs. SPSH removed greater than 90 percent of the estimated contaminant mass and nearly all soil samples collected after the SPSH project showed remedial action objectives for the soil unit were met. Additionally, following completion of the SPSH project, future remedial activities at the PRDA site are now limited to natural attenuation of groundwater. The life cycle cost analysis showed that, at the time frame of this remediation, SPSH was more cost effective than the other remedial technologies that were evaluated in the CMS. Newer innovative technologies such as enhanced anaerobic bioremediation may have been viable, but were not available at that time.

The evaluations of the projects at Niagara Falls ARS IRP Site 10 and Yorktown Fuels NSFO Tank Farm showed that thermally enhanced source remediation approaches were less effective in terms of cost and removal efficiency than if soils at each site were excavated and treated/disposed. At Niagara Falls ARS IRP Site 10, soil samples collected before and after SPSH were contaminated with TCE above NYSDEC soil remediation limits, and additional groundwater remediation measures have been required. At Yorktown Fuels, 198,000 gallons of NSFO have been recovered in four years of operation, but an estimated 3,000,000 gallons were released. The depths of contamination at both sites were shallow enough to allow conventional excavation, and the overall cost of excavation and disposal/treatment were significantly less than the costs of SPSH or steam recirculation heating.

Evaluation of the steam injection project at SRS 321-M site presents somewhat inconclusive findings. The steam injection project was effective in terms of mass recovery, in meeting soil cleanup objectives for the targeted area of soil, for removing contaminant mass from the clayey layers present at the site, and for temporarily reducing contaminant concentrations in groundwater below the site. However, soil vapor extraction (SVE) without thermal enhancement was also shown to effectively remove contaminant mass from the sandy soil regions and was less costly than the addition of steam to enhance contaminant recovery. The effectiveness of SVE on the clayey layers was not measured, but experience at other sites indicates its effectiveness is reduced in clayey soil, thus reducing its overall effectiveness in achieving remediation of the vadose zone. Remediation of groundwater at the 321-M site was not achieved. However, it should be noted that the plume under the 321-M site is contained within a larger plume and remediation of the plume under the 321-M site would have been only temporary as groundwater flow from the larger plume would have re-contaminated the groundwater under the 321-M site.

Based on the detailed evaluation of these four sites, is appears that while thermally enhanced source remediation has in many cases significantly enhanced the recovery of contaminant mass as compared to non-thermal technologies, implementation of thermal enhancement did not result in the complete closure of any of these four sites. Remediation of the soil unit at PRDA Fort Richardson, AK and of the overburden soil at Niagara Falls ARS Site 10, are considered complete, but additional active groundwater remediation measures are still required at the Niagara Falls site. Additionally, based on the life cycle cost analyses, with the exception of the PRDA site in Alaska and possibly the SRS 321-M site, implementation of thermally enhanced source remediation technologies had significantly higher costs than non-thermal technologies.

Based on all information gathered during this project, it can be concluded that implementation of thermal enhancement did not lead to complete site closure at any of the 21 facilities that were evaluated under this project. Thermally enhanced soil vapor extraction did lead to closure of the soil operable units at Air Force Plant 4, TX and at the PRDA, Fort Richardson, AK, and of the overburden soil at Niagara Falls ARS, NY. Additionally, thermal enhancement did result in regulatory acceptance of monitored natural attenuation (MNA) at the PRDA site in Alaska, and may have assisted in acceptance of MNA at two additional sites (Edwards Air Force Base [AFB], CA, and Whittier DFSP, AK). However, at both the Edwards AFB site and at Whittier DFSP, MNA would likely have been accepted even in the absence of the thermal enhancement projects. At the two remaining sites at which closure of the soil units were obtained (Air Force Plant 4 and Niagara Falls ARS), active groundwater remediation activities are still required.

Ultimately, it appears that thermal enhancement was effective at achieving closure of the soil units at three of 21 sites, and resulted in regulatory acceptance of MNA, definitively, at only one of those three sites. This translates into closure of soils units at 14 percent of sites, obtaining MNA as the sole remedy at 5 percent of sites, and achieving complete site closure at 0 percent of sites. Although thermal enhancement intuitively seems like a logical approach, results of this study would indicate that Air Force RPMs should approach the technology cautiously, carefully evaluating all remedial alternatives prior to adopting this aggressive and costly technology.

6.3 IMPORTANT CONSIDERATIONS REGARDING APPROPRIATENESS OF THERMAL ENHANCEMENT

Numerous site-specific issues must be considered when selecting a remedial technology for addressing source areas. These issues include the size of the source area, the depth of contamination, the geology at the source area, the nature of the contaminant, the presence of sensitive receptors, and the time frame available for cleanup. Based on this evaluation, the factors that appear to be the most important regarding thermal enhancement are the nature of the contaminant, the geology of the source area, and the time frame available for cleanup.

If the contaminant has a relatively high vapor pressure, similar to TCE or gasoline, thermal enhancement may not be warranted. Longer operation of an SVE system may be all that is necessary to achieve cleanup. However, the effectiveness of this technology becomes limited as the vapor pressure of the contaminant decreases. Sites contaminated with creosote, heavy fuel oil, or coal gasification tars will likely not respond to SVE unless the source area is heated, but one must consider if these types of source areas need to be addressed, if they are not significantly impacting groundwater.

Similarly, the geology of the site, most importantly the permeability of the soil or bedrock, will affect the effectiveness of *in-situ* technologies. At the Fort Richardson PRDA site, the contaminants were TCE and 1,1,2,2-PCA, both with relatively high vapor pressures. However, the low permeability of the soil limited the effectiveness of SVE. Application of a higher vacuum during a dual phase extraction pilot test did not significantly affect the removal rates as compared to standard SVE. Removal rates increased dramatically during the soil heating projects, and cleanup of the soil was achieved.

Finally, the time frame available for cleanup of soils operable units may drive the selection of thermal enhancement. SVE systems typically require several years to over a decade to complete remediation of soil. As was shown in this evaluation, the soil operable units at Niagara Falls ARS IRP Site 10, Fort Richardson PRDA, and Air Force Plant 4 achieved regulatory closure in six to nine weeks of heating at each array. Closure of the soil unit below 40 feet bgs at the SRS 321-M site was achieved in one year of soil heating. Additionally, thermal enhancement may have aided the selection of MNA as the sole remedial technology at the Edwards AFB and Whittier DFSP sites. Thermal enhancement may be an appropriate technology for achieving cleanup of soil if the property is to be transferred, new construction is scheduled at the site, or some other regulatory or owner requirement exists to expedite cleanup of site soils. However, one should consider the impact of thermal treatment on groundwater and whether or not cleanup of soil will significantly impact groundwater contamination and therefore the life cycle cost of completely remediating the site.

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APPENDIX A

INITIAL QUESTIONNAIRE

Questionnaire

Thermal Enhancement for the Cost-Effective Remediation of NAPLs Questionnaire

Type of source area:

- (•) Fuel Hydrocarbon LNAPL
- ( ) Chlorinated Solvent DNAPL
- ( ) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
- ( ) Other: ______

Type of Thermal Technology employed:

- (•) Steam injection
- ( ) Electrical Resistive Heating
- ( ) Conductive Heating
- ( ) Radio-Frequency Heating
- ( ) Hot water injection
- ( ) Thermal Enhancement for SVE (hot air, 6-phase, etc)
- ( ) Deep soil mixing with steam injection
- ( ) Other: ______

What is/was the Vendor's name?

______

Project Type:

- (•) Pilot Test
- ( ) Full-scale project

Project Stage:

- (•) Planning
- ( ) In progress
- ( ) Complete

Impression of success:

- (•) Project was a failure
- ( ) Project was somewhat successful
- ( ) Project was very successful

Cost Data Availability:

- (•) No cost data available
- ( ) Some cost data available

Extensive cost data available

Impact of thermal technology on life-cycle costs:

- Technology definitely decreased life-cycle cost of project
- Technology probably reduced life-cycle cost of project
- Technology had no impact on life-cycle cost of project
- Technology increased life-cycle cost of project
- Unknown

Yes	No	Question:
		Was the thermal technology selected in a feasibility study or corrective measures study?
		Was the thermal technology selected as an interim action?
		Was the thermal technology selected as a technology demonstration?
		Did your regulators suggest or encourage use of the thermal technology selected?
		Was the technology selected based on vendor marketing efforts
		Knowing project results, would you use the selected thermal technology again?
		Knowing project results, would you select a different thermal technology?
		Knowing project results, would you select a technology that was not dependent on any thermal enhancement technology?
		Are you willing to participate further in this thermal technology evaluation?
		Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements?

Submit

APPENDIX B

SECOND QUESTIONNAIRE AND INTERVIEW SUMMARIES WITH THERMAL PROJECT POCs

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: ______________________________

2. Facility Name: ______________________________

3. Facility Location: ______________________________

4. Facility Address: ______________________________
____
____

5. Facility POC (Name, phone, fax, e-mail):
____
____
____

6. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL
   b) Chlorinated Solvent DNAPL
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

7. Confirm type of thermal technology employed:
   a) Steam injection
   b) Electrical Resistive Heating
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

8. Identify the vendor/contractor.______________________________

9. Project Scale
   a) Pilot Test
      Aerial extent and depth of contamination for the pilot test
      ____
      ____
      Will the project go to full scale? ______
      If not planning to go to full scale, why?
      ____
      ____
      ____

b) Full-scale project

Was a pilot study conducted before going to full scale? ____________

____

What was the aerial extent and depth of contamination for the full-scale treatment effort? ____

____

____

10. Project status

a) Planning (including design)
b) In situ treatment is ongoing
c) Post-treatment monitoring
d) Long-term monitoring
e) Complete

11. Confirm impression of success

a) Project was a failure

Why was it considered a failure?

