

# Demonstration of Steam Injection/Extraction Treatment of a DNAPL Source Zone at Launch Complex 34 in Cape Canaveral Air Force Station

## Final Innovative Technology Evaluation Report



Prepared for



The Interagency DNAPL Consortium:

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## **Notice**

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## **Executive Summary**

Dense, nonaqueous-phase liquid (DNAPL) contaminants are a challenge to characterize and remediate at many sites where such contaminants have entered the aquifer due to past use or disposal practices. Chlorinated solvents, comprised of chlorinated volatile organic compounds (CVOCs), such as trichloroethylene (TCE) and perchloroethylene (PCE), are common DNAPL contaminants at sites where operations, such as aircraft maintenance, dry cleaning, metal finishing, and electronics manufacturing historically have occurred. In the past, because of the difficulty in identifying DNAPL source zones, most remediation efforts focused on controlling the migration of dissolved CVOc plumes. In recent years, many site owners have experienced success in locating DNAPL sources. DNAPL source remediation is thought to be beneficial because once the source has been significantly mitigated, the strength and duration of the resulting plume can potentially be lowered in the long term, and sometimes in the short or intermediate term as well.

### **The Interagency DNAPL Consortium**

The Interagency DNAPL Consortium (IDC) was formally established in 1999 by the U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (U.S. EPA), Department of Defense (DoD), and National Aeronautics and Space Administration (NASA) as a vehicle for marshalling the resources required to test innovative technologies that promise technical and economic advantages in DNAPL remediation. The IDC is advised by a Technical Advisory Group comprised of experts drawn from academia, industry, and government. The IDC and other supporting organizations facilitate technology transfer to site owners/managers through dissemination of the demonstration plans and results, presentations at public forums, a Web site, and visitor days at the site.

### **Demonstration Site and Technology**

In 1998, a preliminary site characterization was conducted by Westinghouse Savannah River Company at Launch Complex 34 in Cape Canaveral, FL. The results indicated the presence of a sizable DNAPL source consisting primarily of TCE. Based on these results, the IDC selected this site for demonstrating three DNAPL remediation technologies. The surficial aquifer at this site approximately between 5 to 45 ft bgs. This aquifer can be subdivided into three stratigraphic units—the Upper Sand Unit, the Middle Fine-Grained Unit, and the Lower Sand Unit. Although the Middle Fine-Grained Unit is a conspicuous hydraulic barrier, a Lower Clay Unit underlying the surficial aquifer acts as an aquitard and appears to be pervasive throughout the demonstration area, although it is only up to 3 ft thick. The hydraulic gradient in the surficial aquifer is relatively flat. The native aquifer contains relatively high levels of chloride and total dissolved solids (TDS).

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For the demonstration, the TCE-DNAPL source zone was divided into three demonstration plots, each 75 ft × 50 ft in size, for testing three technologies—in situ chemical oxidation (ISCO), resistive heating, and steam injection/extraction (SI/E). Each plot was separated from the next by 15 ft, and about 15 ft of each plot extended under the Engineering Support Building. SI/E was selected because it had the potential to heat the aquifer and move TCE-DNAPL to extraction wells. ISCO and resistive heating were tested concurrently between September 1999 and April/July 2000 in the two outer plots, which are separated by about 80 ft. Subsequently, SI/E was tested in the middle plot, between July and December 2001.

The IDC contracted MSE Technology Applications, Inc., to conduct the vendor selection and subcontracting for the three technologies, as well as for tracking the costs of the demonstration. Integrated Water Resources, Inc. (IWR), the vendor selected for implementing steam injection at Launch Complex 34, applied a patented version of the technology called Dynamic Underground Stripping and Hydrous Pyrolysis/Oxidation (DUS/HPO). In this application, air was co-injected with the steam to keep volatilized TCE suspended in the vapor phase until removed by the extraction system in order to prevent downward migration of TCE-DNAPL through the relatively thin aquitard.

## **Performance Assessment**

The IDC contracted Battelle in 1998 to plan and conduct the technical and economic performance assessment of the three technologies. The U.S. EPA Superfund Innovative Technology Evaluation (SITE) Program provided quality assurance (QA) oversight and field support for the performance assessment. Before the field application of the steam injection technology, Battelle prepared a Quality Assurance Project Plan (QAPP) or test plan (Battelle, 2001c) that was reviewed by all the project stakeholders.

This report describes the results of the performance assessment of the steam injection technology. The objectives of the performance assessment were to:

- Estimate the change in TCE-DNAPL mass reduction.
- Evaluate changes in aquifer quality.
- Evaluate the fate of the TCE-DNAPL removed from the steam injection plot.
- Verify steam injection operating requirements and costs.

Estimating the TCE-DNAPL mass reduction in the SI/E demonstration plot was the primary objective of the demonstration in terms of resources expended for planning, data gathering, and interpretation; the other three were secondary, but important, objectives.

In February 1999, Battelle conducted the preliminary characterization of the TCE-DNAPL source region on the northwest side of the Engineering Support Building. This characterization provided preliminary TCE-DNAPL mass estimates and aquifer data to support the vendor's design of the technology application and provided data on the spatial variability of the TCE-DNAPL. In December 2000, a detailed pre-demonstration characterization of the steam injection plot was conducted to initiate the performance assessment of the steam injection technology. From July 19, 2001 to December 28, 2001, when the steam injection field application was conducted, Battelle collected subsurface data to monitor the progress of the demonstration; the vendor collected additional aboveground data to aid in the operation of the technology. In February 2002, the post-demonstration assessment of the steam injection plot was conducted after all parts of the aquifer had cooled to 90°C or less.

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## Change in TCE-DNAPL Mass

Detailed soil sampling was used as the main tool for determining changes in TCE-DNAPL mass in the demonstration plot. The spatial distribution data for TCE from the pre-demonstration characterization were used to determine a statistically significant number and location of soil samples required to obtain adequate coverage of the S/E plot. A systematic unaligned sampling scheme was used to conduct pre- and post-demonstration soil coring at 12 locations in a 4 × 3 grid in the demonstration plot. Continuous soil samples were collected at every 2-ft vertical interval in each core, resulting in approximately 300 soil samples in the steam injection plot during pre- and post-demonstration characterization. A vertical section (approximately 150 g of wet soil) from each 2-ft interval was collected and extracted with methanol in the field; the methanol extract was sent to a certified off-site laboratory for analysis. In this manner, the entire soil column was analyzed from ground surface to aquitard (Lower Clay Unit), at most coring locations. In some coring locations, drilling did not extend entirely to the depth of the aquitard to avoid advancing through to the aquifer below.

Special steps were taken during the post-demonstration soil sampling to cool the retrieved cores and to minimize volatilization losses from the hot soil. Achievement of good recovery of TCE from both hot and cold soil cores using the improved field handling and extraction procedures was verified through spiking and extraction of a surrogate compound in selected soil cores. Evaluation of the soil cooling and extraction method at Launch Complex 34 showed between 84 and 113% spike recovery was possible with this sampling method.

The TCE concentrations (mg/kg of dry soil) obtained by this method were considered "total TCE." The portion of the total TCE that exceeded a conservative threshold concentration of 300 mg/kg was considered "DNAPL." This threshold was determined as the maximum TCE concentration in the dissolved and adsorbed phases in the Launch Complex 34 soil; any TCE concentration exceeding this threshold would be DNAPL.

An evaluation of the change in TCE-DNAPL mass reduction by soil sample analyses indicated the following:

- Simple linear interpolation of the TCE results after the application of S/E showed that the total TCE mass estimated to be present within the plot prior to the demonstration decreased by 85% and the DNAPL mass decreased by approximately 89%.
- Kriging, a geostatistical tool which takes into account the uncertainties associated with interpolation of spatial TCE distribution data, indicated that the total TCE mass within the demonstration plot decreased between 80 and 90% following the S/E treatment.
- TCE mass reduction was apparent in most parts of the demonstration plot. Much of the remaining TCE-DNAPL in the demonstration plot after the demonstration was at the base of the aquifer, right above the Lower Clay Unit. This may have been a difficult location for the steam to access because the density differential between steam and groundwater would cause the steam to migrate vertically upward away from the Lower Clay Unit. In addition, the steam injection wells did not extend to the Lower Clay Unit. Minor pockets of TCE-DNAPL remained in shallower parts of the aquifer under the Engineering Support Building and near the northwestern end of the demonstration plot.

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## Changes in Aquifer Quality

In order to maintain hydraulic control and mitigate potential migration of DNAPL from the plot, the vendor maintained an aggressive groundwater extraction rate of 22 gpm along the boundary of the steam injection plot. During the course of the demonstration, the vendor extracted a total of 4,013,588 gal of water (equivalent to approximately 11 pore volumes of the demonstration plot), including approximately 372,473 gal of steam condensate. Water entering the steam injection plot from the surrounding aquifer may have affected the TCE levels measured in the demonstration plot wells because portions of the aquifer surrounding the demonstration plot remain contaminated with TCE-DNAPL. Other groundwater parameters which are considered key indicators of TCE destruction, such as chloride and alkalinity, also may have been affected by the hydraulic controls. Except for TCE and other chlorinated volatile organic compound (CVOCs), the vendor did not measure any of the other groundwater parameters in the extracted water above ground. Therefore, it was difficult to discern strong trends in groundwater parameters that would be traceable to SI/E.

Application of the SI/E technology showed the following changes in the treated aquifer:

- Dissolved TCE concentrations decreased in some wells in the SI/E plot, but increased in other wells that were relatively clean before the SI/E demonstration, probably due to influx of permanganate from the ISCO plot. In all wells in the SI/E plot, TCE levels in groundwater were still relatively high after steam treatment and much higher than the State of Florida groundwater cleanup standard of 3 µg/L. In addition to the DNAPL remaining in the steam plot itself, another reason for the persistence of elevated TCE levels in the plot wells may be the large influx of groundwater from the surrounding aquifer.
- Levels of *cis*-1,2-dichloroethylene (*cis*-1,2-DCE) rose in some steam plot wells, but declined in others. The *cis*-1,2-DCE levels also may have been affected by influx of water from the surrounding aquifer. However, some of the groundwater and soil parameters taken together do indicate heightened microbial activity in the demonstration plot. Total organic carbon (TOC) levels in the soil and biological oxygen demand (BOD) levels in the groundwater declined after treatment, indicating that carbon sources in the aquifer were being depleted. This could be due to both biotic and abiotic causes. Hydrous pyrolysis/oxidation of the TCE and *cis*-1,2-DCE, as well as other organic matter in the aquifer, is one of the removal mechanisms claimed by the steam technology vendor.
- The microbial count results showed that although microbial populations declined somewhat after the steam injection, much of the microbial community survived the heating and may have been increasingly active at moderate to high temperatures (given the TOC and BOD depletion in the aquifer).
- Probably as a result of the large influx of groundwater from the surrounding aquifer, none of the other measured groundwater parameters (such as chloride, sodium, calcium, alkalinity, etc.) showed any discernible trends attributable to SI/E.

### ***Fate of TCE-DNAPL Reduction Mass in the Demonstration Plot***

The decrease in TCE-DNAPL mass from the plot following the demonstration could have taken one or more of the following pathways:



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- TCE recovery in the vapor recovery system. The vendor reported that between 5,200 and 9,700 kg (7,400 ±2,200 kg) of TCE was measured in the recovered vapor and groundwater. The estimated pre-demonstration TCE mass in the steam injection plot before the demonstration was between 11,150 and 14,150 kg of TCE. However, the source of the TCE recovered above ground by the vendor is unclear. It is possible that some dissolved TCE was drawn into the extracted water from the surrounding aquifer, parts of which are in untreated DNAPL source areas.
  - TCE degradation by biotic or abiotic means. It is possible that some of the TCE was degraded to other products due to SI/E. There is some evidence of heightened microbial activity in the steam injection plot at the elevated temperatures observed during the demonstration. Also, hydrous pyrolysis/oxidation of the TCE at elevated temperatures is one of the claims of SI/E technology, although this was not verified. No measurable buildup of expected degradation products, such as chloride, alkalinity, or *cis*-1,2-DCE, was observed; this may have been due to the masking effect of extracted groundwater from outside the plot. There was no noticeable buildup of expected degradation products due to any of these mechanisms, possibly due to the diluting effect of 11 pore volumes of water extracted from the plot and the surrounding aquifer.
  - DNAPL migration to surrounding regions. The possibility of DNAPL migration from the steam injection plot to surrounding regions is minimal. The hydraulic containment maintained by the vendor was relatively strong (an average of 22 gpm of water was extracted by the vendor along the boundaries of the plot). Therefore, it is unlikely that any DNAPL migrated to the surrounding aquifer, despite the expected reduction in surface tension of the DNAPL due to heating. No elevated TCE concentrations were found in the vadose zone soil samples collected during post-demonstration soil coring. No elevated TCE levels or elevated temperatures were apparent in the confined aquifer wells below the steam injection plot, once the steam injection demonstration began. Also, the continuous pumping (22 gpm) in the surficial aquifer may have exerted an upward gradient across the Lower Clay Unit. TCE levels were slightly elevated above background levels in the surface emission tests conducted on the ground around the plenum, indicating that the recovery system may have been underdesigned. Most of the vaporized TCE appears to have been recovered in the vapor recovery system.
  - Potential TCE losses during post-demonstration sampling of hot soil cores. The potential for TCE loss through this pathway is minimal. The hot soil cores were cooled to ambient temperature in the sleeves they were brought to the ground surface in. Recoveries of 84 to 113% of a surrogate compound spiked into the hot and cold soil cores were achieved during tests conducted to verify the field sampling and extraction procedures.

Therefore, despite some uncertainties created by the large influx of groundwater into the SI/E plot, it is likely that much of the TCE reduction in the plot was recovered above ground in the vapor recovery system. It is unclear how much of the TCE in the SI/E plot was degraded in situ, due to the steam application. The TCE recovered aboveground was ultimately recovered on the GAC or destroyed in the thermal oxidizer.

### ***Verifying Operating Requirements***

Mobilization and setup of the steam injection equipment at the Launch Complex 34 site commenced on April 23, 2001 and continued until July 6, 2001. A helium tracer test was conducted in the SI/E plot between June 28 and July 13, 2001 to evaluate the injection characteristics of the aquifer. SI/E started on July 19, 2001 and was

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operational more or less continuously until December 20, 2001. The vapor recovery system remained on until December 28 before it was shut down. There was a brief interruption to the SI/E system between December 1 and 9 because of a malfunction in the thermal oxidizer. The thermal oxidizer was used to treat the CVOC vapors in the effluent from the air stripper, which was treating the extracted groundwater and steam condensate. The SI/E system was demobilized between January 7 and January 25, 2002.