____

____

____

____

____

b) Project was somewhat successful.

Why was it considered somewhat successful?

____

____

____

____

____

Is the site going full scale? ______

What was the percent of mass removed? ______________________

____

What was the percent reduction in mass flux? ___________________

____

Is there ground water contamination? ______

What was the percent reduction in ground water concentrations?

____

____

Was rebound measured?

____

____

What was the result of rebound tests?

____

____

____

c) Project was very successful

Why was it considered successful?______________________________

____

____

____

What was the percent of mass removed?______________________

____

What was the percent reduction in mass flux?_________________

____

Is there residual ground water contamination? ______

What was the percent reduction in ground water concentrations?

____

____

Was rebound measured?

____

____

What was the result of rebound tests?

____

____

d) Is long-term monitoring planned? ______

Have regulators agreed upon the success of the treatment? _____________

____

____

Was this treatment applied at a full scale that could lead to a site closure?

____

____

____

Have stakeholders approved the site closure followed by the remediation?

____

____

____

12. What is the lithology of the site?

A) Geology: Heterogeneous, homogenous, or moderately homogeneous?

____

____

____

a) Sand
b) Silt
c) Clay
d) Sedimentary
e) Gravel
f) Till
g) Unconsolidated
h) Metamorphic
i) Igneous
j) Consolidated
k) Other
l) Unknown

B. Hydrogeology:

a. Average depth to groundwater at the site? ____________________
b. Confined or unconfined. ______________________________

____
c. Vertical profile depth(s) of confining layer(s)?____________________

____

____
d. Is there significant fracturing of the bedrock?____________________

____

____
e. Is there a significant seasonal fluctuation in groundwater table?__________

____

____
f. Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? ______________________________

____

____

C. Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment?

____

____

____

13. What was the nature of NAPL at the site? ____________________

____

____

a) Was NAPL mobile, immobile residual, other? ______________________

b) Was the entire area impacted by NAPL addressed by the project? ______

If not, was the NAPL impacted area adequately characterized? ______

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? ______________________

14. Cost Data Availability

a) No cost data available ______________________

b) Some cost data available ______________________

Was a cost and performance report written? ______________________

c) Extensive cost data available ______________________

Was a cost and performance report written? ______________________

15. Above ground treatment system.

A. Major aboveground system components ______________________

B. Were there any equipment failures during system operation? ______________

C. How much DNAPL was collected in the knock-out tank? ______________

D. Approximately how much liquid was extracted from the system ______________

E. How were the liquid phases handled, treated, disposed? ____________________

F. Extracted NAPL mass ____________________

G. Water monitoring and NPDES requirements? ____________________

H. Air monitoring and discharge requirements? ____________________

I. Activated carbon requirements? ____________________

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project ____________________

b) Technology probably reduced life-cycle cost of project____________________

c) Technology had no impact on life-cycle cost of project____________________

d) Technology increased life-cycle cost of project____________________

e) Unknown____________________

For all the above, what is the basis of this impression? ____________________

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? ______

b) Was the thermal technology selected as an interim action? ______

c) Was the thermal technology selected as a technology demonstration?_____

d) Did your regulators suggest or encourage use of the thermal technology selected? ______
If so, how was the selection encouraged? ____________________________
____
____

e) Was the technology selected based on vendor marketing efforts? ______
If so, what were the primary issues that aided the selection?____________
____
____

f) Knowing project results, would you use the selected thermal technology again? ____
____
____

g) Knowing project results, would you select a different thermal technology?____
____
____

h) Knowing project results, would you select a non-thermal technology?____
____
____

i) Are you willing to participate further in this thermal technology evaluation?____
____
____

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements?________________________________
____
____

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: U.S. Air Force/Lockheed

2. Facility Name: Air Force Plant 4

3. Facility Location: Texas

4. Facility POC (Name, phone, fax, e-mail):
George Walters
(937) 255-1988
george.walters@wpafb.f.mil

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL:
   b) Chlorinated Solvent DNAPL: *100% TCE from 20,000 gallon tank leak*
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection
   b) Electrical Resistive Heating: *Pilot test used 6 phase while full-scale system used 3 phase. Three phase heating was recommended due to more uniform distribution of heat. Three phase electrodes can be arranged in linear arrays, while 6 phase requires a hexagonal array.*
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor: URS and Thermal Remediation Services

8. Project Scale
   a) Pilot Scale: ___
   b) Full Scale: Yes

   Was a pilot study conducted before going full-scale: Yes

   What was the aerial extent and depth of contamination: One-half acre inside an active aircraft parts production building. Area was 150’ by 150’ by 35 feet deep (bedrock at 35’).

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing
   c) Post-treatment monitoring
   d) Long-term monitoring
   e) Complete *Soil did not heat sufficiently in all areas due to highly conductive soils. Heated soils for total of 30 weeks, and 10 months later, groundwater temperature was still 30 - 50ºC. The SVE system is still in operation. The 6 phase pilot test cost $800,000 and the 3 phase full-scale system cost $2.3MM. These costs do not include the SVE system that was already in place. Total recoveries for the pilot and full scale system were 330# and 1400# TCE, respectively.*

10. Confirm impression of success
   a) Project was a failure: No

   b) Project was somewhat successful: No

   c) Project was very successful: Yes
   Why was it considered successful? It was cheaper than pump and treat. The facility estimated costs for P&T at $6,000 per pound TCE removed and for thermal enhancement at $1100 per pound. Also met the soil clean up RAO of 11.4 mg/kg as measured by post-heating soil samples.

   What was the percent of mass removed? Unclear

   What was the percent reduction in mass flux? Has not been measured as site is still to hot to sample.

   Is there residual ground water contamination? Yes

   What was the percent reduction in ground water concentrations? Limited sampling of hottest well showed a decrease in TCE concentration from 180 mg/l to 8 mg/l. Other wells had TCE ranging from 100 to 200 mg/l before heating and decreased to an average of 22 mg/L after heating.

   Was rebound measured? Have not collected sufficient post-heating samples to determine, but facility believes rebound is occurring.

   d) Is long-term monitoring planned? Yes

   Have regulators agreed upon the success of the treatment? Yes, they have agreed that the source zone soils meet the RAOs.

Was this treatment applied at a full scale that could lead to a site closure? Yes. The site has met the soil RAOs. The RAO of 10,000 µg/L in source area had not been met at all locations. The RAO of 400 µg/L in dissolved plume (within the building and adjoining parking lot) and off-site RAO of 5µg/L should be met within 15 years of pump and treat.

Have stakeholders approved the site closure followed by the remediation? Yes, public appears satisfied with results, but AF Plant 4 employees 16,000 people from the surrounding community.

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?

Up to 20' of fill material sitting over limestone bedrock, which occurs at 20' to 35' bgs.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 32'
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? No
5) Is there a significant seasonal fluctuation in groundwater table? No
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No, the site is inside a building.

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? Yes, the site is inside an active aircraft parts production building that contains numerous ASTs, dip lines and industrial processes.

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? Have not found mobile NAPL at the site.

b) Was the entire area impacted by NAPL addressed by the project? No. Uneven heating left a small portion of the source area unheated.

If not, was the NAPL impacted area adequately characterized? Yes, but complete characterization was difficult due to interference with equipment.

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available

Was a cost and performance report written? Yes, but data is fairly recent and is being compiled into a Final Report.

14. Above ground treatment system.

a) Major aboveground system components: Existing SVE system, condenser, catalytic oxidizer (that was required in ROD but was not actually used), air stripper and GAC sorbers for vapor and liquid streams.

b) Were there any equipment failures during system operation? A few crossed wires for heating system (almost killed project). System ran well after completed installation, and URS/TRS did a good job.

c) How much DNAPL was collected in the knock-out tank? None

d) Approximately how much liquid was extracted from the system? System ran at 90 gpm for a total of 191,000 gallons. Only recovered 1.2# TCE from this 191,000 gallons.

e) How were the liquid phases handled, treated, disposed? Through an air stripper then GAC polish. Treated water was sent to the sanitary sewer.

f) Extracted NAPL mass: None

g) Water monitoring and NPDES requirements: No, discharge limits were set and system operated within those limits.

h) Air monitoring and discharge requirements: Used continuous air monitoring to meet OSHA breathing air limits (labor health and safety issue) within the building. The air stripper was not monitored, but the vapor phase GAC was. The total emission limit was 3# TCE per day.

i) Activated carbon requirements: No data was provided.