For the most part, the SI/E equipment operated smoothly and, once in the field, operations progressed relatively smoothly. Operators wore Level D personal protective equipment. Operation of heavy equipment (during mobilization and demobilization) and handling of hot fluids and surfaces were the primary hazards during the operation. There were no injuries during the demonstration. Monitoring wells inside the demonstration plot were sealed and were not sampled until the aquifer had cooled to below 90°C.

### ***Economics***

The economic evaluation involved a comparison of the short-term SI/E technology with an equivalent pump-and-treat system. An equivalent pump-and-treat system is one that captures the groundwater flowing through the 75-ft x 50-ft x 45-ft demonstration plot. A present value (PV) analysis was used to compare the two systems. The total cost of the SI/E application at Launch Complex 34 was \$1,201,000. This total cost includes \$55,100 for waste disposal, incurred by NASA. The estimated PV of an equivalent pump-and-treat system (2-gpm capacity) is \$1,406,000, over 30 years of operation.

This analysis indicates that the SI/E technology is cost competitive with a pump-and-treat system. However, for a true economic comparison, some other factors may need to be considered. Most DNAPL sources, and the resulting plumes, are expected to last much longer than 30 years. This would increase the cost of a slow plume containment remedy, such as a pump-and-treat system. In addition, the cost analysis assumes that the pump-and-treat system will be operational 100% of the time. At many sites, however, system downtime has resulted in pump-and-treat systems being operational as little as 50% of the time. This would affect the protectiveness of the remedy and the associated cost.

The short-term cost of SI/E application assumes that natural attenuation would be sufficient to address any residual source. Following field application, SI/E and natural attenuation require none of the aboveground structures, recurring operational costs, and maintenance that pump-and-treat systems require. In general, the economics favor DNAPL source treatment over a pump-and-treat system at this site.

Site characterization costs were not included in the cost comparison because a good design of either a source treatment (e.g., SI/E) or plume control (e.g., pump-and-treat treatment) remedial action would require approximately the same degree of characterization. The site characterization conducted by Battelle in February 1999 is typical of the characterization effort that may be required for delineating a 75-ft x 50-ft x 45-ft DNAPL source; the cost of this effort was \$255,000, which included a work plan, 12 continuous soil cores to 45 ft bgs, installation of 36 monitoring wells, field sampling, laboratory analysis of samples, field parameter measurements, hydraulic testing, data analysis, and reporting.

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## **Regulatory and Administrative Considerations**

DNAPL source remediation, in general, and SI/E, in particular, is a treatment option that may result in risk reduction under certain conditions through removal of DNAPL from the subsurface. Contaminant mass reduction and, to a minimal extent, toxicity reduction resulted from the TCE extraction and its possible degradation in the aquifer due to SI/E treatment.

Although the eventual target for the Launch Complex 34 aquifer is meeting Florida state-mandated groundwater cleanup goals (3 µg/L of TCE, 70 µg/L of *cis*-1,2-DCE, and 1 µg/L of vinyl chloride), the Technical Advisory Group recommended a more feasible and economically viable goal of 90% reduction of DNAPL mass within the treatment plot. From the experience of the demonstration, it appears that, at least from the site owner's perspective, three types of cleanup goals may be envisioned for source remediation—a short-term goal, an intermediate-term goal, and a long-term goal. At Launch Complex 34, the **short-term goal** of the cleanup was at least 90% reduction of the DNAPL mass, and was the immediate goal given to the technology vendors. Although the reduction of DNAPL mass was observed in the SI/E plot, TCE concentrations in groundwater did not decrease below the state-mandated goal of 3 µg/L. However, given the high concentrations of TCE in groundwater across the site prior to the demonstration, the 3 µg/L target cleanup goal may be difficult to meet in the short term unless most of the residual DNAPL mass is removed. In addition, the large influx of groundwater (11 pore volumes) from the surrounding contaminated aquifer may have masked some of the TCE reduction caused by the SI/E treatment.

On the other hand, there was some evidence of heightened microbial activity in the demonstration plot. If this increased microbial activity continues while the aquifer is still warm (cooling to ambient temperatures is expected to take several months), it is possible that TCE degradation will occur, and that a weakened plume will result in the intermediate term (i.e., a few years after the source treatment). Therefore, there is a possibility that the source treatment, in conjunction with natural attenuation (or other plume control measure, if necessary), would allow cleanup targets to be met at a downgradient compliance point (e.g., property boundary). With source treatment, meeting groundwater cleanup targets is likely to be an **intermediate-term goal**, rather than short-term, goal.

The **long-term goal** of source treatment would be faster dismantling of any interim plume control remedy (pump-and-treat or other treatment) that may be implemented to meet groundwater cleanup targets at the compliance point. Faster dismantling of any interim remedy is likely to result from the fact that DNAPL mass reduction would hasten the eventual depletion of the TCE source.



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## Acronyms and Abbreviations

3-D	three-dimensional
ACL	alternative concentration limit
AFRL	Air Force Research Laboratory
amsl	above mean sea level
ARAR	applicable or relevant and appropriate requirement
bgs	below ground surface
BOD	biological oxygen demand
BTU	British thermal unit
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CES	Current Environmental Solutions
CFR	Code of Federal Regulations
CFU	colony-forming unit
CVOC	chlorinated volatile organic compound
CWA	Clean Water Act
DCE	dichloroethylene
DNAPL	dense, nonaqueous-phase liquid
DO	dissolved oxygen
DoD	Department of Defense
DOE	Department of Energy
DUS	dynamic underground stripping
EM50	Environmental Management 50 (Program)
ESB	Engineering Support Building
FDEP	(State of) Florida Department of Environmental Protection
FSU	Florida State University
GAC	granular activated carbon
gpm	gallon(s) per minute
HAZWOPER	Hazardous Waste Operations and Emergency Response
HCl	hydrochloric acid
HPO	hydrous pyrolysis oxidation
HSWA	Hazardous and Solid Waste Amendments
IDC	Interagency DNAPL Consortium
ISCO	in situ chemical oxidation

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ITRC	Interstate Technology Regulatory Council
IWR	Integrated Water Resources, Inc.
LCS	laboratory control spike
LCSD	laboratory control spike duplicate
LRPCD	Land Remediation and Pollution Control Division
MCL	maximum contaminant level
MPN	most probable number
MS	matrix spikes
MSD	matrix spike duplicates
MSE	MSE Technology Applications, Inc.
msl	mean sea level
mV	millivolts
MYA	million years ago
NA	not available
N/A	not analyzed
NAAQS	National Ambient Air Quality Standards
NAPL	nonaqueous-phase liquid
NASA	National Aeronautics and Space Administration
ND	not detected
NFESC	Naval Facilities Engineering Service Center
NPDES	National Pollutant Discharge Elimination System
O&M	operation and maintenance
ORP	oxidation-reduction potential
OSHA	Occupational Safety and Health Administration
PCE	perchloroethylene
PID	photoionization detector
POTW	publicly owned treatment works
ppb	parts per billion
PV	present value
PVC	polyvinyl chloride
QA	quality assurance
QAPP	Quality Assurance Project Plan
QC	quality control
RCRA	Resource Conservation and Recovery Act
RFI	RCRA Facility Investigation
RI/FS	Remedial Investigation/Feasibility Study
RPD	relative percent difference
RSKERC	R.S. Kerr Environmental Research Center (of U.S. EPA)
SARA	Superfund Amendments and Reauthorization Act
scfm	standard cubic feet per minute
SDWA	Safe Drinking Water Act
S/E	steam injection/extraction
SIP	State Implementation Plan
SITE	Superfund Innovative Technology Evaluation (Program)
SPH™	Six-Phase Heating™ (also electrical resistive heating)
TCA	trichloroethane
TCE	trichloroethylene

---

TDS	total dissolved solids
TOC	total organic carbon
U.S. EPA	United States Environmental Protection Agency
VOA	volatile organic analysis
VOC	volatile organic compound
WKO	water knockout tank
WSRC	Westinghouse Savannah River Company

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## 1. Introduction

This project was a demonstration of the steam injection/extraction (SI/E) technology for remediation of a dense, nonaqueous-phase liquid (DNAPL) source zone at Launch Complex 34, Cape Canaveral Air Force Station, FL.

### 1.1 Project Background

The goal of this project was to evaluate the cost and performance of the SI/E technology for remediation of DNAPL source zones. SI/E was demonstrated at Launch Complex 34, where the chlorinated volatile organic compound (CVOC) trichloroethylene (TCE) is present in the aquifer as a DNAPL. Smaller amounts of dissolved *cis*-1,2-dichloroethylene (DCE) and vinyl chloride also are present in the groundwater as a result of the natural degradation of TCE.

Field application of the technology started in July 2001 and ended in December 2001. Performance assessment activities were conducted before, during, and after the demonstration.

#### 1.1.1 The Interagency DNAPL Consortium

The steam injection demonstration was part of a larger demonstration of three different DNAPL remediation technologies completed at Launch Complex 34 with the combined resources of several U.S. government agencies. The government agencies participating in this effort have formed the Interagency DNAPL Consortium (IDC). The IDC is composed primarily of the following agencies, which are providing the majority of the funding for the demonstration:

- Department of Energy (DOE), Environmental Management 50 (EM50) Program
- United States Environmental Protection Agency (U.S. EPA), Superfund Innovative Technology Evaluation (SITE) Program
- National Aeronautics and Space Administration (NASA)

- Department of Defense (DoD), Naval Facilities Engineering Service Center (NFESC).

In the initial stages of the project, until January 2000, the Air Force Research Laboratory (AFRL) was the DoD representative on this consortium and provided significant funding. NFESC replaced AFRL in March 2000.

In addition, the following organizations are participating in the demonstration by reviewing project plans and data documents, funding specific tasks, and/or promoting technology transfer:

- Patrick Air Force Base
- U.S. EPA, R.S. Kerr Environmental Research Center (RSKERC)
- Interstate Technology Regulatory Council (ITRC).

Key representatives of the various agencies constituting the IDC have formed a Core Management Team, which guides the progress of the demonstration. An independent Technical Advisory Group has been formed to advise the Core Management Team on the technical aspects of the site characterization and selection, remediation technology selection and demonstration, and the performance assessment of the technologies. The Technical Advisory Group consists of experts drawn from industry, academia, and government.

The IDC contracted MSE Technology Applications, Inc. (MSE), to conduct technology vendor selection, procure the services of the three selected technology vendors, and conduct the cost evaluation of the three technologies. Integrated Water Resources, Inc. (IWR) was the vendor selected for implementing the steam injection technology at Launch Complex 34. IT Corporation and Current Environmental Solutions (CES) were the vendors for the in situ chemical oxidation (ISCO) (also known as chemical oxidation) and electrical resistive heating (also known as SPH™) technologies, respectively. In addition, the IDC also contracted Westinghouse Savannah River Company (WSRC) to conduct the preliminary site



characterization for site selection, and Florida State University to coordinate site preparation and onsite field management. Figure 1-1 summarizes the project organization for the IDC demonstration.

### 1.1.2 Performance Assessment

The IDC contracted Battelle to plan, conduct, and report on the detailed site characterization at Launch Complex 34 and perform an independent performance assess-

ment for the demonstration of the three technologies. U.S. EPA and its contractor TetraTech EM, Inc., provided quality assurance (QA) oversight and field support for the pre-demonstration performance assessment activities. Before the field demonstration, Battelle prepared a Quality Assurance Project Plan (QAPP) that was reviewed by all the project stakeholders. This QAPP was based on the general guidelines provided by the U.S. EPA's SITE Program for test plan preparation, quality assurance, and data analysis (Battelle, 2001c).

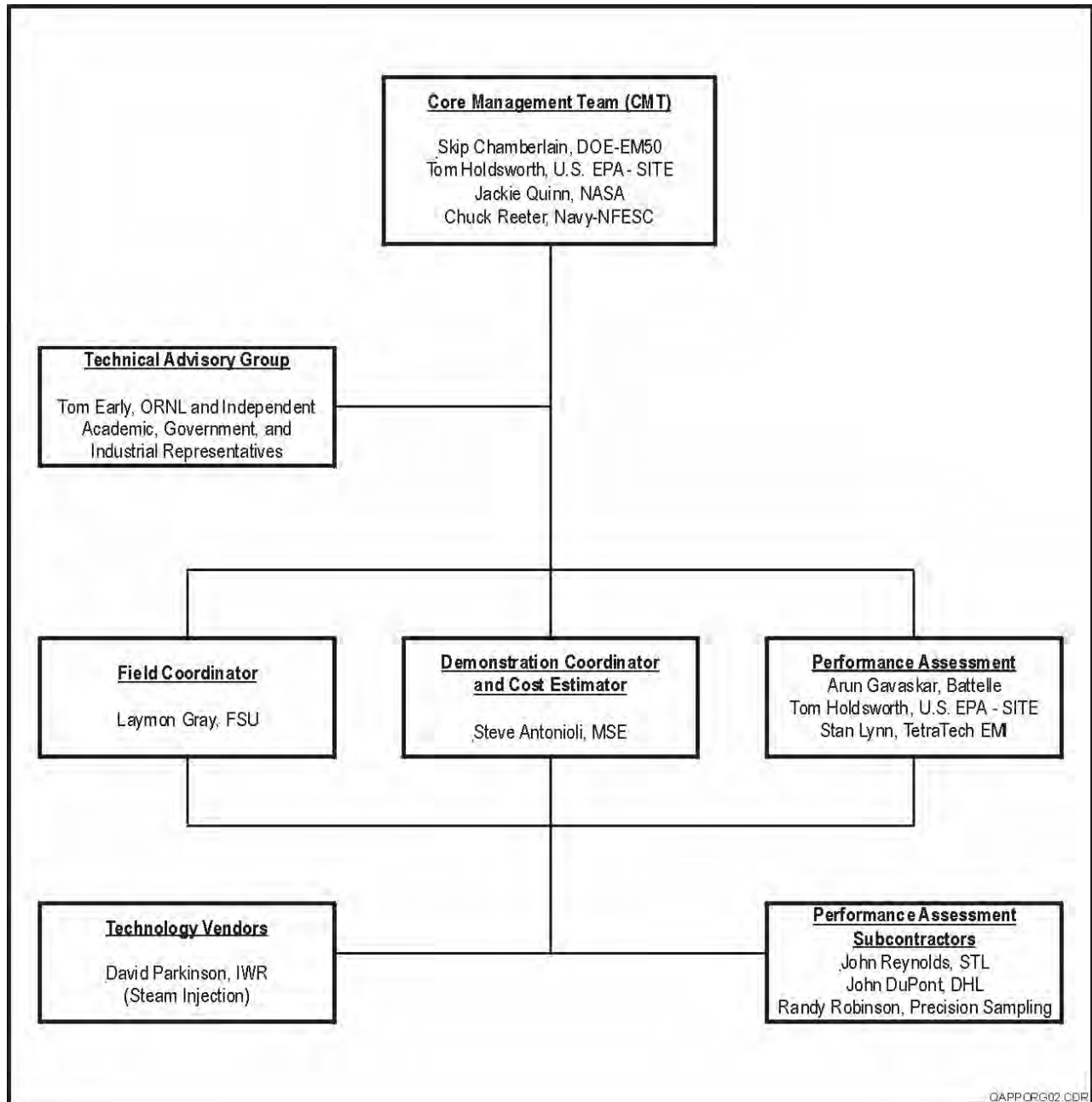


Figure 1-1. Project Organization for the IDC Demonstration at Launch Complex 34

### 1.1.3 The SITE Program

The performance assessment planning, field implementation, and data analysis and reporting for the steam injection demonstration followed the general guidance provided by the U.S. EPA's SITE Program. The SITE Program was established by U.S. EPA's Office of Solid Waste and Emergency Response and the Office of Research and Development in response to the 1986 Superfund Amendments and Reauthorization Act, which recognized a need for an "Alternative or Innovative Treatment Technology Research and Demonstration Program." ORD's National Risk Management Research Laboratory in the Land Remediation and Pollution Control Division (LRPCD), headquartered in Cincinnati, OH, administers the SITE Program. The SITE Program encourages the development and implementation of (1) innovative treatment technologies for hazardous waste site remediation and (2) innovative monitoring and measurement tools.

In the SITE Program, a field demonstration is used to gather engineering and cost data on the innovative technology so that potential users can assess the technology's applicability to a particular site. Data collected during the field demonstration are used to assess the performance of the technology, the potential need for preprocessing and post-processing of the waste, applicable types of wastes and waste matrices, potential operating problems, and approximate capital and operating costs.

U.S. EPA provides guidelines on the preparation of an Innovative Technology Evaluation Report at the end of the field demonstration. These reports evaluate all available information on the technology, and analyze its overall applicability to other site characteristics, waste types, and waste matrices. The reports also include testing procedures, performance and cost data, and quality assurance and quality standards. This IDC report on the steam injection technology demonstration at Launch Complex 34 is based on these general guidelines.

## 1.2 The DNAPL Problem

Figure 1-2 illustrates the formation of a DNAPL source at a chlorinated solvent release site. When solvent is released into the ground due to previous use or disposal practices, it travels downward under gravitational force through the vadose zone to the water table. Because many chlorinated solvents are denser than water, the solvent continues its downward migration through the saturated zone (assuming sufficient volume of solvent is involved) until it encounters a low-permeability layer or aquitard, on which it may form a pool. During its downward migration, the solvent leaves a trace of residual solvent in the soil pores. Many chlorinated solvents are

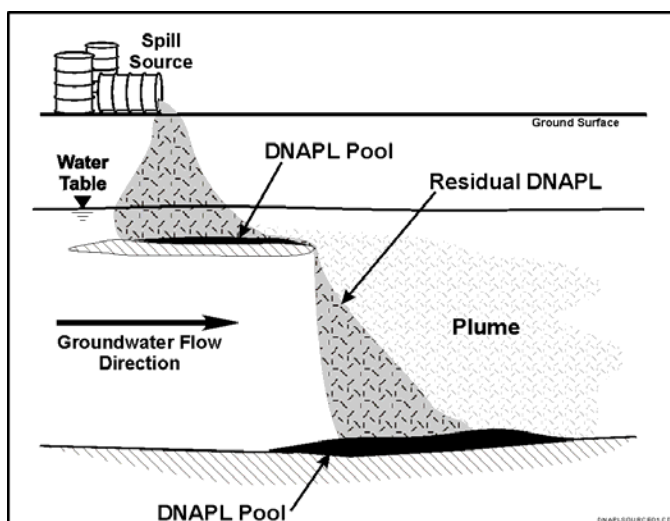


Figure 1-2. Formation of a DNAPL Source in an Aquifer

only sparingly soluble in water; therefore, they can persist as a separate phase for several years (or decades). This free-phase solvent is called DNAPL.

DNAPL in pools often can be mobilized toward extraction wells when a strong hydraulic gradient is imposed; this solvent is called mobile DNAPL. In contrast, residual DNAPL is DNAPL trapped in pores that cannot be mobilized toward extraction wells, regardless of the strength of the applied gradient. Residual DNAPLs form as DNAPL pools and may partially dissolve in the groundwater flow over time, leaving behind residual DNAPL in the soil structure. At most sites, DNAPL pools are rare; DNAPL is often present in residual form.

As long as DNAPL is present in the aquifer, a plume of dissolved solvent is generated. DNAPL therefore constitutes a secondary source that keeps replenishing the plume long after the primary source (leaking above-ground or buried drums, drain pipes, vadose zone soil, etc.) has been removed. Because DNAPL persists for many decades or centuries, the resulting plume also persists for many years. As recently as five years ago, DNAPL sources were difficult to find, and most remedial approaches focused on plume treatment or plume control. In recent years, efforts to identify DNAPL sources have been successful at many chlorinated solvent-contaminated sites. The focus is now shifting from plume control to DNAPL source removal or treatment.

Pump-and-treat systems have been the conventional treatment approach at DNAPL sites and these systems have proved useful as an interim remedy to control the progress of the plume beyond a property boundary or other compliance point. However, pump-and-treat

systems may not be economical for remediation of the DNAPL itself. Pools of DNAPL, which can be pumped and treated above ground, are rare. Residual DNAPL is immobile and does not migrate toward extraction wells. As with plume control, the effectiveness and cost of DNAPL remediation with pump and treat is governed by the time (decades) required for slow dissolution of the DNAPL source in the groundwater flow. An innovative approach is required to address the DNAPL problem.

### 1.3 Steam Injection Technology

The introduction of heat to the subsurface produces a wide variety of physical and chemical effects beneficial for the breakdown or removal of DNAPL contaminants in both saturated and unsaturated subsurface materials:

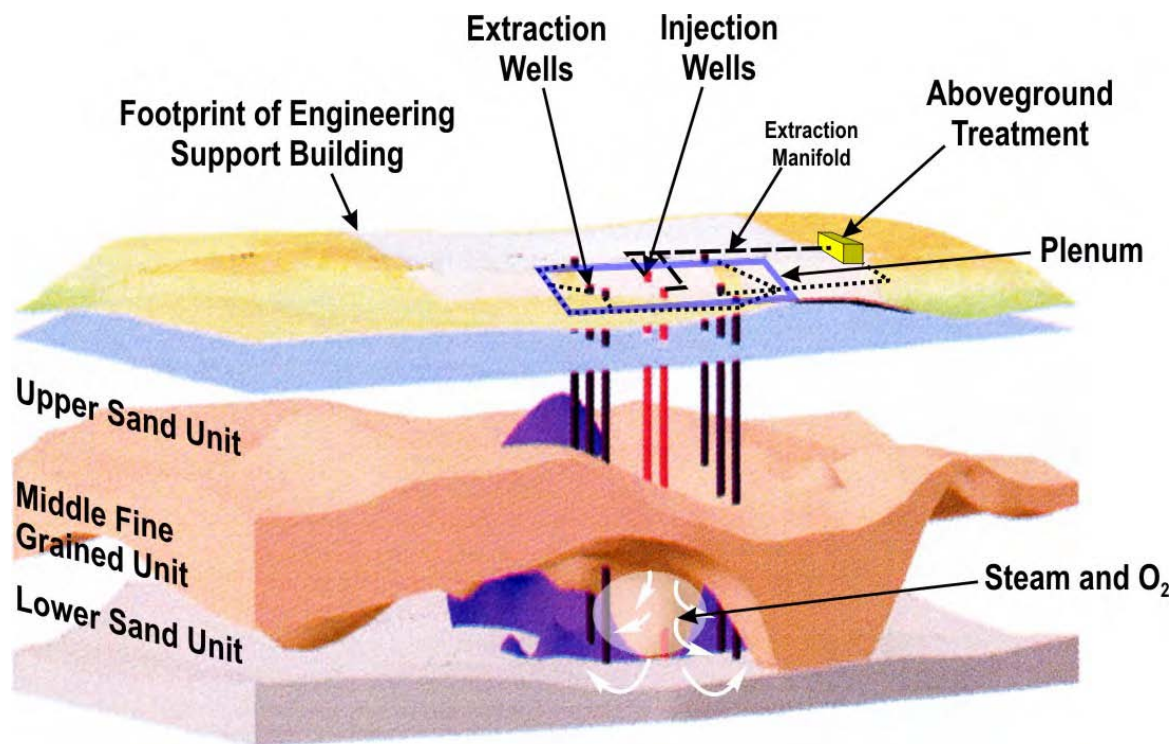
- Decreased viscosities, which in turn leads to increased mobility
- Increased volatility
- Distillation
- Hydrous pyrolysis and oxidation (HPO)
- Increased diffusion rates.

The SI/E process removes DNAPL using a combination of volatilization, steam stripping, and oxidation. The SI/E

process also removes DNAPL through enhanced extraction, which occurs as the solubility of DNAPL increases and viscosity decreases as a result of the applied heat. The process is controlled through timing, placement, and depth of stream injection and vacuum extraction wells, and (as necessary) the placement of in-borehole electrodes for electrical heating.

The steam stripping system uses boilers to generate steam that then is pumped into injection wells at the center of the plot. The steam-front volatilizes and mobilizes the contaminants as it moves toward a network of vertical and/or horizontal vapor extraction wells located at the periphery of the plot (see Figure 1-3). The vapors are condensed and the effluent air stream is discharged after being treated with a thermal oxidizer.

The steam injection system installed at Launch Complex 34 was designed to include the co-injection of air. The co-injection of air with the steam creates a broader thermal front that can contain a larger volume of contaminant-saturated air. The air/steam mixture reduces the injection temperatures to the subsurface, and the co-injected air simultaneously increases the carrying capacity of contaminant in vapor. The optimal ratio of air to steam is based on expected concentration of contaminant, and the vapor pressure of the contaminant.



**Figure 1-3.** Illustration of Steam Injection Technology for Subsurface Treatment

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## 1.4 Demonstration Site

Launch Complex 34, the site selected for this demonstration, is located at Cape Canaveral Air Force Station, FL (see Figure 1-4). Launch Complex 34 was used as a rocket launch site for the Saturn space program from 1960 to 1968. Historical records and worker accounts suggest that rocket engines were cleaned on the launch pad with chlorinated organic solvents such as TCE. Other rocket parts were cleaned on racks at the western portion of the Engineering Support Building and inside the building. Some of the solvents ran off to the surface or discharged into drainage pits. The site was abandoned in 1968 and since has been overgrown by vegetation, although several on-site buildings remain operational.

Preliminary site characterization efforts suggested that approximately 20,600 kg (Battelle, 1999a) to 40,000 kg (Eddy-Dilek et al., 1998) of solvent may be present in the subsurface near the Engineering Support Building at Launch Complex 34. Figure 1-5 is a map of the Launch Complex 34 site that shows the target DNAPL source area, located in the northern vicinity of the Engineering Support Building. The DNAPL source zone was large enough that the IDC and the Technical Advisory Group could assign three separate demonstration plots encompassing different parts of this source zone. Figure 1-5 also shows the layout of the three demonstration plots along the northern edge of the Engineering Support Building. The steam injection plot is in the middle of three plots. Figure 1-6 is a photograph looking south toward the three demonstration plots and the Engineering Support Building. All three demonstration plots partially extend under the Engineering Support Building in order to encompass the portion of the DNAPL source under the building, and to determine if the technology could be deployed beneath active facilities.

## 1.5 Report Outline

This S/E technology evaluation report starts with an introduction to the project organization, the DNAPL problem, the technology demonstrated, and the demonstration site (Section 1). The rest of the report is organized as follows:

- Site Characterization (Section 2)
- Technology Operation (Section 3)
- Performance Assessment Methodology (Section 4)
- Performance Assessment Results and Conclusions (Section 5)
- Quality Assurance (Section 6)
- Economic Analysis (Section 7)
- Technology Applications Analysis (Section 8)
- References (Section 9).

Supporting data and other information are presented in the appendices to the report. The appendices are organized as follows:

- Performance Assessment Methods (Appendix A)
- Hydrogeologic Measurements (Appendix B)
- CVOC Measurements (Appendix C)
- Inorganic and Other Aquifer Parameters (Appendix D)
- Microbiological Assessment (Appendix E)
- Surface Emissions Testing and Temperature Monitoring (Appendix F)
- Quality Assurance/Quality Control Information (Appendix G)
- Economic Analysis Information (Appendix H).