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project: *Based on life-cycle cost of pump and treat versus 3 phase heating.*
c) Technology had no impact on life-cycle cost of project
d) Technology increased life-cycle cost of project
e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No, ROD stipulated surfactant flushing with an unnamed innovative technology as a contingency. Pilot testing of surfactant flushing failed, and the regulators were flexible and agreed to soil heating.

b) Was the thermal technology selected as an interim action? No

c) Was the thermal technology selected as a technology demonstration? No

d) Did your regulators suggest or encourage use of the thermal technology selected? Not really, facility proposed technology and regulators accepted.

e) Was the technology selected based on vendor marketing efforts? No, the facility sought out the technology and the contractor.

f) Knowing project results, would you use the selected thermal technology again? Would not recommend soil heating at this site, would rather have installed a high vacuum, dual-phase SVE system.

g) Knowing project results, would you select a different thermal technology? Yes at a similar site, but would heat to much higher temperatures (600ºC) to thermally destruct/vitrify the contaminants.

h) Knowing project results, would you select a non-thermal technology? Yes, for this site. See answer for question 16f.

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: U.S. Air Force

2. Facility Name: Edwards AFB

3. Facility Location: California

4. Facility POC (Name, phone, fax, e-mail):
   Steven Watts
   (661) 277-1443
   steven.watts@edwards.af.mil

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL
   b) Chlorinated Solvent DNAPL
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
      No evidence of DNAPL. Fuel NAPL only – no TCE dissolved in NAPL. Dissolved plume is all TCE
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection *High vacuum extraction with concurrent steam and compressed air injection.*
   b) Electrical Resistive Heating
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor. Steam Tech – Bakersfield, CA

8. Project Scale
   a) Pilot Test
      Aerial extent and depth of contamination for the pilot test
      900 SF test area with 60' depth. GW at 32'.
      HVAC radius of influence = 140'
      1 steam injection well, 4 SVE wells.
      Dissolved phase plume size is 40 acres.

      Will the project go to full scale? No

If not planning to go to full scale, why? Regulators did not require clean up to MCLs due to lack of sensitive receptors near the site (Edwards AFB). Mr. Watts was unsure whether he would recommend thermal enhancement if treatment to MCLs was required. He did believe the cost of thermal enhancement would be less in the long run than pump and treat, but the capitol cost of steam injection would make it difficult to obtain the funding. He added that if funding the capitol cost was possible and treatment to MCLs was required, he would probably recommend steam injection thermal enhancement of SVE.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing
   c) Post-treatment monitoring
   d) Long-term monitoring
   e) Complete

10. Confirm impression of success
   a) Project was a failure: No

   b) Project was somewhat successful: No

   c) Project was very successful

   Why was it considered successful? Pilot test showed recovery TCE and petroleum hydrocarbons in fractured bedrock. The pilot study performed as was expected, was the first known study performed in fractured bedrock, and the total project cost ($525,000) was within the expected budget. Total recoveries included 250 # diesel-range LNAPL and 2000# total VOCs in the off gas. Off gas constituency was 280# TCE, 370# other VOCs, and 1350# petroleum hydrocarbons. Approximately 99% of the total hydrocarbon recovery (not including the LNAPL) was in the vapor phase. Only about 1% of the recovery was in the non-NAPL liquid phase. Achieved > 100ºC in 2 extraction wells and >80ºC in other 2 extraction wells and soil temperatures in excess of 100ºC within portions of the test area and >40ºC throughout the test area. Operational time of the test was 60 days.

   What was the percent of mass removed? Initial mass was not estimated so the mass removal could not be quantified

   What was the percent reduction in mass flux? Not quantified

   Is there residual ground water contamination? Yes

What was the percent reduction in ground water concentrations?
Unknown due to poor characterization of the site prior to the pilot test. Soil sample indicated ND after pilot test.

Was rebound measured? Yes, Groundwater rebounded quickly. TCE ranged from 470 to 2200 µg/L before test and rebounded to 0.8 to 1800 µg/L after test. TCE concentrations in the SVE decreased to a fraction of the initial concentrations but the concentrations of fuel hydrocarbons increased.

d) Is long-term monitoring planned? Yes

Have regulators agreed upon the success of the treatment? Regulators agreed that the pilot study was successful, based on work plan estimates, but agreed that full-scale implementation was unnecessary due to lack of sensitive receptors. The EPA SITE Program was initially involved, but backed out due to lack of funding.

Was this treatment applied at a full scale that could lead to a site closure? No (see above), and EPA RPM agreed that MNA was sufficient for this site. Also, Edwards estimated the full-scale implementation costs at approx. $20,000,000, which was not warranted due to lack of receptors.

Have stakeholders approved the site closure followed by the remediation?

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?
2 to 11' of overburden over granitic bedrock

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 32’
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? Yes
5) Is there a significant seasonal fluctuation in groundwater table? Minimal (< 0.1’) due to desert location
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No, desert location

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? No

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? Unsure. Did not know NAPL existed until it was mobilized by steam during pilot test? NAPL was likely immobile under natural conditions. No DNAPL was indicated.

b) Was the entire area impacted by NAPL addressed by the project? No, entire source area is approx 4 acres, and pilot affected only 900 SF with steam injection and approx 1 acre with SVE

If not, was the NAPL impacted area adequately characterized? No

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Unclear

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available

Was a cost and performance report written? No but data could be gathered. Contractor developed scale-up costs based on 5 acres implementation. Cost were $3.8MM/acre for 100’ depth and $5.5MM/ acre for 200’ depth. An economy of scale would be realized for greater than 5 acres.

14. Above ground treatment system.

a) Major aboveground system components: Trailer mounted boiler, positive displacement vacuum pump, liquid/vapor separator, heat exchanger, NAPL and water tanks, GAC sorbers for liquid and vapor streams.

b) Were there any equipment failures during system operation? No other than SVE well plugging due to poorly developed wells.

c) How much DNAPL was collected in the knock-out tank? No DNAPL was collected. All TCE came out in vapor phase with less than 1% TCE recovered in dissolved phase.

d) Approximately how much liquid was extracted from the system? 43,000 gallons of water, as steam, was injected, and 110,000 gallons of water was extracted

e) How were the liquid phases handled, treated, disposed? Treated through GAC sorbers and discharged to sanitary sewer system

f) Extracted NAPL mass: 250#

g) Water monitoring and NPDES requirements: Discharge limits were set for discharge to sanitary sewer

h) Air monitoring and discharge requirements: No permit was required. Discharge limits were set for exhaust from GAC sorbers

i) Activated carbon requirements: 21,000 #

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project
c) Technology had no impact on life-cycle cost of project
d) Technology increased life-cycle cost of project
e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No

b) Was the thermal technology selected as an interim action? Yes

c) Was the thermal technology selected as a technology demonstration? Initially, but SITE Program funding did not come through.

d) Did your regulators suggest or encourage use of the thermal technology selected? Yes

If so, how was the selection encouraged? ______

e) Was the technology selected based on vendor marketing efforts? No
If so, what were the primary issues that aided the selection?

f) Knowing project results, would you use the selected thermal technology again?
No, regulators did not force clean up to MCLs, so technology was unnecessary.

g) Knowing project results, would you select a different thermal technology? No

h) Knowing project results, would you select a non-thermal technology? Yes

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: U.S. Army

2. Facility Name: Fort Richardson

3. Facility Location: Alaska

4. Facility POC (Name, phone, fax, e-mail):
   Scott Kendall
   (907) 753-5661
   scott.kendall@poa02.usace.army.mil

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL
   b) Chlorinated Solvent DNAPL *Used DANC to clean up chemical weapons identification kits and dilute mustard gas. DANC contains 1,1,2,2-tetrachloroethane. DNAPL was indicated in on-site well. Very little TCE in soil before soil heating.*
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection
   b) Electrical Resistive Heating *6 Phase heating in two phases, the first using 3 separate arrays and the second using a more linear arrangement of 3 arrays.*
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor. Current Environmental Solutions

8. Project Scale
   a) Pilot Test
   b) Full Scale

   Was a pilot study conducted before going full scale? Yes, using first array. Two more arrays conducted during first phase and three more during second phase.

   What was the aerial extent and depth of contamination system?
   One acre total for both phases with 40 depth. GW at 20'. Heated soil from 8' to 40' bgs.

9. Project status

   a) Planning (including design)
   b) In situ treatment is ongoing
   c) Post-treatment monitoring
   d) Long-term monitoring
   e) Complete *Two summers of treatment. Conducted three arrays for six weeks each in 1997 and three arrays concurrently for 9 weeks each in 1998. Soil reached desired temperature within 10 days of heating. Total cost was $3MM. Used diesel generator in 1997, which used 400 – 700 gallons fuel per day. Brought in municipal power in 1998, which cost $30,000 per month.*

10. Confirm impression of success

   a) Project was a failure: No

   b) Project was somewhat successful: No

   c) Project was very successful

      Why was it considered successful? Goal was removal of source mass and meeting RAOs as established in ROD. Many post-heating soil samples met the RAOs (did not meet RAOs everywhere), and decreases in soil contaminant levels were from over 1000 mg/kg to non-detect. System recovered 1385# total VOCs (primarily TCE which is breakdown product that occurs when heating 1,1,2,2-TCA) in vapor phase and 65# in condensate.

      What was the percent of mass removed? Not completely clear, but when one outlying soil sample was not included in calculation, achieved 90-95% removal. If the one outlying sample is included, removal was 40 - 50%.

      What was the percent reduction in mass flux? Not quantified

      Is there residual ground water contamination? Yes

      What was the percent reduction in ground water concentrations? 40 – 60% reduction in GW right after treatment.