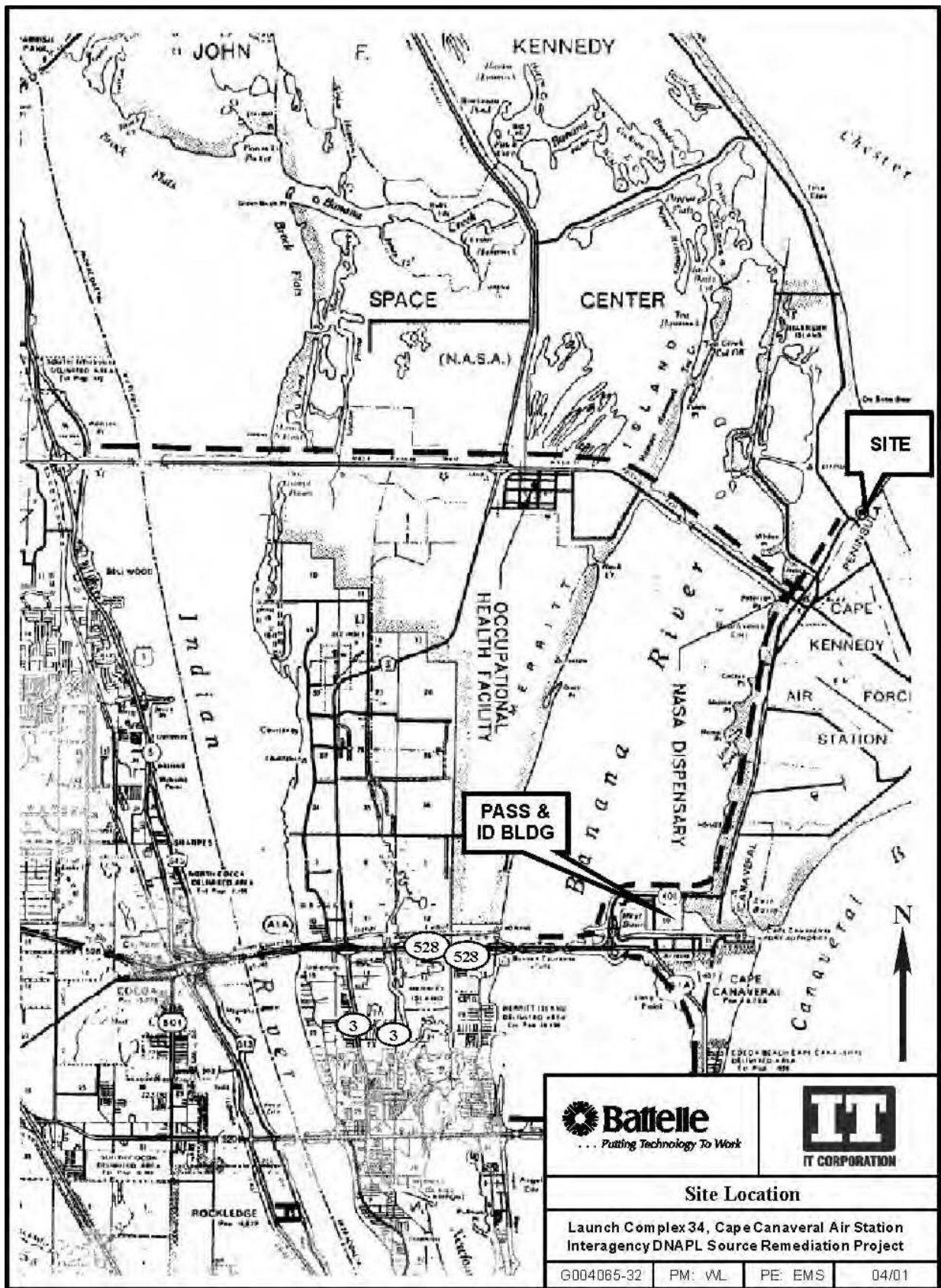
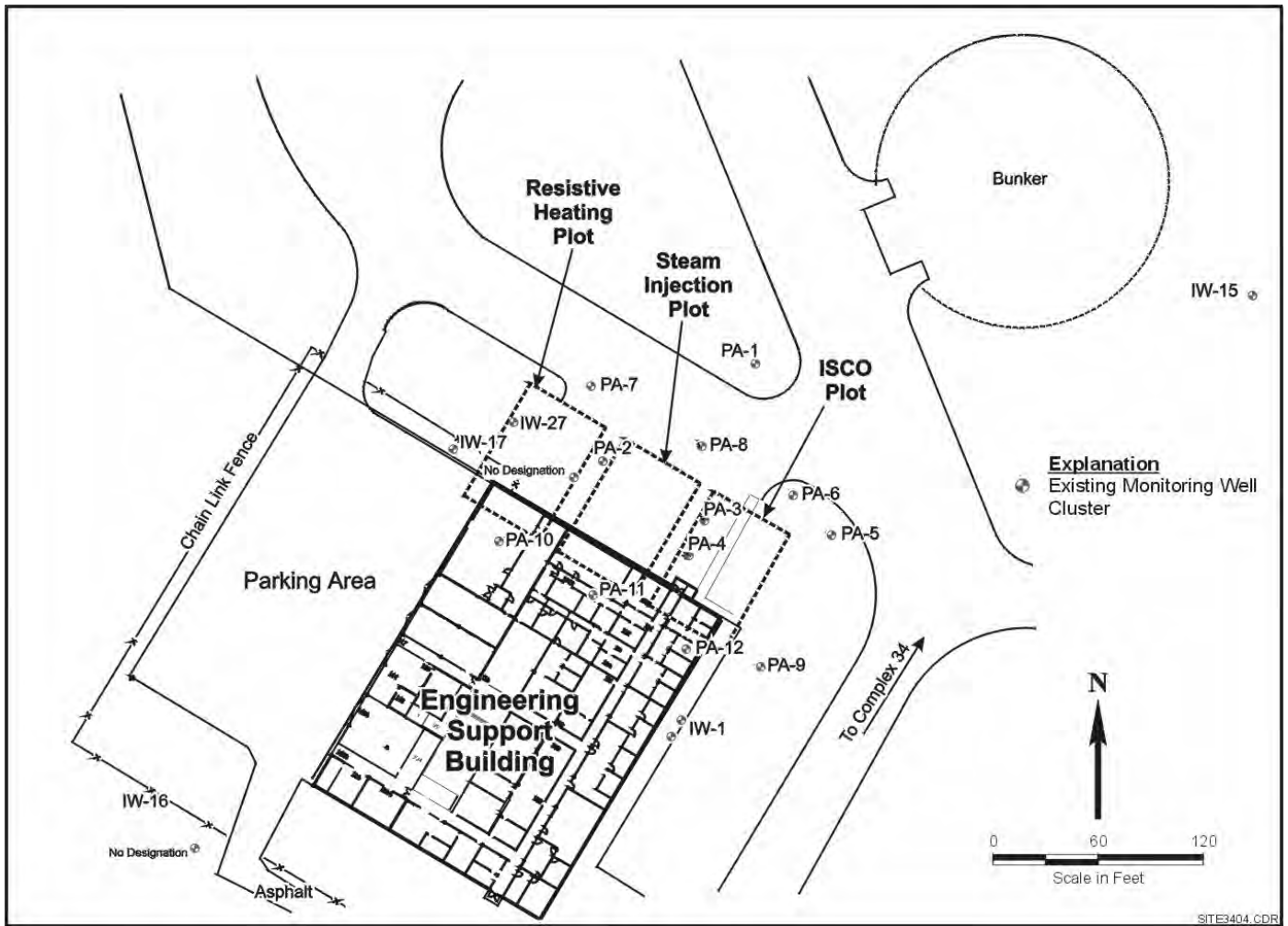
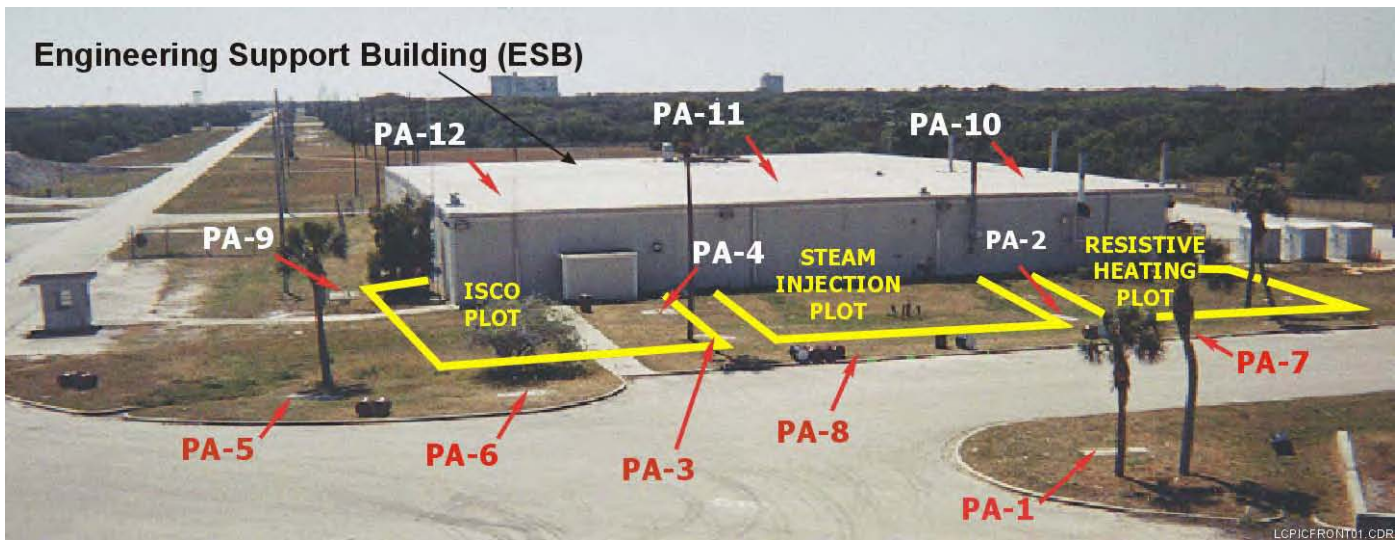


Figure 1-4. Demonstration Site Location



**Figure 1-5.** Location Map of Launch Complex 34 Site at Cape Canaveral Air Force Station



**Figure 1-6.** Looking Southward toward Launch Complex 34, the Engineering Support Building, and the Three Demonstration Plots



## 2. Site Characterization

This section provides a summary of the hydrogeology and chemistry of the site based on the data compilation report (Battelle, 1999a), the additional site characterization report (Battelle, 1999b), and the pre-demonstration characterization report (Battelle, 2001a).

### 2.1 Hydrogeology of the Site

A surficial aquifer and a semi-confined aquifer comprise the major aquifers in the Launch Complex 34 area, as described in Table 2-1. The surficial aquifer extends from the water table to approximately 45 ft below ground surface (bgs) in the Launch Complex 34 area. A clay semi-confining unit separates the surficial aquifer from the underlying semi-confined aquifer.

Figures 2-1 and 2-2 are geologic cross sections, one along the east-west direction across the middle of the three demonstration plots, and the other along the north-south direction across the middle of the steam injection plot. As seen in these figures, the surficial aquifer is sub-classified as having an Upper Sand Unit, a Middle Fine-Grained Unit, and a Lower Sand Unit. The Upper Sand Unit extends from ground surface to approximately 26 ft bgs and consists of unconsolidated, gray fine sand and shell fragments. The Middle Fine-Grained Unit is a layer of gray, fine-grained silty/clayey sand that exists between about 26 and 36 ft bgs. In general, this unit contains soil that is finer-grained than the Upper Sand Unit

and Lower Sand Unit, and varies in thickness from approximately 10 to 15 ft. The Middle Fine-Grained Unit is thicker in the northern portions of the demonstration plots and appears to become thinner in the southern and western portions of the test area (under the Engineering Support Building and in the resistive heating plot). Below the Middle Fine-Grained Unit is the Lower Sand Unit, which consists of gray fine to medium-sized sand and shell fragments. The unit contains isolated fine-grained lenses of silt and/or clay.

A 1.5- to 3-ft-thick layer consisting of greenish-gray sandy clay is present at approximately 45 ft bgs. This semi-confining unit (i.e., the Lower Clay Unit) was encountered in all borings across the Launch Complex 34 site, and it appears to be a pervasive unit. However, the clay unit is fairly thin (around 1.5 to 3 ft thick) in some areas, especially under the resistive heating plot. Site characterization data (Battelle, 1999a and 1999b; Eddy-Dilek et al., 1998) suggest that the surfaces of the Middle Fine-Grained Unit and the Lower Clay Unit are somewhat uneven (see Figures 2-3 to 2-5). The Lower Clay Unit slopes downward toward the southern part of all three demonstration plots and toward the center plot and the building. The thickness of the confining unit initially was uncertain, because most coring locations were terminated when the clay unit was encountered, in order to prevent groundwater from flowing between the confined aquifer and the overlying surficial aquifer. Only

**Table 2-1.** Local Hydrostratigraphy at the Launch Complex 34 Site

Hydrostratigraphic Unit	Thickness (ft)	Sediment Description	Aquifer Description	
Upper Sand Unit	20-26	Gray fine sand and shell fragments	Unconfined, direct recharge from surface	
Surficial Aquifer	Middle Fine-Grained Unit	10-15	Gray, fine-grained silty/clayey sand	Low-permeability, semi-confining layer
	Lower Sand Unit	15-20	Gray fine to medium-sized sand and shell fragments	Semi-confined
Lower Clay Unit (semi-confining unit)	1.5-3	Greenish-gray sandy clay	Thin low-permeability semi-confining unit	
Semi-Confined Aquifer	>40	Gray fine to medium-sized sand, clay, and shell fragments	Semi-confined, brackish	



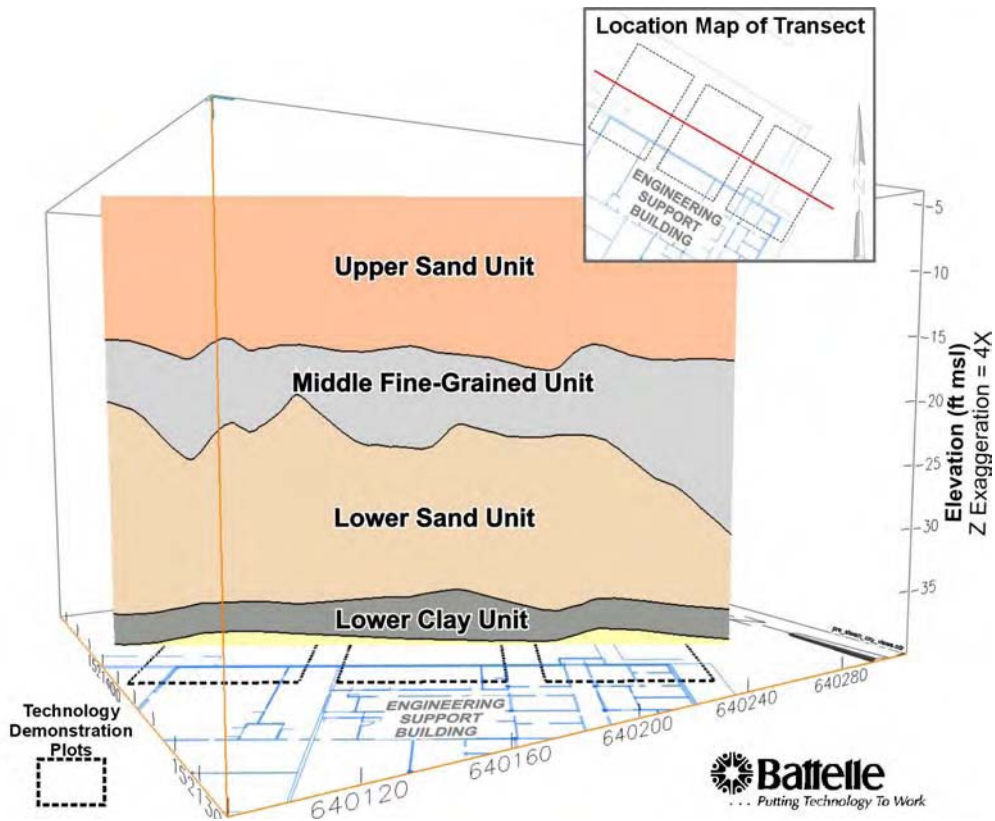


Figure 2-1. West-East Geologic Cross Section through the Three Demonstration plots

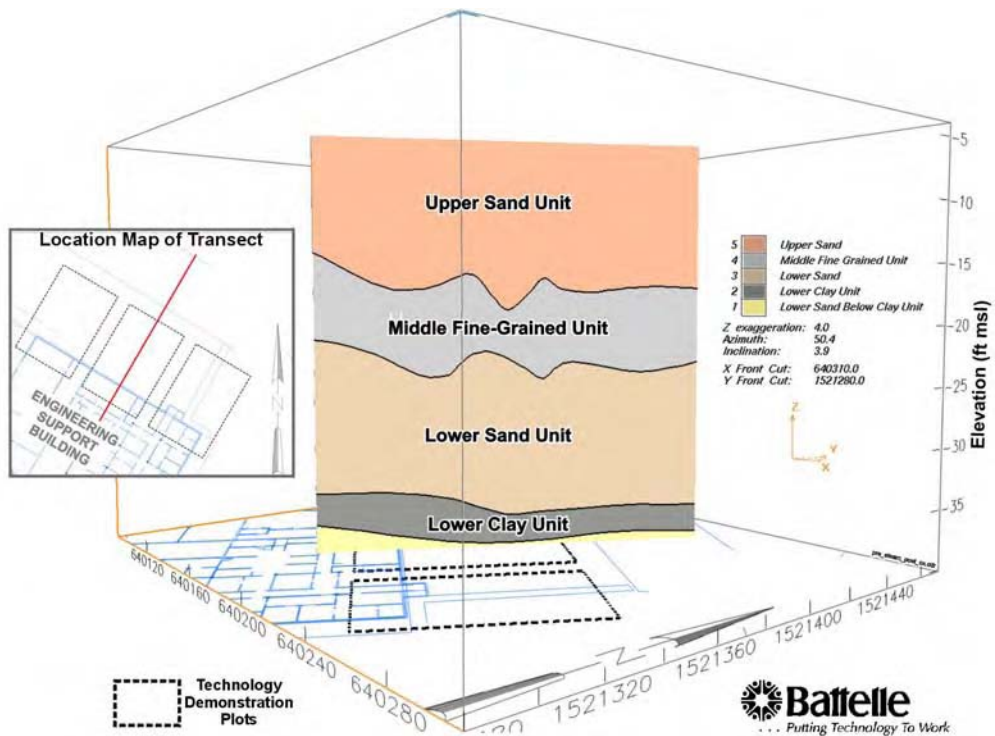
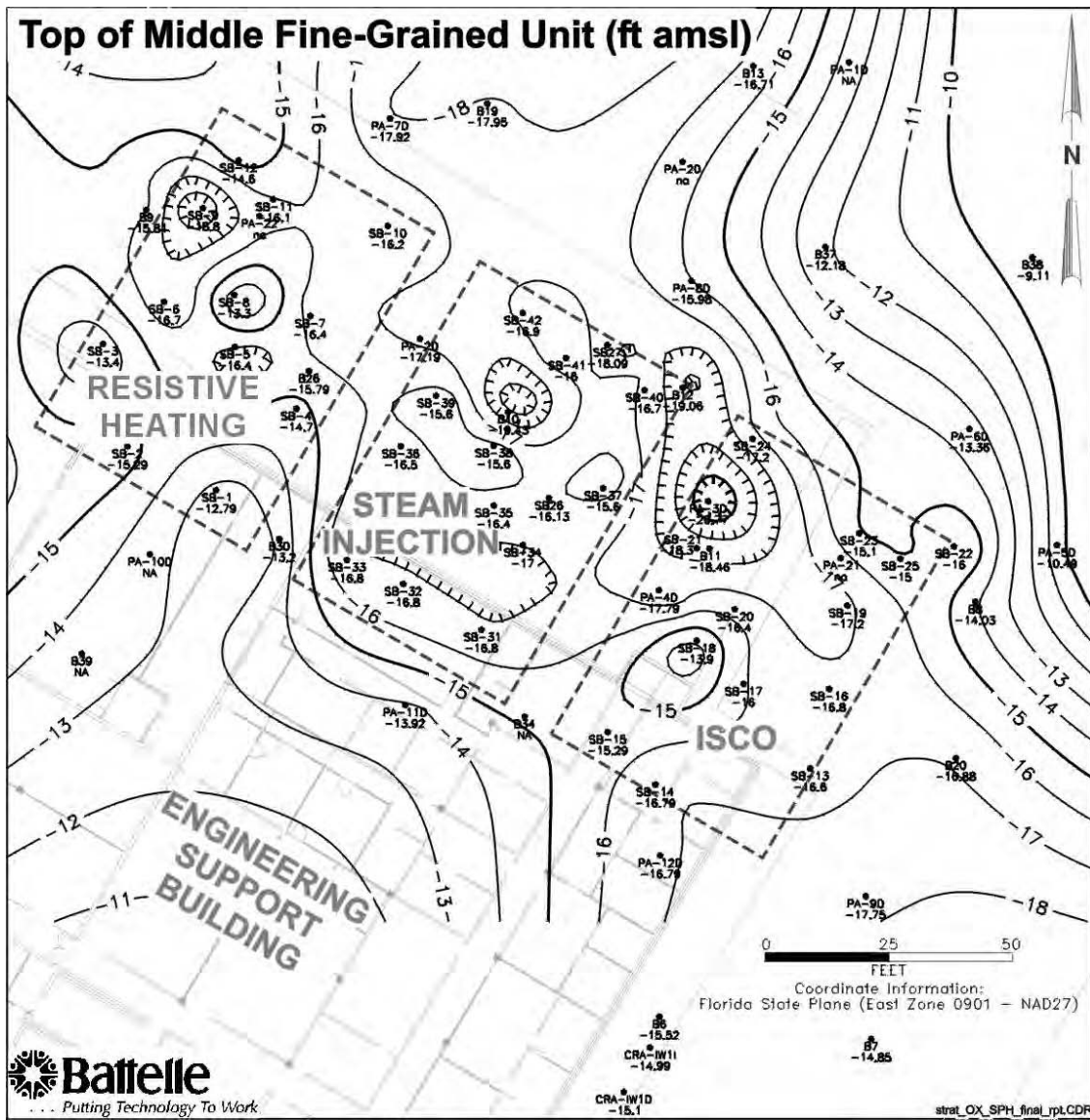


Figure 2-2. South-North Geologic Cross Section through the Steam Injection Plot



**Figure 2-3.** Topography of Top of Middle Fine-Grained Unit

in April 2001 were three soil borings advanced below the confining layer to install monitoring wells in the confined aquifer (Battelle, 2001b).

The semi-confined aquifer underlies the semi-confining unit. The aquifer consists of gray fine to medium-sized sand, clay, and shell fragments. Water levels from wells in the semi-confined aquifer were measured at approximately 4 to 5 ft bgs. Water levels from wells screened in the Lower Sand Unit usually are slightly higher than the water levels from the Upper Sand Unit and/or the Middle Fine-Grained Unit, suggesting that the lower aquifer is confined. Few cores were advanced below the semi-confined aquifer. The thickness of the semi-confined aquifer is greater than 40 ft.

Water-level surveys were performed in the surficial aquifer in December 2000, July and November 2001, and February 2002. Water table elevations in the surficial aquifer were between about 1 and 5 ft above mean sea level (amsl). In general, the surveys suggest that water levels form a radial pattern with highest elevations under the Engineering Support Building. Figure 2-6 shows a water-level map of June 1998, and Table 2-2 summarizes the hydraulic gradients near the Engineering Support Building. The gradient and flow directions vary over time at the site. The gradient ranged from 0.00009 to 0.0007 ft/ft. The flow direction varied from north-northeast to south-southwest.

The surficial aquifer is unconfined above the Middle Fine-Grained Unit and semi-confined below the Middle

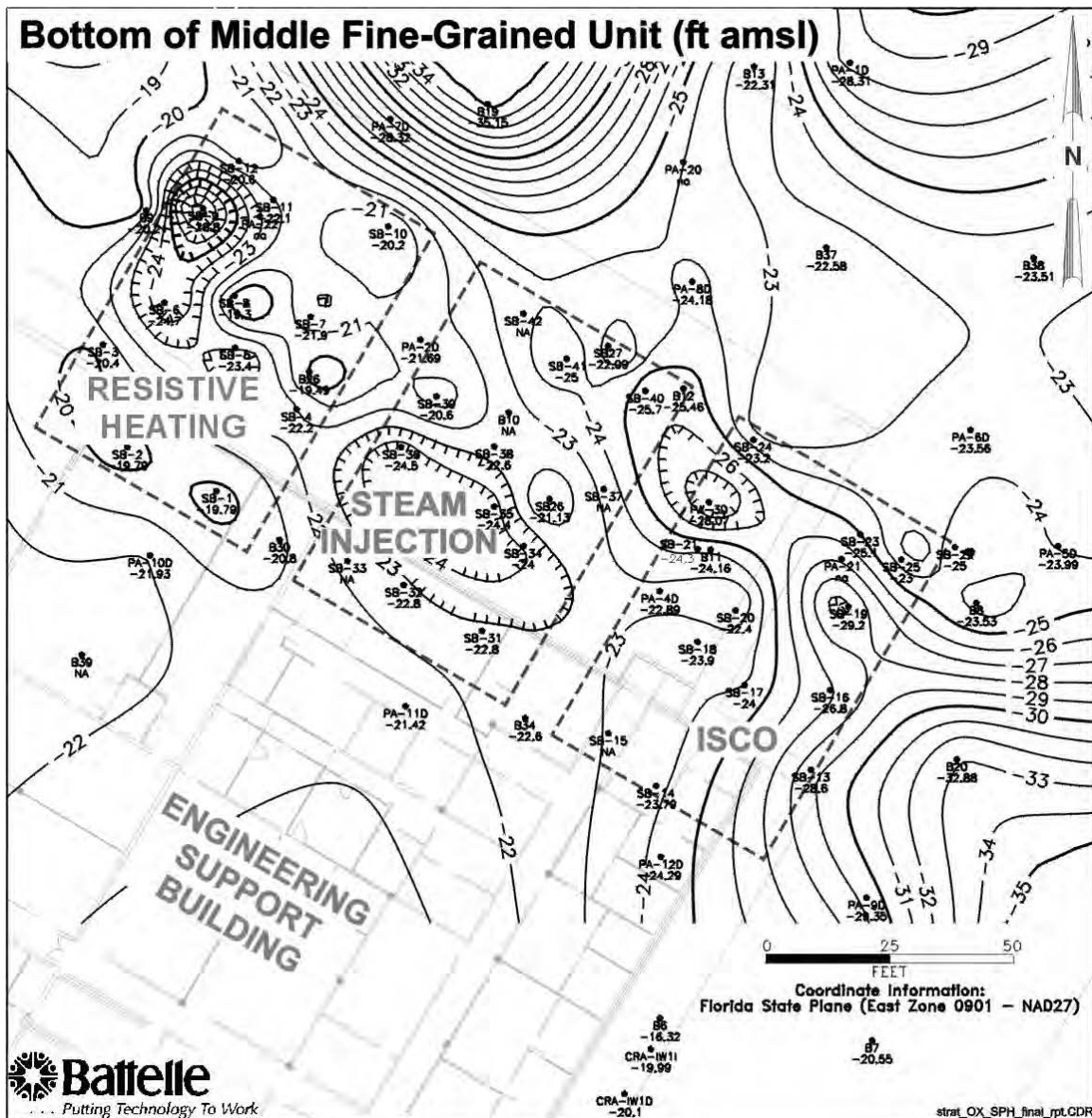


Figure 2-4. Topography of Bottom of Middle Fine-Grained Unit

Fine-Grained Unit. Pre-demonstration water-level measurements in all three surficial aquifer zones — Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit — indicated a relatively flat hydraulic gradient in the localized setting of the three demonstration plots, as seen in Figures 2-7 to 2-9 (Battelle, 1999c). On a regional scale, mounding of water levels near the Engineering Support Building generates a radial gradient; the regional gradient across the demonstration plots appears to be toward the northeast (see Figure 2-6). Probable discharge points for the aquifer include wetland areas, the Atlantic Ocean, and/or the Banana River. The flow system may be influenced by local recharge events, resulting in the variation in the gradients. Recharge to

the surficial aquifer is from infiltration of precipitation through surface soils to the aquifer.