      Was rebound measured? Yes

      No significant rebound compared to samples collected immediately after treatment.

   d) Is long-term monitoring planned? Yes

Have regulators agreed upon the success of the treatment? Regulators agreed that source area treatment was complete, and MNA or TI is acceptable for dissolved GW plume.

Was this treatment applied at a full scale that could lead to a site closure? Yes. Regulators agreed to MNA (or TI) with source control as data shows plume to be stable.

Have stakeholders approved the site closure followed by the remediation? RAB has shown little interest in this site.

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?
Tight glacial till.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:
1) Average depth to groundwater at the site? 20'
2) Confined or unconfined. Confined by dense till at 40'
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? NA
5) Is there a significant seasonal fluctuation in groundwater table? Minimal
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No

c) Aboveground buildings or permanent structures
Are there aboveground structures that could interfere with the thermal treatment? No

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? Had mobile NAPL, primarily 1,1,2,2-TCA.

b) Was the entire area impacted by NAPL addressed by the project? Yes

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes, source area well defined with a large dissolved plume.

13. Cost Data Availability

a) No cost data available:

b) Some cost data available: Will have to work to get the data.
Was a cost and performance report written? No

c) Extensive cost data available:

14. Above ground treatment system.

a) Major aboveground system components: Three rows of eight galvanized steel electrodes, a positive displacement blower, heat exchanger, and a knockout tank.

b) Were there any equipment failures during system operation? In 1997 (pilot test), technology was not all sorted out. Had quite a bit of stray voltages, particularly at the surrounding fence. No significant problems in 1998.

c) How much DNAPL was collected in the knock-out tank? None

d) Approximately how much liquid was extracted from the system? Around 80,000 gallons extracted (poor monitoring) and about 29,000 re-injected around electrodes to keep the soil hydrated.

e) How were the liquid phases handled, treated, disposed? Condensed water was sent to a spray tower where it was completely evaporated. Some of water was used to hydrate electrodes and was not sent to the spray tower. No water was discharged from system.

f) Extracted NAPL mass: None.

g) Water monitoring and NPDES requirements: No water was discharged from system. No permit was required.

h) Air monitoring and discharge requirements: Spray tower discharged directly to the atmosphere.

i) Activated carbon requirements: NA

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project: *Based on reduced long-term monitoring costs in the event a TI waiver is granted. May be cheaper than long-term operation of SVE without thermal enhancement. Regulators wanted base to do something in addition to SVE and this was the cheapest something because the SVE system was already in place. Will still probably have to monitor site forever.*
c) Technology had no impact on life-cycle cost of project
d) Technology increased life-cycle cost of project
e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? SVE was in ROD, and thermal enhancement was contingency if SVE was not effective.

b) Was the thermal technology selected as an interim action? No

c) Was the thermal technology selected as a technology demonstration? No

d) Did your regulators suggest or encourage use of the thermal technology selected? Yes

If so, how was the selection encouraged? Thermal enhancement was contingency included in the ROD.

e) Was the technology selected based on vendor marketing efforts? No. Base had information on 6 phase heating from VISIT Program.

f) Knowing project results, would you use the selected thermal technology again? Yes if regulators required some form of source control that needed to be completed in a short period of time. Geology must be considered, and the NAPL and tight glacial till at this site seemed to fit well with 6 phase heating. Would not recommend if time was not as great a consideration and other technologies are effective.

g) Knowing project results, would you select a different thermal technology? No

h) Knowing project results, would you select a non-thermal technology? Yes

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: Lowry Landfill

2. Facility Name: Lowry Landfill

3. Facility Location: Colorado

4. Facility POC (Name, phone, fax, e-mail):
   Bill Plaehn
   (303) 831-8100
   bill.plaehn@parsons.com

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL: *Observed LNAPL layer with little dissolved CAHs, but CAHs may be from other disposal pits at landfill.*
   b) Chlorinated Solvent DNAPL
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection
   b) Electrical Resistive Heating: *Three phase heating was recommended due to more uniform distribution of heat over a larger area.*
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor: Thermal Remediation Services

8. Project Scale
   a) Pilot Scale: __
   b) Full Scale: Yes
   Was a pilot study conducted before going full-scale: No

   What was the aerial extent and depth of contamination: 0.7 acres with depth of 30'. Target depth for heating was 8' to 30' bgs.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing

c) Post-treatment monitoring

d) Long-term monitoring

e) Complete *The target disposal pit was one of 70 at the landfill. The debris/soil in this pit was highly conductive due to buried metallic debris, and this led to some non-uniform heating. The system ran for 300 days, which was longer than anticipated, and the average soil temperature reached 84ºC. Portions of system, particularly the PVC wells, were deteriorating because of the prolonged operation. The system reached asymptotic removal rates in the 300 days operation. Total VOCs, particularly acetone and MEK, in the SVE stream increased during operation. This was thought due to heating contaminants in an anoxic environment.*

10. Confirm impression of success

a) Project was a failure: No

b) Project was somewhat successful: Yes

Why was it considered successful? Soils at the site reached the endpoint criteria for xylene, as was initially established by EPA. EPA also agreed to performance based criteria, which included asymptotic removal rates and temperature goals. The system achieved a 50% reduction in the concentration of xylene. The method of calculating the reduction had been accepted by EPA prior to the start of the project. EPA agreed that reaching a 50% reduction, the site could be closed by simply capping the disposal pit.

What was the percent of mass removed? 50%

What was the percent reduction in mass flux? Unclear

Is there residual ground water contamination? Yes

What was the percent reduction in ground water concentrations? Ranged from 75% to 85% after heating.

Was rebound measured? No and EPA did not require.

c) Project was very successful: No

d) Is long-term monitoring planned? Yes

Have regulators agreed upon the success of the treatment? No, EPA reneged on earlier agreement that if 50% reduction was met, the site could be capped and closed (EPA used a different averaging technique than the earlier agreement and did not entirely agree with the 50%

number). They required Lowry to complete a focused Feasibility Study.

Was this treatment applied at a full scale that could lead to a site closure? No, because EPA disagreed with 50% reduction and required a feasibility study.

Have stakeholders approved the site closure followed by the remediation? The public liked the technology and the results, but wanted the system to operate for a longer period of time.

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?

Man made pit filled with miscellaneous debris. There are some spotty and discontinuous clay lenses that occurred when the waste was moved around within the pit and native soils were mixed in during the moving.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other *Miscellaneous debris from landfill operations.*
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 15' – 16''
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? NA
5) Is there a significant seasonal fluctuation in groundwater table? Unclear
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No, the existing cap is impermeable.

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? No

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? Mobile petroleum hydrocarbons with some dissolved CAHs. There was liquid product in some wells.

b) Was the entire area impacted by NAPL addressed by the project? Yes

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available Yes, but client may not want to share data.
Was a cost and performance report written? No

14. Above ground treatment system.

a) Major aboveground system components: Engineered cap, venting layer, SVE vacuum blower, condensate/knockout tank, two flameless thermal oxidizers with HCL scrubbers, and water storage tanks.

b) Were there any equipment failures during system operation? The HCL scrubbers of the FTOs were problematic, several of the electrodes corroded prematurely, PVC wells softened, and some valve seal materials swelled as they were incompatible with site contaminants.

c) How much NAPL was collected in the knock-out tank? 12,000 gallons, also recovered 17,000 kg from vapor stream.

d) Approximately how much liquid was extracted from the system? EPA required recycling of the extracted water. The water was used to wet the soils around the electrodes to maintain conductivity. Over 900,000 gallons of water was extracted and most of it was handled in this manner. Some 177,000 gallons of the extracted water contained percentile levels of contaminant. This water was incinerated.

e) How were the liquid phases handled, treated, disposed? See above

f) Water monitoring and NPDES requirements: No, most of the water was recycled, and the rest was incinerated.

g) Air monitoring and discharge requirements: Emission limits were established and system operated within limits.

h) Activated carbon requirements: Not applicable

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project:
c) Technology had no impact on life-cycle cost of project: *Lowry landfill has 70 disposal pits, many of which contribute to the dissolved plume. Thermal enhancement at one of 70 pits had no impact to overall site remediation.*
d) Technology increased life-cycle cost of project
e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No, ROD required an innovative technology that was as close as possible to excavation, ostensibly because of concerns over air emissions. ROD initially required that three pits be excavated, but air emissions were a problem during excavation of first pit.

b) Was the thermal technology selected as an interim action? No

c) Was the thermal technology selected as a technology demonstration? Yes

d) Did your regulators suggest or encourage use of the thermal technology selected? Absolutely. EPA felt that thermally enhanced SVE was most similar to excavation.

e) Was the technology selected based on vendor marketing efforts? No, Parsons sought out the technology and the contractor.

f) Knowing project results, would you use the selected thermal technology again? Yes, at an appropriate site.

g) Knowing project results, would you select a different thermal technology? No

h) Knowing project results, would you select a non-thermal technology? No

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Need to get client's approval.

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: U.S. Air National Guard

2. Facility Name: Niagara Falls ANG Station

3. Facility Location: New York

4. Facility POC (Name, phone, fax, e-mail):
   Gerald Hromowyk
   (716) 236-3126
   gerald.hromowyk@niagarafalls.af.mil

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL:
   b) Chlorinated Solvent DNAPL: *TCE with little JP4 and some cis-1,2-,DCE*
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection:
   b) Electrical Resistive Heating: *Six phase heating of 6' – 10' overburden. Used 40-mil liner over high-permeability layer on top of ground surface to extract soil vapors.*
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor: Battelle/Montgomery Watson

8. Project Scale
   a) Pilot Scale: __
   b) Full Scale: Yes
   Was a pilot study conducted before going full-scale: No

   What was the aerial extent and depth of contamination: 100' diameter fire training pit, 8 - 10' depth.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing

c) Post-treatment monitoring
d) Long-term monitoring
e) Complete *Used four 6 phase arrays. Heated soil for 40 days and the cost of the project was $700,000.*

10. Confirm impression of success
a) Project was a failure: No

b) Project was somewhat successful: No

c) Project was very successful: Yes

Why was it considered successful? Total VOCs in overburden decreased dramatically (benzene from 540 mg to 20 mg) and recovered 59.75 kg of CAHs, including 43.5 kg TCE, 16.12 kg cis-1,2-DCE. Also recovered 4.6 kg of benzene.

What was the percent of mass removed? Unclear as initial mass was not known.

What was the percent reduction in mass flux? Unclear

Is there residual ground water contamination? Yes

What was the percent reduction in ground water concentrations? Approximately 90%: 120 mg/l total VOCs reduced to 10 mg/l.

Was rebound measured? Yes

What were the results of the rebound tests? One well near the source area that had 150 mg/l total VOCs in 1996 showed a reduction to 20 mg/l in 2000.

d) Is long-term monitoring planned? Yes

Have regulators agreed upon the success of the treatment? Regulators agreed that overburden meets cleanup criteria, but groundwater in fractured bedrock still must be addressed.

Was this treatment applied at a full scale that could lead to a site closure? No, because no attempt was made to impact bedrock.

Have stakeholders approved the site closure followed by the remediation? Not much involvement from public. Love Canal is only 5 miles away, so public not too concerned about a little TCE and JP4.

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?

Six to ten feet of clay with little sand overlying fractured dolomite bedrock.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 6'
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? Moderate
5) Is there a significant seasonal fluctuation in groundwater table? No
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No, clayey soils are little influenced by precipitation.

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? No

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? Only slightly mobile TCE with some/little JP4. Free phase plume has migrated less than 100' beyond perimeter of fire training pit. No indications of deeper DNAPL in 52' deep well.

b) Was the entire area impacted by NAPL addressed by the project? Yes

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? A cut-off trench was installed about 200 feet downgradient of the fire training pit. The dissolved plume is controlled by the trench.

13. Cost Data Availability

a) No cost data available

b) Some cost data available: Total project cost was approximately $700,000. Was a cost and performance report written? No

c) Extensive cost data available

14. Above ground treatment system.

a) Major aboveground system components: Six phase array, surface SVE system, knockout tank, and liquid phase GAC sorbers. No off gas treatment.

b) Were there any equipment failures during system operation? One GAC container collapsed upon start up. System was reconfigured with GAC on pressure side of vacuum blower, and no problems after that.

c) How much NAPL was collected in the knock-out tank? None

d) Approximately how much liquid was extracted from the system? Data was not recorded as water was treated through carbon and discharged to the sanitary sewer.

e) How were the liquid phases handled, treated, disposed? See above.

f) Water monitoring and NPDES requirements: No, see above.

g) Air monitoring and discharge requirements: No

h) Activated carbon requirements: A couple of 55-gallons drums

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project: *No detailed assessment, just his gut feel.*
c) Technology had no impact on life-cycle cost of project:
d) Technology increased life-cycle cost of project:
e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No

b) Was the thermal technology selected as an interim action? Yes

c) Was the thermal technology selected as a technology demonstration? Yes

d) Did your regulators suggest or encourage use of the thermal technology selected? No, the Air Force was interested in the technology so the regulators allowed it to be implemented at the site as an IRM.

e) Was the technology selected based on vendor marketing efforts? No, Montgomery Watson was site contractor and were able to bring technology to site.

f) Knowing project results, would you use the selected thermal technology again? Not for bedrock. But thought technology offered faster remediation of vadose zone that simple SVE.

g) Knowing project results, would you select a different thermal technology? No, 6 phase worked well for overburden.

h) Knowing project results, would you select a non-thermal technology? Yes, for bedrock.

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: U.S. Navy

2. Facility Name: North Island Naval Air Station

3. Facility Location: California

4. Facility POC (Name, phone, fax, e-mail):
   Bill Collins
   (619) 556-9901
   collinswe@efdsw.navfac.navy.mil

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL
   b) Chlorinated Solvent DNAPL
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL) *80% JP5, 20% Chlorinated solvents, including TCE and DCE. Fuel loss from 1940's into 1970's*
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection
   b) Electrical Resistive Heating
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor. Shaw/IT

8. Project Scale
   a) Pilot Scale: __
   b) Full Scale: Yes

   Was a pilot study conducted before going full-scale: Yes

   What was the aerial extent and depth of contamination: 10 acres by 80' deep. Initially was a SVE system for vadose zone only, though the thermally enhanced SVE system extended 2 feet below the water table. Groundwater is 10 – 12' bgs. A NAPL area was identified after a SVE system was installed, so the facility used an Action Memo and California Remedial Action Plan to modify the system and stay within the requirements of the decision document. An estimated 24 million gallons of off-spec fuel was dumped into unlined trenches at this site. Thermal enhancement of the SVE system was accomplished by injecting steam periodically over 14 months (to date; system is still active), with a total of about 7 months active steam injection to maintain soil temperature; the soil held heat quite well.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing
   c) Post-treatment monitoring
   d) Long-term monitoring
   e) Complete

10. Confirm impression of success
   a) Project was a failure: No

   b) Project was somewhat successful: No

   c) Project was very successful: Yes

   Why was it considered successful? A total of 80,000# total VOCs was removed using the SVE system for over one year. An estimated 211,000# total VOCs was removed in 14 months after the introduction of steam. This includes 136,000# of LNAPL and 66,000# in the vapor phase.

   Is the site going full scale: The system is full scale

   What was the percent of mass removed? Insignificant (when compared to 24M gallons in subsurface).

   What was the percent reduction in mass flux? System is still in operation.

   Is there residual ground water contamination? Yes, at concentrations greater than 1,000 mg/L.

   What was the percent reduction in ground water concentrations? System is still in operation.

   Was rebound measured? Not applicable as system is still in operation.

   d) Is long-term monitoring planned? Site is monitored in accordance with the decision document.

Have regulators agreed upon the success of the treatment? Yes, operation of the system will continue.

Was this treatment applied at a full scale that could lead to a site closure? Yes.

Have stakeholders approved the site closure followed by the remediation?

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?

Sand/silt/coarse sand from ground surface to 40', a silt bed from 40' to 45', sand from 45' to 80' and clay at 80'.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 10 - 12 '
2) Confined or unconfined. Confined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? Not applicable
5) Is there a significant seasonal fluctuation in groundwater table? Tidally influenced and average level fluctuates by about 1' over the year.
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? Not much precipitation.

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? No, the site used to be a series of troughs and trenches used to dispose off-spec fuel.

12. What was the nature of NAPL at the site?

No mobile NAPL has been identified at the site.

a) Was NAPL mobile, immobile residual, other? Unsure, though likely some immobile residual exists in the source area. Have near saturation levels of VOCs spread over 100 acres and 80 feet deep.

b) Was the entire area impacted by NAPL addressed by the project? Yes, the entire 10-acre source area is being addressed.

If not, was the NAPL impacted area adequately characterized? ______

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available

Was a cost and performance report written? No. Cost $1.5M capitol and $2.5M O&M (to date). Of the $1.5M, only about $0.5M was added for steam as the pre-steam SVE system cost $1M.

14. Above ground treatment system.

a) Major aboveground system components: High-vacuum SVE system (total fluids) with NAPL separator, condenser, and GAC sorbers on aqueous phase.

b) Were there any equipment failures during system operation? System required a couple months to bring fully online. After that, it operated well.

c) How much DNAPL was collected in the knock-out tank? None

d) Approximately how much liquid was extracted from the system? 25 gpm total fluids extracted which contains about 2% LNAPL. 8400# of TCE has been recovered from the dissolved phase.

e) How were the liquid phases handled, treated, disposed? They are incinerated.

f) Extracted NAPL mass: 136,000#

g) Water monitoring and NPDES requirements: No, fluids are incinerated.

h) Air monitoring and discharge requirements: The facility bought air emission off-sets so no permit was required. However, GAC sorbers are used to treat the off-gas stream.

i) Activated carbon requirements: 15,000# per every six weeks. Used on-site carbon regeneration.