In general, pre-demonstration slug tests showed that the Upper Sand Unit is more permeable than the underlying units, with hydraulic conductivity ranging from 0.14 to 13.7 ft/day in the shallow wells at the site (Battelle, 2001a). The hydraulic conductivity of the Middle Fine-Grained Unit ranges from 2.1 to 4.9 ft/day in the intermediate wells; measured conductivities probably are higher than the actual conductivity of this unit because the intermediate well screens include portions of the Upper Sand Unit. The hydraulic conductivity of the Lower Sand Unit ranged from 2.7 to 3.3 ft/day. Porosity averaged

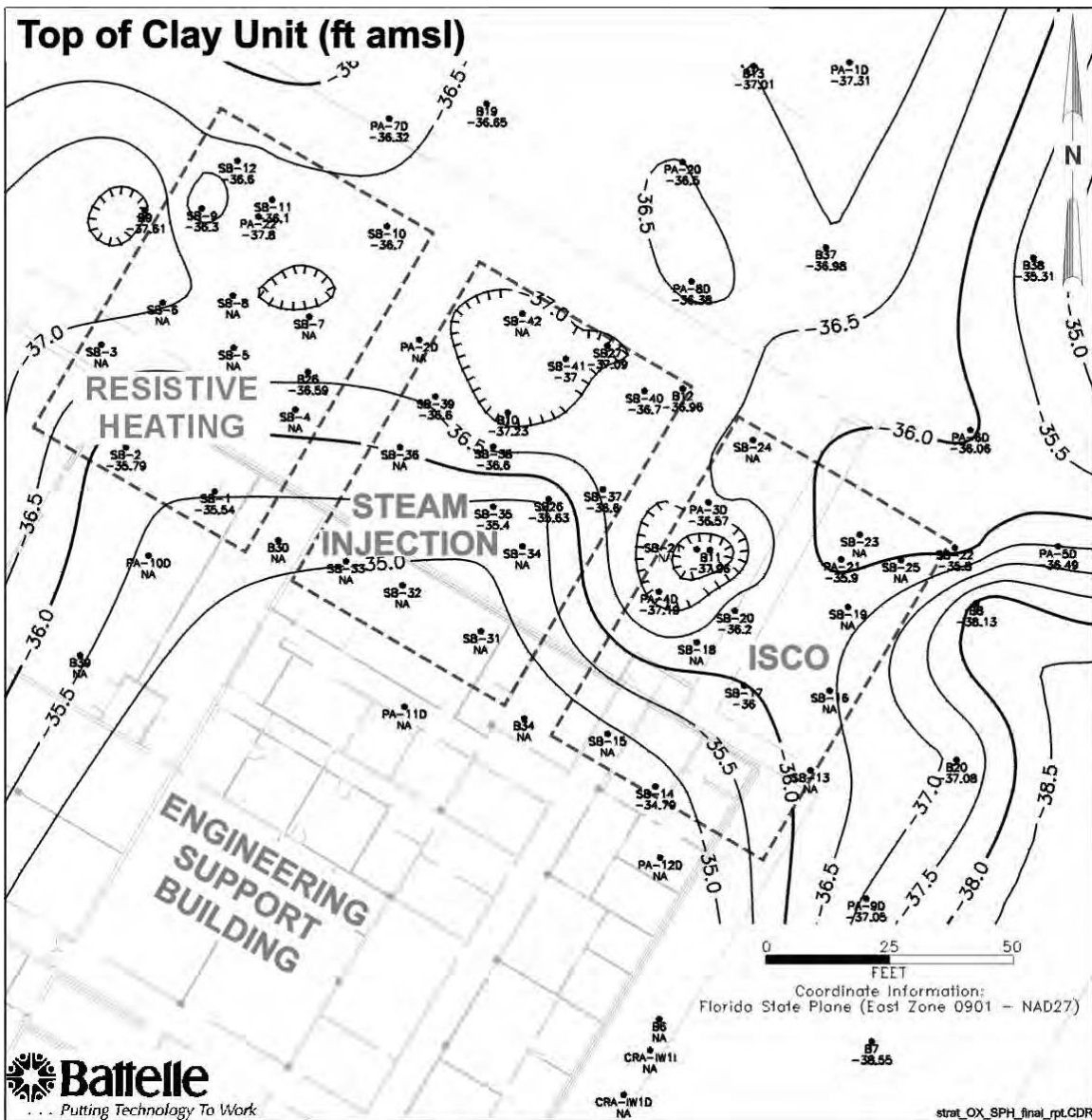


Figure 2-5. Topography of Top of Lower Clay Unit

0.26 in the Upper Sand Unit, 0.34 in the Middle Fine-Grained Unit, 0.29 in the Lower Sand Unit, and 0.44 in the Lower Clay Unit. The bulk density of the aquifer materials averaged  $1.59 \text{ g/cm}^3$  (Battelle, 1999b). Groundwater temperatures ranged from 22.4 to 25.7°C during a March 1999 survey.

Water-level surveys in the confined aquifer were performed in December 2000, July and December 2001, and February 2002. Water-level elevations were measured at approximately 1 to 5 ft msl, and formed a pattern similar to the pattern formed by surficial aquifer water levels. Groundwater elevations are well above the confining unit, indicating that the aquifer is confined. The

gradient in the confined aquifer is positioned in a similar direction to the surficial aquifer. The flow direction varies from east to south-southwest. In general, water levels in the confined aquifer are higher than those in the surficial aquifer, suggesting an upward vertical gradient. Recharge to the aquifer may occur by downward leakage from overlying aquifers or from direct infiltration inland where the aquifer is unconfined. Schmalzer and Hinkle (1990) suggest that saltwater intrusion may occur in intermediate aquifers such as the confined aquifer.

Other notable hydrologic influences at the site include drainage and recharge. Paved areas, vegetation, and topography affect drainage in the area. No streams exist

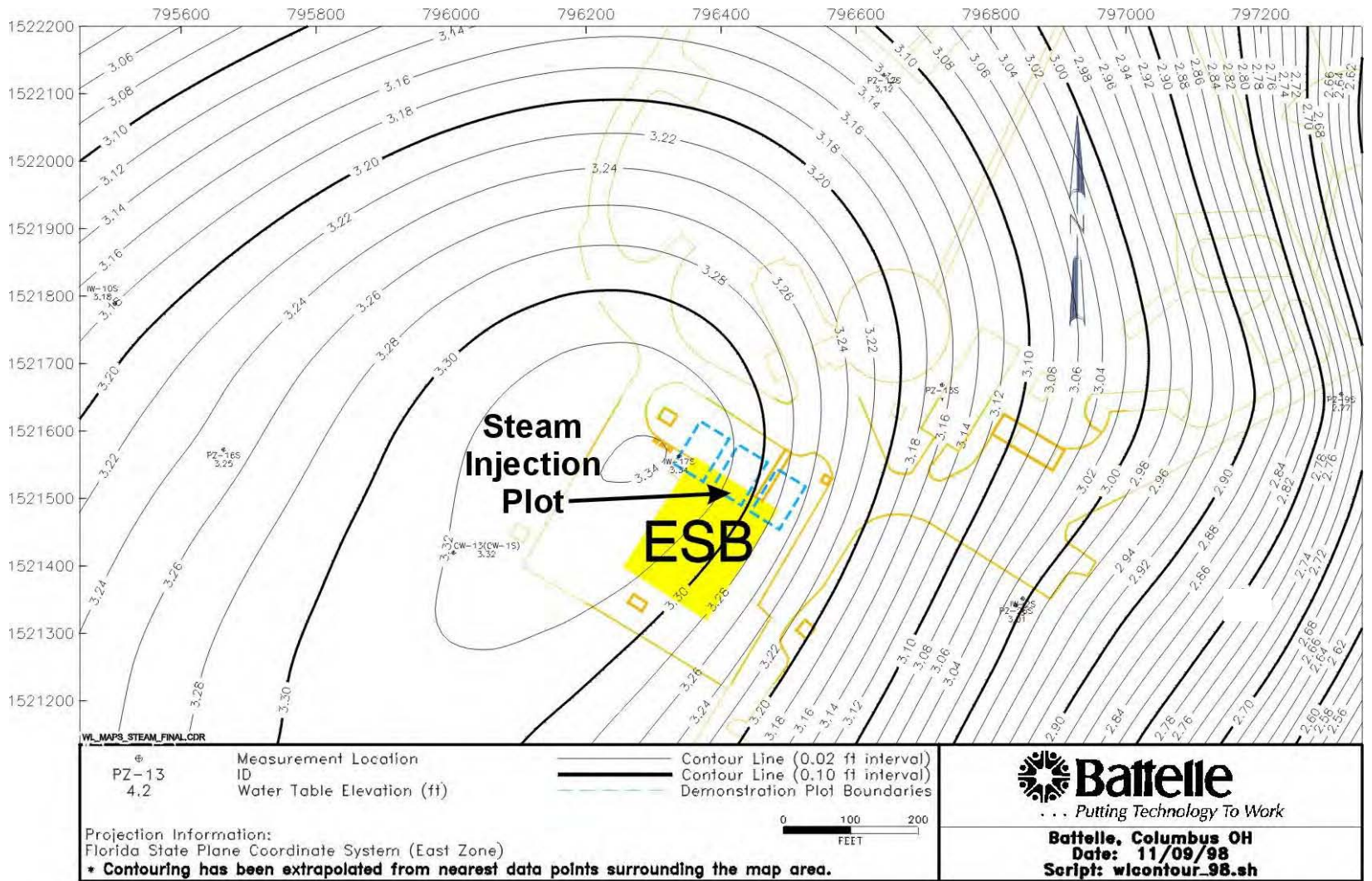


Figure 2-6. Water-Level Map of the Surficial Aquifer (June 1998)

**Table 2-2.** Hydraulic Gradients and Directions in the Surficial and Semi-Confined Aquifers

Hydrostratigraphic Unit	Sampling Date	Hydraulic Gradient
Surficial Aquifer	May 1997	0.00009
	December 1997	0.0001
	June 1998	0.0006
	October 1998	0.0007
	March 1999	undefined
Semi-Confined Aquifer	December 1997	0.0008
	June 1998	0.0005
	October 1998	0.00005

in the site area. Engineered drainage at the site consists of ditches that lead to the Atlantic Ocean or swampy areas. Permeable soils exist from the ground surface to the water table and drainage is excellent. Water infiltrates directly to the water table.

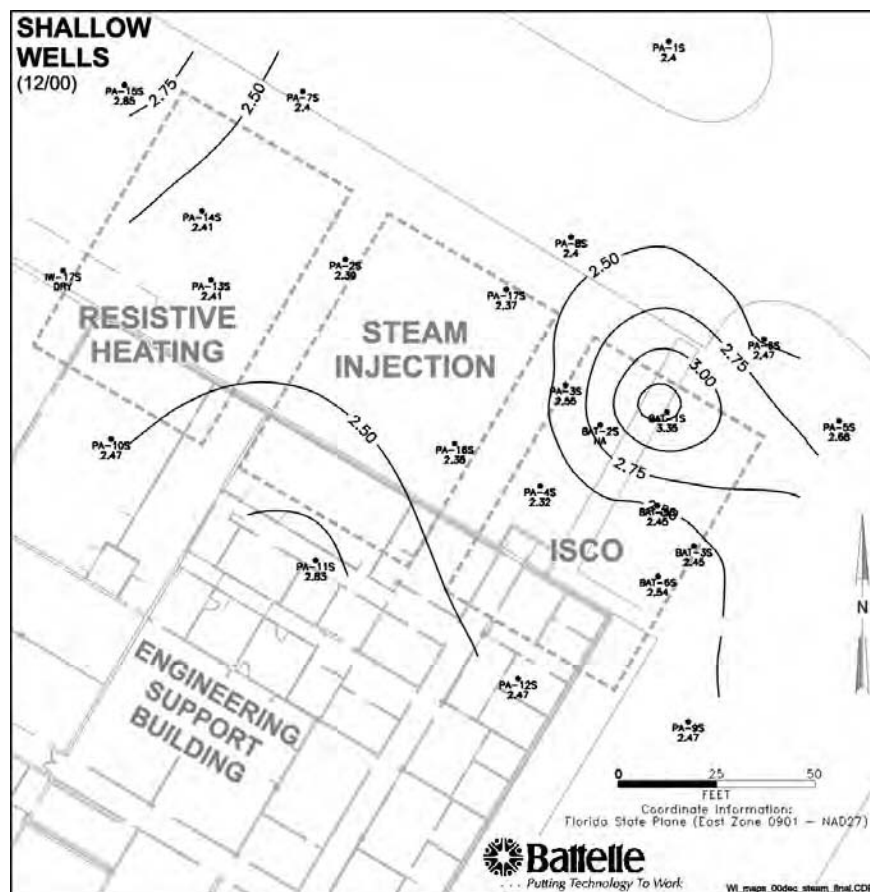
## 2.2 Surface Water Bodies at the Site

The major surface water body in the area is the Atlantic Ocean, located approximately one-half mile to the east

of Launch Complex 34. To determine the effects of surface water bodies on the groundwater system, water levels were monitored in 12 piezometers over 50 hours for a tidal influence study during Resource Conservation and Recovery Act (RCRA) Facility Investigation (RFI) activities (G&E Engineering, Inc., 1996). All the piezometers used in the study were screened in the surficial aquifer. No detectable effects from the tidal cycles were measured, suggesting that the surficial aquifer and the Atlantic Ocean are not well connected hydraulically. However, the Atlantic Ocean and the Banana River seem to act as hydraulic barriers or sinks, as groundwater likely flows toward these surface water bodies and discharges into them.

## 2.3 TCE-DNAPL Contamination in the Demonstration Plot and Vicinity

Figures 2-10 to 2-12 show representative pre-demonstration distributions of TCE, the primary contaminant at Launch Complex 34, in the performance monitoring wells installed (Battelle, 2001a) at shallow, intermediate, and deep depths in the demonstration plot. The shallow wells were installed to approximately 22 ft



**Figure 2-7.** Pre-Demonstration Water Levels (as Elevations msl) in Shallow Wells at Launch Complex 34

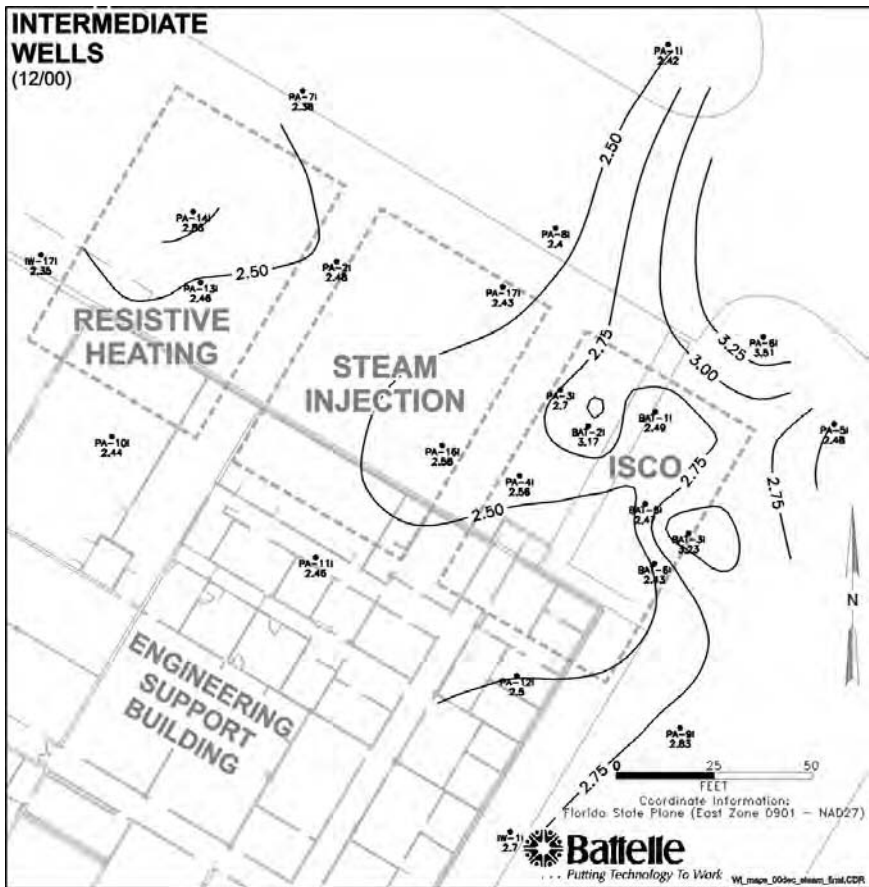


Figure 2-8. Pre-Demonstration Water Levels (as Elevations msl) in Intermediate Wells at Launch Complex 34