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project *Steam injection increased the removal rate, so that 211,000# total VOCs were recovered in 14 months.*
b) Technology probably reduced life-cycle cost of project
c) Technology had no impact on life-cycle cost of project
d) Technology increased life-cycle cost of project
e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No

b) Was the thermal technology selected as an interim action? Yes

c) Was the thermal technology selected as a technology demonstration? Yes

d) Did your regulators suggest or encourage use of the thermal technology selected? No, steam was added to the SVE system so that the facility could stay within the requirements of the Remedial Action Plan.

e) Was the technology selected based on vendor marketing efforts? No, the contractor was already on site.

f) Knowing project results, would you use the selected thermal technology again? Yes.

g) Knowing project results, would you select a different thermal technology? No

h) Knowing project results, would you select a non-thermal technology? No

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: DOE

2. Facility Name: Portsmouth Gaseous Diffusion Facility

3. Facility Location: Ohio

4. Facility POC (Name, phone, fax, e-mail):
   John Sokol
   (740) 897-4426
   ko8@becthel.jacobs.org

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL
   b) Chlorinated Solvent DNAPL *TCE in vadose, groundwater and bedrock*
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection
   b) Electrical Resistive Heating
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor. Steam Tech

8. Project Scale
   a) Pilot Test

   Aerial extent and depth of contamination for the pilot test
   100' by 60' by 35' deep
   System operated for 6-8 months, which was longer than planned.

   Will the project go to full scale? No

   If not planning to go to full scale, why? Steam injection was very inefficient due to loss in heterogeneous subsurface.

9. Project status
   a) Planning (including design)

b) In situ treatment is ongoing
c) Post-treatment monitoring
d) Long-term monitoring
e) Complete

10. Confirm impression of success

a) Project was a failure: No

b) Project was somewhat successful:

Why was it considered somewhat successful? Approximately 50 gallons of TCE were recovered during the study. However, the costs were too great (in excess of $1MM) and the time to heat the soil was greater than expected due to steam loss in heterogeneous subsurface. There was also some concern that the steam could mobilize contaminant mass away from the study area.

Is the site going full scale: No

What was the percent of mass removed? Insignificant

What was the percent reduction in mass flux? Not quantified

Is there residual ground water contamination? Yes

What was the percent reduction in ground water concentrations? Groundwater concentrations were not affected by the study.

Was rebound measured? Yes

Groundwater rebounded quickly and returned to the pre-study concentrations. In-situ oxidation was also tested, and groundwater rebounded to pre-test concentrations.

c) Project was very successful: No

d) Is long-term monitoring planned? Site is still being studied

Have regulators agreed upon the success of the treatment? Regulators agreed that steam injection at this site is not appropriate due to heterogeneous subsurface and cost associated with steam.

Was this treatment applied at a full scale that could lead to a site closure? No

Have stakeholders approved the site closure followed by the remediation?

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?

Silty soil with clay pockets above a layer of clayey sand and gravel, above fractured shale bedrock.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 30 - 35
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? No
5) Is there a significant seasonal fluctuation in groundwater table? No
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No, a pump and treat system at the toe of the source area keeps the water table fairly stable.

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? No, the site used to be sludge lagoons used to contain material excavated from treatment ponds.

12. What was the nature of NAPL at the site?

No mobile NAPL has been found at the site.

a) Was NAPL mobile, immobile residual, other? Unsure, though likely some immobile residual exists in the source area.

b) Was the entire area impacted by NAPL addressed by the project? No

If not, was the NAPL impacted area adequately characterized? No

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? No, a great deal of characterization has been completed at the site, but the source area has not been completely identified.

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available

Was a cost and performance report written? Yes, for EM50. Check Oakridge website for report, or contact Elizabeth Folkes at Oakridge.

14. Above ground treatment system.

a) Major aboveground system components: Facility steam, SVE system with knockout tank.

b) Were there any equipment failures during system operation? System performed well.

c) How much DNAPL was collected in the knock-out tank? Approximately 50 gallons TCE.

d) Approximately how much liquid was extracted from the system? Unknown

e) How were the liquid phases handled, treated, disposed? Used facility's central waste water treatment plant to treat liquid phase.

f) Extracted NAPL mass: ____

g) Water monitoring and NPDES requirements: No, discharge to central WWTP.

h) Air monitoring and discharge requirements: No permit was required.

i) Activated carbon requirements: Air treatment was not known

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project
c) Technology had no impact on life-cycle cost of project
d) Technology increased life-cycle cost of project *Steam injection was not appropriate for this site. There was very little return for over $1MM investment*

and there was no end in site regarding system operation. DOE shut down the system due to costs.

e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No, the decision document selected in-situ oxidation.

b) Was the thermal technology selected as an interim action? No

c) Was the thermal technology selected as a technology demonstration? Yes

d) Did your regulators suggest or encourage use of the thermal technology selected? No

e) Was the technology selected based on vendor marketing efforts? Not really. DOE had invested in the technology then sought out a vendor to implement.

f) Knowing project results, would you use the selected thermal technology again? No, is not appropriate at this site.

g) Knowing project results, would you select a different thermal technology? Are considering 6 phase heating as it may produce more uniform heating of soil.

h) Knowing project results, would you select a non-thermal technology? Yes, are probably going to implement in-situ oxidation. They have also tested surfactant flushing, in-situ soil mixing, zero-valent iron and in-situ UV oxidation.

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: U.S. Army

2. Facility Name: Rocky Mountain Arsenal

3. Facility Location: Colorado

4. Facility POC (Name, phone, fax, e-mail):
   Ronald Versaw
   (303) 980-3707
   rversaw@ttfwi.com

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL:
   b) Chlorinated Solvent DNAPL:
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain): *hexachlorocyclopentadiene from pesticide production*

6. Confirm type of thermal technology employed:
   a) Steam injection:
   b) Electrical Resistive Heating: *Three phase, 480-volt*
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor: Terra Therm. Inc.

8. Project Scale
   a) Pilot Scale: __
   b) Full Scale: Yes

   Was a pilot study conducted before going full-scale: No, a bench-scale characterization of site soils and contaminants was completed.

   What was the aerial extent and depth of contamination: 110’ by 90’ by 12’ deep.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing

c) Post-treatment monitoring
d) Long-term monitoring
e) Complete *The remedial technology was selected in 1999, the bench scale study in 1999 and the full scale project was started and completed in 2000. The system did not reach the desired temperature of 600ºF due to complete equipment failure after ten days of heating (see below). Total cost of the project was $3MM.*

10. Confirm impression of success

a) Project was a failure: Yes

Why was it considered a failure? The system operated for 10 days, then fell apart due to corrosion of all metal parts even though 304 stainless steel was used for all equipment and piping. Additionally, a fire occurred in the GAC sorber due to acid reaction with carbon. The soil heating caused a reaction with the site contaminants and produced concentrated hydrochloric acid. Generation of acid was recognized during the bench test, but the thought was the soil would buffer the acid and not cause problems. The pH of the condensate was 0.0 units. The source area was excavated and disposed of the next year.

b) Project was somewhat successful: No

c) Project was very successful: No

d) Is long-term monitoring planned? Yes as part of the overall site plume.

Have regulators agreed upon the success of the treatment? Regulators still liked the technology even with the acid problem, and wanted the Army to rebuild the system using different materials of construction (Teflon, etc.). The Army would not agree to try again based on health and safety issues of handling boiling hydrochloric acid.

Was this treatment applied at a full scale that could lead to a site closure? No

Have stakeholders approved the site closure followed by the remediation? No, site was excavated the next year.

11. What is the lithology of the site?

a) Geology: Heterogeneous, relatively homogenous, or moderately homogeneous?

A disposal pit was excavated into alluvium, and then filled with excavated soil and waste materials. Lime was added to the pit to control the pH.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other *excavated soil and waste product placed into a disposal pit.*
12) Unknown

b) Hydrogeology:
1) Average depth to groundwater at the site? 20'
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? Not applicable
5) Is there a significant seasonal fluctuation in groundwater table? No
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No

c) Aboveground buildings or permanent structures
Are there aboveground structures that could interfere with the thermal treatment? No

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? NAPL was a tar-like material composed of 90% hexachlorocyclopentadiene with the remaining 10% being mixed pesticides and pesticide precursors.

b) Was the entire area impacted by NAPL addressed by the project? Yes, a total of 276 electrodes were installed in an attempt to address the entire disposal pit.

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes, and the groundwater has not been impacted at this site.

13. Cost Data Availability
a) No cost data available

b) Some cost data available: *Could go through Army to get cost data.*

Was a cost and performance report written? No, but Terra Therm did complete a failure report that should be available on the EPA SITE Program website.

c) Extensive cost data available

14. Above ground treatment system.

a) Major aboveground system components: SVE system, cyclone separator, condensor, flameless thermal oxidizer with acid gas scrubber, GAC sorbers for liquid treatment.

b) Were there any equipment failures during system operation? Everything failed due to corrosion caused by concentrated hydrochloric acid.

c) How much NAPL was collected in the knock-out tank? None

d) Approximately how much liquid was extracted from the system? 300 gallons of pure hydrochloric acid.

e) How were the liquid phases handled, treated, disposed? Was supposed to be treated though GAC, but the sorber caught fire.

f) Water monitoring and NPDES requirements: Not applicable

g) Air monitoring and discharge requirements: Not applicable

h) Activated carbon requirements: Not applicable

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project:
c) Technology had no impact on life-cycle cost of project:
d) Technology increased life-cycle cost of project: *Project cost $3MM plus another $1 to $1.5 MM for preliminary work. The Army wanted to simply excavate the disposal pit but EPA forced them to try an innovative technology. This was the first full-scale application for Terra Therm, and the Army had to pay for their design learning curve.*

e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No, the EPA used the ROD to force the Army to select an innovative technology even though the Army wanted to excavate the material, the cost of which was much less than trying an innovative technology. Specifically, the ROD called for application of a thermal technology at one of the 31 disposal sites at the arsenal, and they (EPA) chose thermally enhanced SVE.

b) Was the thermal technology selected as an interim action? No

c) Was the thermal technology selected as a technology demonstration? Yes, the site was selected as an EPA SITE Program project.

d) Did your regulators suggest or encourage use of the thermal technology selected? Yes, see the answer for question 16a.

e) Was the technology selected based on vendor marketing efforts? No, EPA selected the technology.

f) Knowing project results, would you use the selected thermal technology again? Yes, but not at this site. Thermal technology may be good for treating the vadose zone at some sites that have lower levels of contaminants, but would probably not be cost effective.

g) Knowing project results, would you select a different thermal technology? Not at this site.

h) Knowing project results, would you select a non-thermal technology? Yes, excavation.

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: DOE

2. Facility Name: Savannah River (DUS/HPO)

3. Facility Location: Aiken, South Carolina

4. Facility POC (Name, phone, fax, e-mail):
   Chris Bergren
   (803) 952-6530
   chris.bergren@srs.gov

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL
   b) Chlorinated Solvent DNAPL: *90% PCE, 10% TCE*
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection
   b) Electrical Resistive Heating
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor: Integrated Water Resources, Santa Barbara, CA

8. Project Scale
   a) Pilot Scale: __
   b) Full Scale: Yes
   Was a pilot study conducted before going full-scale: No

   What was the aerial extent and depth of contamination: 1MM cubic feet. 100' by 100' by 160' deep.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing
   c) Post-treatment monitoring
   d) Long-term monitoring

e) Complete: *System cost $4MM*

10. Confirm impression of success

a) Project was a failure: No

b) Project was somewhat successful: No

c) Project was very successful: Yes

Why was it considered successful? Recovered over 68,000# total VOCs in 12 months and met clean up criteria. Criteria were based on reaching asymptotic mass removal rates. System was designed to treat soil from 18' to 160' bgs. Sand zones heated quickly, while clay layers took longer. The system used pulsed steam injections to heat the sand layers which in turn heated the clay layers. The entire vertical profile was heated to above the boiling point for PCE.

What was the percent of mass removed? Facility believes 100% as soil in source area after treatment showed non-detectable contaminant levels.

What was the percent reduction in mass flux? Unclear as groundwater has not recovered (in terms of water levels) at the site.

Is there residual ground water contamination? Unknown due to low water levels in source area.

What was the percent reduction in ground water concentrations? Unknown.

Was rebound measured? Not yet due to low groundwater levels.

d) Is long-term monitoring planned? Yes

Have regulators agreed upon the success of the treatment? Yes. Regulators agreed source area removal is complete, but Savannah will collect another round of soil samples to confirm.

Was this treatment applied at a full scale that could lead to a site closure? Yes. Regulators allowed system to be shutdown and removed. Will require groundwater monitoring. Regulators also agreed to Savannah plan to implement steam enhanced SVE at a larger site at the facility.

Have stakeholders approved the site closure followed by the remediation? Yes, both regulators an public.

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?

Coastal plain sediments to at least 160'

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 120'
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? Not applicable
5) Is there a significant seasonal fluctuation in groundwater table? No
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? No

12. What was the nature of NAPL at the site?

Mobile DNAPL over entire vertical profile with indication of vertical migration.

a) Was NAPL mobile, immobile residual, other? See above

b) Was the entire area impacted by NAPL addressed by the project? Yes, but this was one source area of a 2 square mile dissolved plume.

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available

Was a cost and performance report written? Yes, a report was written for EM50 and should be available there or on Savannah River website.

14. Above ground treatment system.

a) Major aboveground system components: Plant steam, high-vacuum SVE system (total fluids) with NAPL separator, condenser, and an existing air stripper used to treat both aqueous steam and condensate stream.

b) Were there any equipment failures during system operation? Heat exchanger took a few days to get operation down. Rest of system worked well.

c) How much DNAPL was collected in the knock-out tank? About 3 gallons, most PCE/TCE was recovered from vapor phase.

d) Approximately how much liquid was extracted from the system? Sent more than 2MM gallons of condensate to the air stripper.

e) How were the liquid phases handled, treated, disposed? Through an existing air stripper, treated to < 1μg/L total CAHs, then to a NPDES outfall.

f) Extracted NAPL mass: 68,000#

g) Water monitoring and NPDES requirements: Yes.

h) Air monitoring and discharge requirements: Air stripper emission had to meet OSHA levels only.

i) Activated carbon requirements: None

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project: *Compared to endless pump and treat, and SVE.*

b) Technology probably reduced life-cycle cost of project

c) Technology had no impact on life-cycle cost of project

d) Technology increased life-cycle cost of project

e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? Yes, driven by a RCRA Part B permit.

b) Was the thermal technology selected as an interim action? No

c) Was the thermal technology selected as a technology demonstration? No

d) Did your regulators suggest or encourage use of the thermal technology selected? Not really, facility proposed technology and regulators accepted.

e) Was the technology selected based on vendor marketing efforts? No, they sought out the technology and the contractor.

f) Knowing project results, would you use the selected thermal technology again? Yes, for a site with similar conditions.

g) Knowing project results, would you select a different thermal technology? No

h) Knowing project results, would you select a non-thermal technology? No

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: DESC

2. Facility Name: Whittier DFSP

3. Facility Location: Alaska

4. Facility POC (Name, phone, fax, e-mail):
   Jack Appollini/Wayne Barnum
   (907) 552-4650 or (703) 767-8314
   jack.appolloni@dla.mil

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL: *JP4 loss of estimated 100,000 gallons*
   b) Chlorinated Solvent DNAPL
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection: *Whittier tried SVE alone, but recovered only 1 quart during one year of operation.*
   b) Electrical Resistive Heating:
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor: IT

8. Project Scale
   a) Pilot Scale: __
   b) Full Scale: Yes

   Was a pilot study conducted before going full-scale: No, a bench-scale characterization of site soils and contaminants was completed.

   What was the aerial extent and depth of contamination: 200’ by 300’ by 30’ deep. Smear zone is spread from 15’ to 30’ bgs as groundwater at the site is tidally and glacial melt influenced. Also, ground freeze makes year round operation difficult, and water table drops by almost 15 feet in coldest part of year.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing
   c) Post-treatment monitoring
   d) Long-term monitoring
   e) Complete *No plans to reactivate system due to excessive O&M costs. DESC pushed quick remediation in order to release site for lease/sale to commercial oil storage enterprise. DESC, regulators and IT (already on site contractor) agreed steam could speed remediation. Lease/sale fell through and DESC's interest in quick remediation died. Steam injection system allowed recovery of 15,000 gallons in vapor phase, but this is pretty insignificant compared to loss. Free product is evident in on site wells, but has not migrated off site. A dissolved plume extends off site, but it appears to be stable. DESC now plans on hot spot excavation and MNA.*

10. Confirm impression of success
   a) Project was a failure: No

   b) Project was somewhat successful: No

   c) Project was very successful: Yes

   Why was it considered successful? The system worked as expected and increased fuel recovery from less than one gallon in 12 months with SVE alone to approximately 15,000 gallons during 21 months of steam injection. There were not RAOs established regarding thermal enhanced SVE.

   What was the percent of mass removed? Unclear, maybe 15%

   What was the percent reduction in mass flux? Unclear

   Is there residual ground water contamination? Yes

   What was the percent reduction in ground water concentrations? Data is misleading due to extreme groundwater fluctuation over a 15 feet thick smear zone. Also, steam definitely mobilized contaminant mass.

   Was rebound measured? No

   d) Is long-term monitoring planned? Yes

   Have regulators agreed upon the success of the treatment? Regulators liked the technology but agreed it was misapplied at Whittier. They have acknowledged that contamination will always be there and are not too concerned as free phase has not migrated off site.

Was this treatment applied at a full scale that could lead to a site closure? No, O&M costs and amount of fuel lost made treatment ineffective.

Have stakeholders approved the site closure followed by the remediation? Residents were either ok or did not care. They did not show up at the RAB meetings.

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?

Fifteen feet of gravel fill (to build tanks on rocky and unlevel ground) over fractured bedrock.

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other *Gravel fill over bedrock.*
12) Unknown

b) Hydrogeology:

1) Average depth to groundwater at the site? 15' – 30'
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? Yes
5) Is there a significant seasonal fluctuation in groundwater table? Yes
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? Groundwater impacted more by temperature, tide and glacial melt water.

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? A manifold building (source of fuel loss) with a dirt floor, ASTs and associated above ground piping.

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? Mobile fuel hydrocarbon that moves around within a 150' by 150' area.

b) Was the entire area impacted by NAPL addressed by the project? Yes

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available Yes, system cost $3.8MM, over half of which was O&M costs. More data can be obtained from DESC.