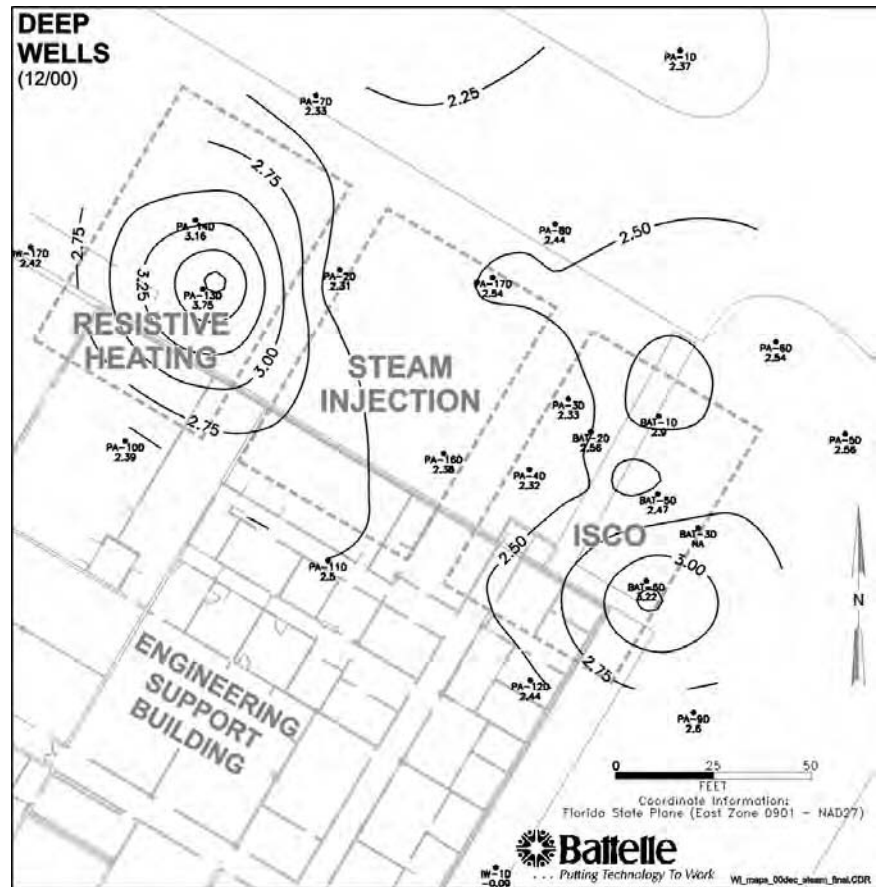


Figure 2-9. Pre-Demonstration Water Levels (as Elevations msl) in Deep Wells at Launch Complex 34

bgs. The intermediate wells were installed to approximately 29 ft bgs. The deep wells were installed to 45 ft bgs. Well construction logs are contained in Appendix B. No free-phase solvent was visible in any of the wells during the pre-demonstration sampling; however, groundwater analysis in many wells showed TCE at levels near or above its solubility, indicating the potential for DNAPL at the site (see Appendix C). Lower levels of *cis*-1,2-DCE and vinyl chloride also were present in the aquifer, indicating some historical natural attenuation of TCE. Groundwater sampling indicated that the highest levels of TCE in the SI/E plot are in the Lower Sand Unit (deep wells) and closer to the Engineering Support Building. In the Upper Sand Unit and Middle Fine-Grained Unit, TCE levels were relatively low in the SI/E plot compared to the pre-demonstration sampling results in the neighboring plots, indicating that the contamination in these layers may have been affected by the two treatments in the neighboring plots (Battelle, 2002 and 2003).

Figures 2-13 to 2-15 show representative pre-demonstration horizontal distributions of TCE in soil from the Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit (Battelle, 2001a). TCE levels were highest in the Lower Sand Unit, and concentrations indicate that DNAPL extends under the building. As seen in the vertical cross section in Figure 2-16, much of the DNAPL (yellow, orange, or red areas) was present in the Middle Fine-Grained Unit and in the Lower Sand Unit, right above the clay aquitard.

The pre-demonstration soil sampling and TCE analysis data were interpreted by two methods, both of which gave similar estimates of TCE mass:

- Linear interpolation of the TCE concentration (including the dissolved TCE) distribution indicated that approximately 10,435 kg of total TCE was present in the SI/E plot before the demonstration (Battelle, 2000a). Approximately 9,301 kg of this TCE may occur as DNAPL (excluding the dissolved TCE), based on a threshold TCE concentration of about 300 mg/kg in the soil.
- Kriging or geostatistical evaluation of the TCE concentration measurements indicated that between 11,145 and 14,159 kg of TCE (including the dissolved TCE) was present in the SI/E plot before the demonstration. Kriging is better able to account for the uncertainties in interpolating measured TCE concentrations at a limited number of sampled points to all points in the plot.

The native organic carbon content of the Launch Complex 34 soil is relatively low and the threshold TCE concentration is driven by the solubility of TCE in the pore water. The threshold TCE concentration in soil was

determined by estimating the maximum amount of TCE that can occur in the dissolved and adsorbed phases, given the porosity and organic matter content of the soil. The threshold concentration in soil was calculated as follows:

$$C_{\text{sat}} = \frac{C_{\text{water}} (K_d \rho_b + n)}{\rho_b} \quad (2-1)$$

- where
- $C_{\text{sat}}$  = maximum TCE concentration in the dissolved and adsorbed phases (mg/kg)
  - $C_{\text{water}}$  = TCE solubility (mg/L) = 1,100
  - $\rho_b$  = bulk density of soil (g/cm<sup>3</sup>) = 1.6
  - $n$  = porosity (unitless) = 0.3
  - $K_d$  = partitioning coefficient of TCE in soil [(mg/kg)/(mg/L)], equal to ( $f_{\text{oc}} \cdot K_{\text{oc}}$ )
  - $f_{\text{oc}}$  = fraction organic carbon (unitless)
  - $K_{\text{oc}}$  = organic carbon partition coefficient [(mg/kg)/(mg/L)].

Based on Equation (2-1), the threshold TCE concentration in soil for this site was approximated to 300 mg/kg.

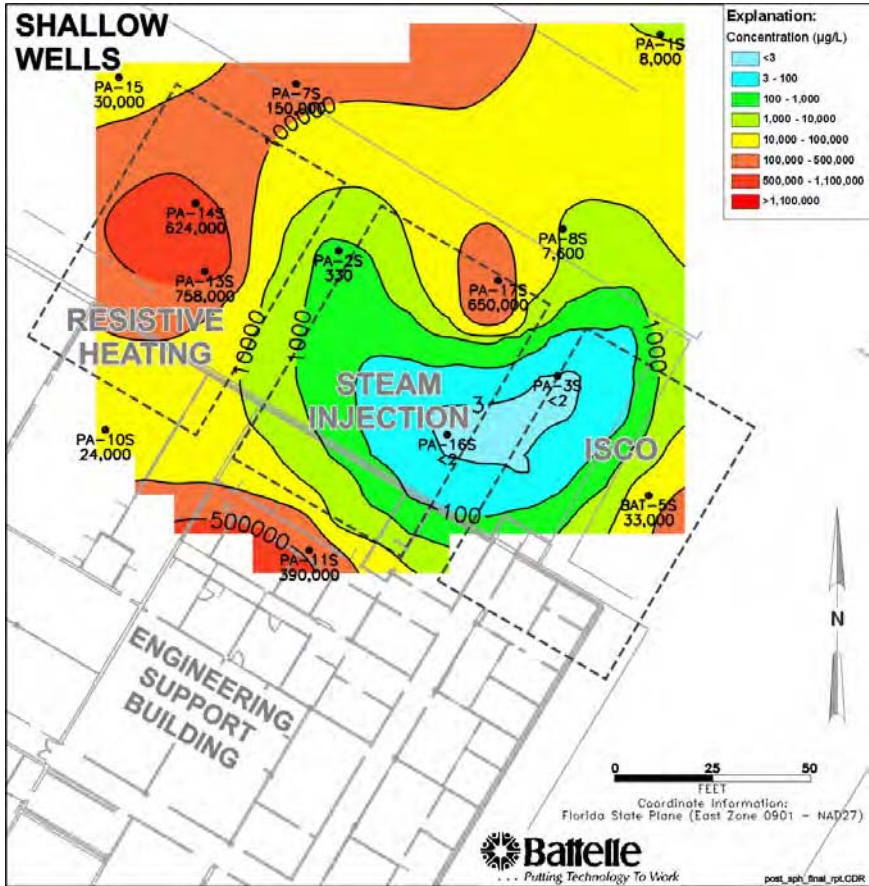
The portion of the measured total TCE in soil that exceeds the maximum threshold concentrations of TCE in the dissolved and adsorbed phases is considered to be DNAPL. At values below the threshold concentration, TCE was considered to be in the dissolved phase. The actual threshold levels may vary slightly in different parts of the demonstration plot, depending on the exact soil texture, porosity, and natural organic matter content; the threshold concentration of 300 mg/kg for soil was selected as a conservative estimate for all three demonstration plots.

In Figures 2-13 to 2-16, the colors yellow and red indicate presence of TCE-DNAPL, whereas the dissolved phase TCE was contoured from blue to green. Contouring software from EarthVision™ was used to divide the plot into isoconcentration shells. Section 5.1 contains a more detailed description of the total TCE and TCE-DNAPL mass estimation procedures for the SI/E plot.

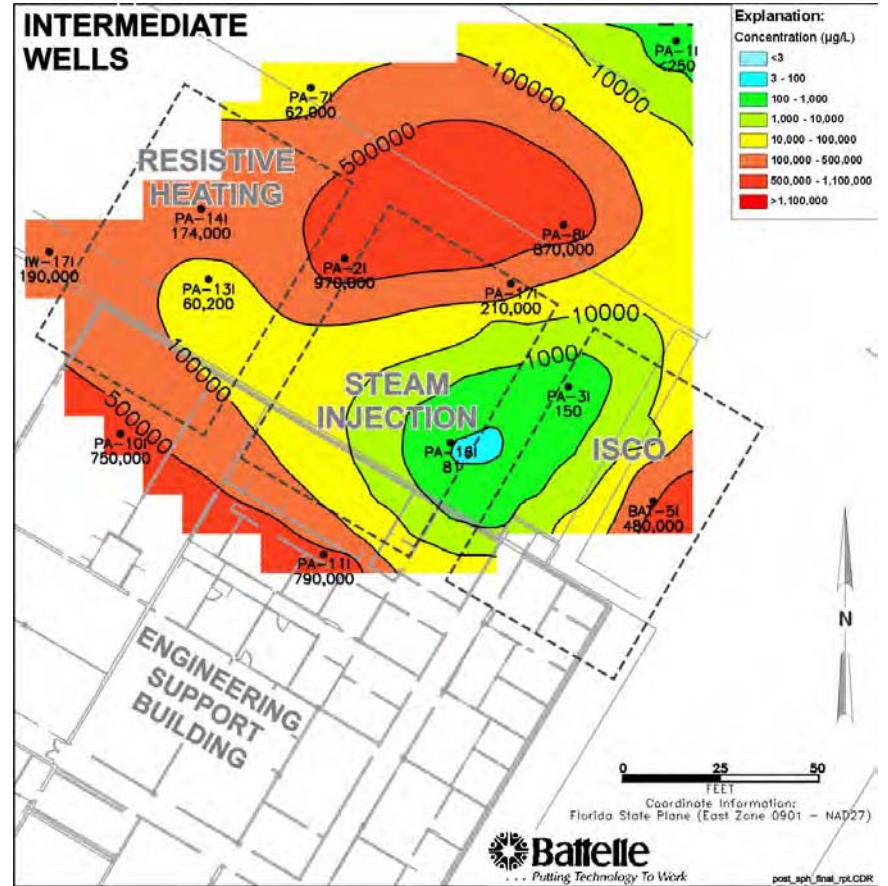
## 2.4 Aquifer Quality/Geochemistry

Appendix A.3 lists the various aquifer parameters measured and the standard methods used to analyze them. Pre-demonstration groundwater field parameters were measured in several wells in the demonstration area in August 1999 (Battelle, 1999c). The pH was relatively constant with depth, and ranged from 6.7 to 9.1. Dissolved oxygen (DO) levels were measured with a flow-through cell, and were mostly less than 1 mg/L in the deep wells, indicating that the aquifer was anaerobic, especially at greater depths. Oxidation-reduction potential





**Figure 2-10.** Pre-Demonstration Dissolved TCE Concentrations ( $\mu\text{g/L}$ ) in Shallow Wells at Launch Complex 34 (December 2000)



**Figure 2-11.** Pre-Demonstration Dissolved TCE Concentrations ( $\mu\text{g/L}$ ) in Intermediate Wells at Launch Complex 34 (December 2000)