Was a cost and performance report written? No

14. Above ground treatment system.

a) Major aboveground system components: SVE system, methane fired boiler, knockout tank and condenser.

b) Were there any equipment failures during system operation? Up time averaged 90%, but system had to be shut down during high glacial melt periods.

c) How much NAPL was collected in the knock-out tank? 1000 gallons, also recovered 15,000 gallons from condensed vapor stream.

d) Approximately how much liquid was extracted from the system? Data was not available.

e) How were the liquid phases handled, treated, disposed? Recovered liquid was used to feed boiler or re-injected into subsurface.

f) Water monitoring and NPDES requirements: No

g) Air monitoring and discharge requirements: Emission limits were established and system operated within limits.

h) Activated carbon requirements: Not applicable

15. Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project:
c) Technology had no impact on life-cycle cost of project:
d) Technology increased life-cycle cost of project: *O&M costs were 3 times estimated costs and mass removed was insignificant when compared to the mass released.*
e) Unknown

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? No, this was considered an IRA at a RCRA facility.

b) Was the thermal technology selected as an interim action? Yes

c) Was the thermal technology selected as a technology demonstration? No

d) Did your regulators suggest or encourage use of the thermal technology selected? Regulators provided some input but did not seem to care a great deal about the site.

e) Was the technology selected based on vendor marketing efforts? No

f) Knowing project results, would you use the selected thermal technology again? Yes, but not at Whittier

g) Knowing project results, would you select a different thermal technology? Yes, but not at Whittier.

h) Knowing project results, would you select a non-thermal technology? Yes, now going with hot spot excavation and MNA.

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes

Thermal Enhancement for the Cost-Effective Remediation of NAPLs
Questionnaire #2

1. Organization Name: NAVFAC/DESC

2. Facility Name: Yorktown Fuels

3. Facility Location: Virginia

4. Facility POC (Name, phone, fax, e-mail):
   Jennifer Davis
   (757) 322-4775
   davisjj@efdlant.navfac.navy.mil

5. Confirm type of source area:
   a) Fuel Hydrocarbon LNAPL: *Bunker fuel loss estimated at 3MM gallons. Site used USTs (WW I vintage) to store navy fuels. Eleven acre storage site operated until 1970's, after which the USTs were collapsed within their tank pit and the pit backfilled to grade.*
   b) Chlorinated Solvent DNAPL
   c) Chlorinated Solvent dissolved in Fuel Hydrocarbon (LNAPL)
   d) Other (please explain)

6. Confirm type of thermal technology employed:
   a) Steam injection: *Was built in phases due to concern of contaminant mobilization from steam injection and to show hydraulic control at the site before steam injection was fully implemented. Skimmers were first installed and operated for about one year before steam injection was initiated. Steam was injected at only ½ the site for 3.5 years to confirm contaminant mobilization was not occurring. The final phase of the project, steam injection at the remaining ½ of the site, is scheduled to occur this year (2004).*
   b) Electrical Resistive Heating:
   c) Conductive Heating
   d) Radio-Frequency Heating
   e) Hot water injection
   f) Thermal Enhancement for SVE (hot air, 6-phase, etc)
   g) Deep soil mixing with steam injection
   h) Other (please explain)

7. Identify the vendor/contractor: OHM

8. Project Scale
   a) Pilot Scale: ___
   b) Full Scale: Yes
   Was a pilot study conducted before going full-scale: Yes

What was the aerial extent and depth of contamination: 11 acres by 25 feet deep.

9. Project status
   a) Planning (including design)
   b) In situ treatment is ongoing: *Project started in 1998 with skimmers in wells. Steam injection began on ½ the site in Sept 2000 and continues. The steam injection system will be expanded to address the remaining ½ of the site and steam injection will commence there later this year. Construction costs for the first ½ of the site were $6MM and O&M costs are $1MM per year. The estimated cost for expansion of the project to address the remaining ½ of the site is $4MM. Steam injection is expected to require another 15 years before cleanup criteria are met.*
   c) Post-treatment monitoring
   d) Long-term monitoring
   e) Complete

10. Confirm impression of success
   a) Project was a failure: No

   b) Project was somewhat successful: Yes

   Why was it considered successful? The project is removing an average of 5000 gallons bunker fuel per month for a total of 168,000 gallons in 3.5 years. The recovered fuel is sold to a vendor, which allows for some cost recovery. Prior to steam injection, the skimming system recovered about 30,000 gallons over a one year period.

   What was the percent of mass removed? Approx 6%

   What was the percent reduction in mass flux? Unclear, and system is still in operation

   Is there residual ground water contamination? Yes

   What was the percent reduction in ground water concentrations? Did not provide data.

   Was rebound measured? NA

   c) Project was very successful: No

   d) Is long-term monitoring planned? Yes, quarterly for VOCs, SVOCs and metals. Also will conduct annual soil sampling for TPH.

Have regulators agreed upon the success of the treatment? Yes, and regulators recommended technology at another site in Virginia based on results from Yorktown. State has set cleanup criteria of 0.1' free product in wells or asymptotic removal rates of fuel.

Was this treatment applied at a full scale that could lead to a site closure? Not initially due to concern of mobilization of fuel by steam injection. But DESC is now expanding steam injection at remainder of site to achieve cleanup criteria. These actions are in accordance with the state approved Corrective Action Plan.

Have stakeholders approved the site closure followed by the remediation? The U.S. Park Service has property adjoining site and they have expressed concern about contaminant migration. The other stakeholders (U.S. Coast Guard and private resident) are ok with actions to date.

11. What is the lithology of the site?

a) Geology: Heterogeneous, homogenous, or moderately homogeneous?
Coastal plant sediments consisting of sand, silt and clay

1) Sand
2) Silt
3) Clay
4) Sedimentary
5) Gravel
6) Till
7) Unconsolidated
8) Metamorphic
9) Igneous
10) Consolidated
11) Other
12) Unknown

b) Hydrogeology:
1) Average depth to groundwater at the site? 15' – 25'
2) Confined or unconfined. Unconfined
3) Vertical profile depth(s) of confining layer(s)? see above
4) Is there significant fracturing of the bedrock? No
5) Is there a significant seasonal fluctuation in groundwater table? Not much, but did drop 10 feet during drought.
6) Is the geology significantly impacted by precipitation (i.e. sandy and very permeable)? No

c) Aboveground buildings or permanent structures

Are there aboveground structures that could interfere with the thermal treatment? Treatment system building. All USTs were collapsed and filled over.

12. What was the nature of NAPL at the site?

a) Was NAPL mobile, immobile residual, other? Modeling indicates free phase may migrate a few inches per year.

b) Was the entire area impacted by NAPL addressed by the project? Not initially, but system will be expanded in 2004 to address entire source area.

c) Was characterization satisfactorily conducted to delineate NAPL and dissolved plume at the site? Yes, dissolved plume is contiguous with free phase plume.

13. Cost Data Availability

a) No cost data available

b) Some cost data available

c) Extensive cost data available Yes

Was a cost and performance report written? Not yet. NAVFAC optimization report is scheduled for 2005.

14. Above ground treatment system.

a) Major aboveground system components:

b) Were there any equipment failures during system operation? Up time averages 99.2%. Only downtime is due to lightning strikes on Virginia power grid.

c) How much NAPL was collected in the knock-out tank? Approximately 5000 gallons per month or 168,000 gallons to date.

d) Approximately how much liquid was extracted from the system? Approximately 473,000 gallons per month in 2002 and 500,000 gallons per month in 2003.

e) How were the liquid phases handled, treated, disposed? Separated aqueous phase is treated through GAC and discharged to the York River.

f) Water monitoring and NPDES requirements: Yes, water discharge is under a NPDES permit.

g) Air monitoring and discharge requirements: Equipment is permitted and was monitored for OSHA limits for first two years.

h) Activated carbon requirements: Will need to check on carbon use data.

15 Confirm impression of impact of thermal technology on life-cycle costs

a) Technology definitely decreased life-cycle cost of project
b) Technology probably reduced life-cycle cost of project:
c) Technology had no impact on life-cycle cost of project:
d) Technology increased life-cycle cost of project:
e) Unknown: *System installation cost, including the estimated 2004 capitol cost, is $10MM. O&M cost for last three years was $1MM per year, but this represents steam injection at only ½ of the site. The minimum costs for steam injection, assuming a 15 year project, will be $25MM. In 1996, the Navy estimated dig and haul costs for the site at $30MM, but this did not include infrastructure replacement (i.e., roads, utilities, etc.). The overall cost of steam will probably not differ that much from the cost of dig and haul.*

16. Confirm answers to the below questions:

a) Was the thermal technology selected in a feasibility study or corrective measures study? Yes, site is following a Corrective Action Plan that was included in the FS.

b) Was the thermal technology selected as an interim action? No

c) Was the thermal technology selected as a technology demonstration? No

d) Did your regulators suggest or encourage use of the thermal technology selected? Regulators would not accept a passive skimming system because they wanted to ensure no oil left the site (oil had migrated onto Coast Guard property in the past). They encourage either steam or electrical resistivity heating to enhance product removal.

e) Was the technology selected based on vendor marketing efforts? No

f) Knowing project results, would you use the selected thermal technology again? The Navy would to increase removal and pacify political pressure.

g) Knowing project results, would you select a different thermal technology? No

h) Knowing project results, would you select a non-thermal technology? No

i) Are you willing to participate further in this thermal technology evaluation? Yes

j) Are you willing to share cost data for use in this life cycle cost evaluation of thermal technology enhancements? Yes