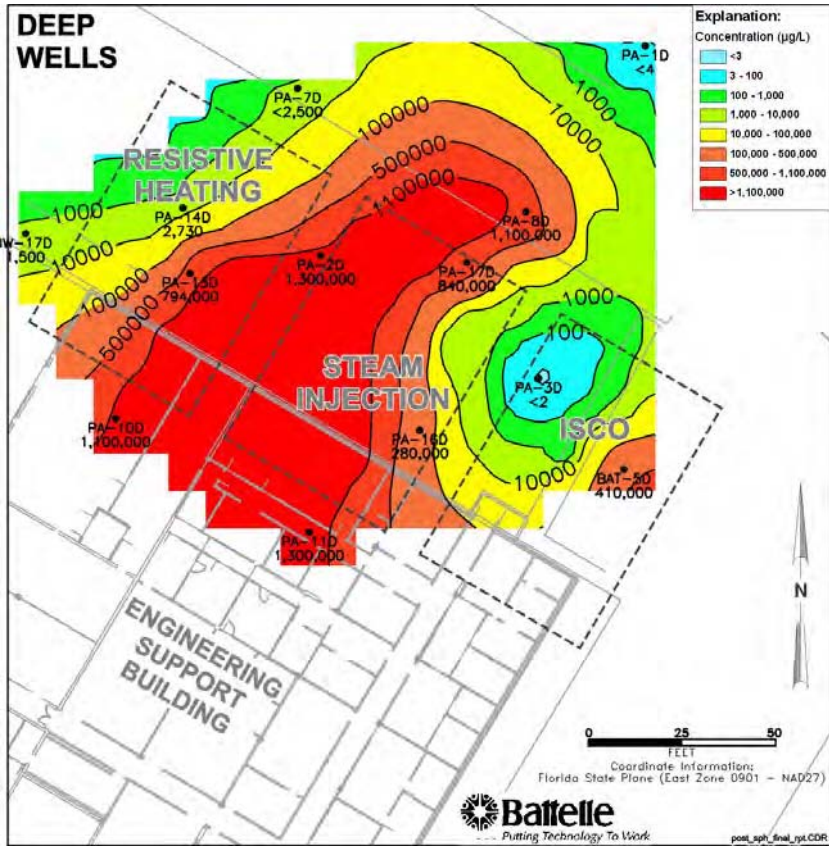


Figure 2-12. Pre-Demonstration Dissolved TCE Concentrations (µg/L) in Deep Wells at Launch Complex 34 (December 2000)

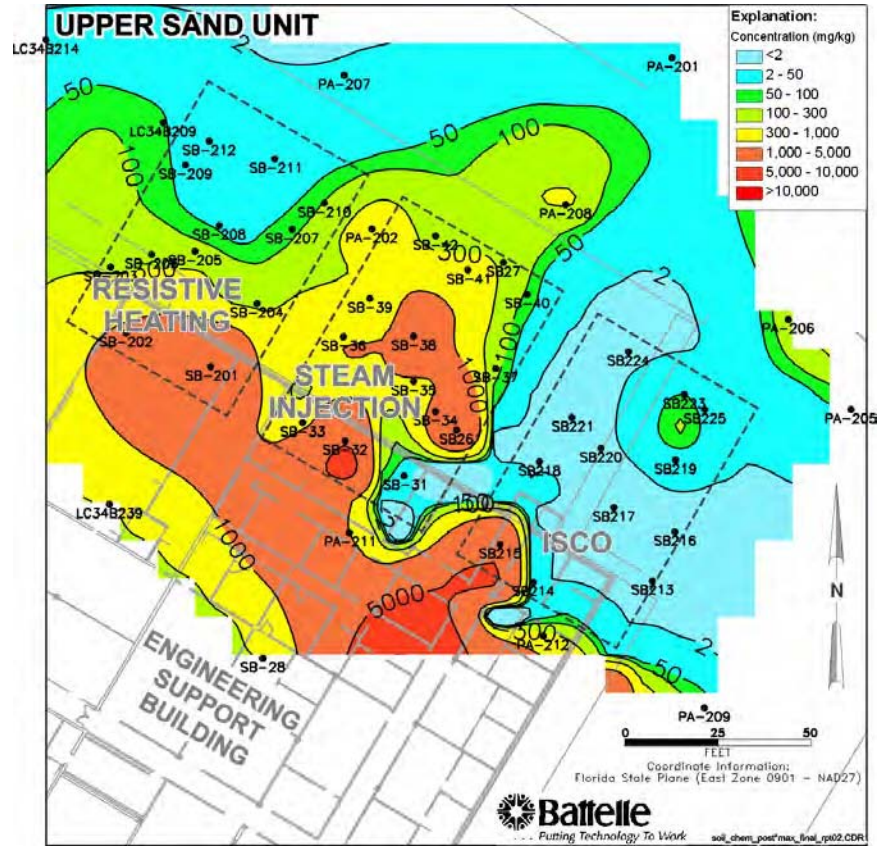


Figure 2-13. Pre-Demonstration TCE Concentrations (mg/kg) in the Upper Sand Unit Soil at Launch Complex 34

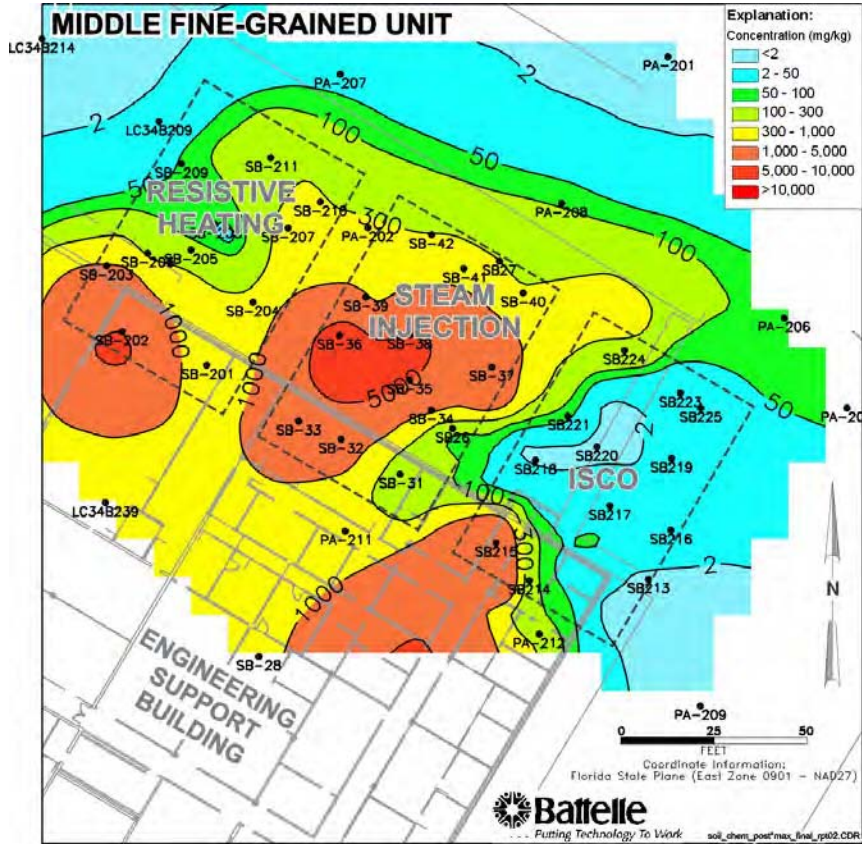


Figure 2-14. Pre-Demonstration TCE Concentrations (mg/kg) in the Middle Fine-Grained Unit Soil at Launch Complex 34

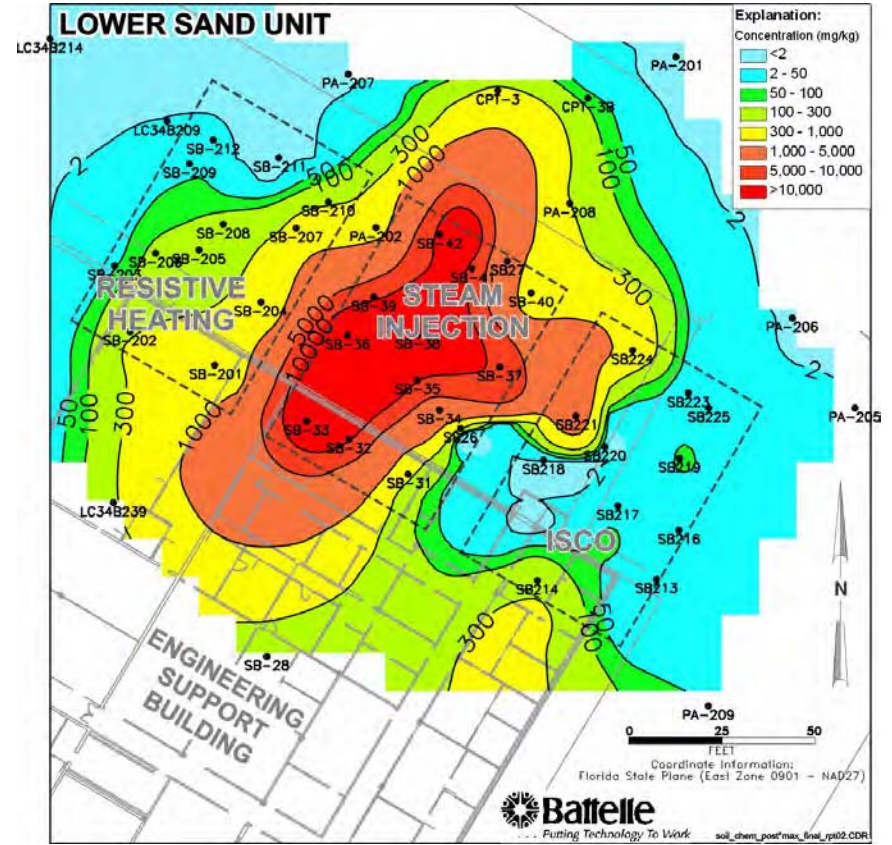
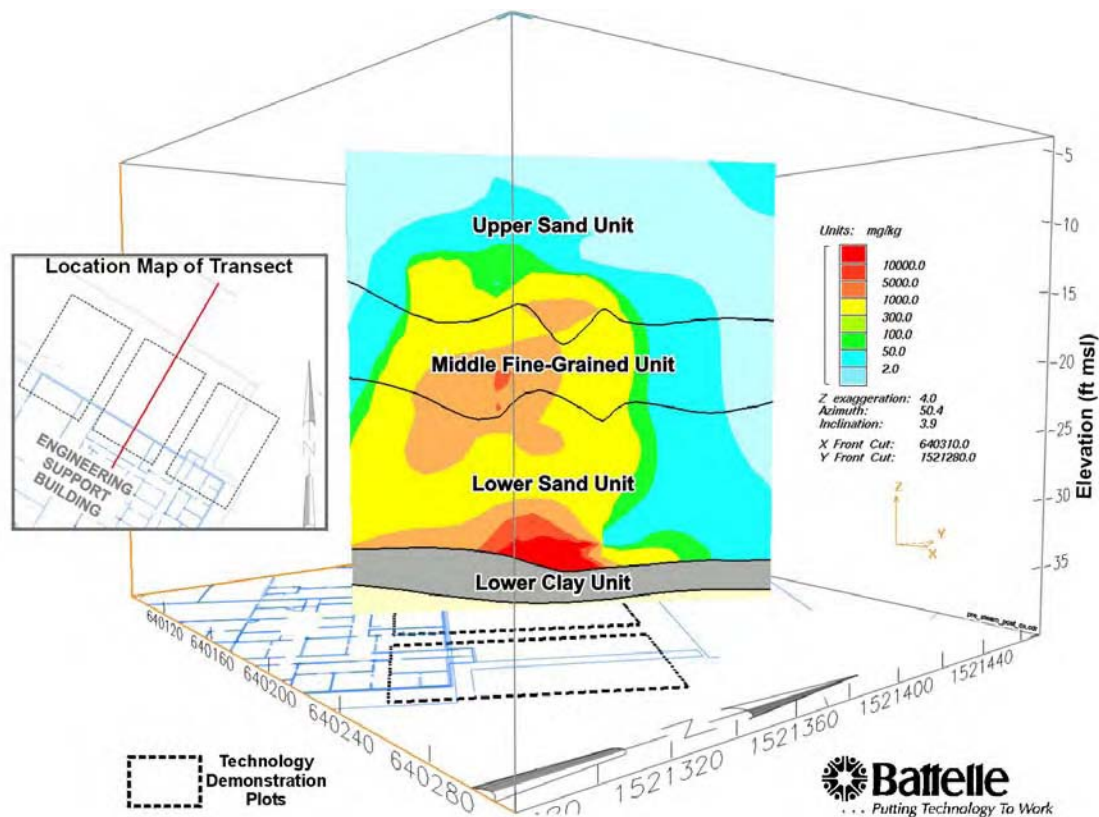


Figure 2-15. Pre-Demonstration TCE Concentrations (mg/kg) in the Lower Sand Unit Soil at Launch Complex 34



**Figure 2-16.** Vertical Cross Section through Steam Plot Showing TCE Concentrations (mg/kg) in Soil

(ORP) from all the sampled wells ranged from -152 to -163 millivolts (mV). Total organic carbon (TOC) concentrations ranged from 2.1 to 34 mg/L in water samples and from 0.9 to 1.8% in soil samples; much of this TOC is probably TCE/DNAPL, as the samples were collected from the DNAPL source region. Biological oxygen demand (BOD) ranged from <3 to 84 mg/L in groundwater.

Inorganic groundwater parameters were tested in August 1999 in select wells to determine the pre-demonstration quality of the groundwater in the target area (Battelle, 1999c) before the first two demonstrations of ISCO and resistive heating. Inorganic parameters in the groundwater at Launch Complex 34 are summarized as follows:

- Total dissolved solids (TDS) concentrations increased sharply with depth, suggesting that the water becomes more brackish with depth. The TDS levels ranged from 387 to 1,550 mg/L. Chloride concentrations ranged from 38 to 752 mg/L and increased sharply with depth, indicating for some salt water intrusion in the deeper layers (namely, the Lower Sand Unit part of the aquifer).

- Alkalinity levels ranged from 204 to 323 mg/L and showed little trend with depth or distance.
- Iron concentrations ranged from <0.05 to 2.5 mg/L in the groundwater, and manganese concentrations ranged from <0.015 to 1.1 mg/L with little vertical or lateral trend.
- Calcium concentrations ranged from 41 to 88 mg/L and magnesium concentrations ranged from 53 to 84 mg/L.
- Sulfate concentrations were between 29 and 138 mg/L and showed no discernable trends. Nitrate concentrations were below detection.

## 2.5 Aquifer Microbiology

A separate exploratory microbiological study was conducted in the SI/E plot during pre-demonstration and post-demonstration characterization under a Work Plan prepared by Battelle and Lawrence Berkeley National Laboratory (Battelle, 2000b). The approach and preliminary results of this study are presented in Appendix E.



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## 3. Technology Operation

This section describes how the steam injection technology was implemented at Launch Complex 34.

### 3.1 Steam Injection/Extraction Concept

SI/E involves the application of heat to the subsurface by injecting steam (see Figure 1-3). A wide variety of physical and chemical effects occur that are beneficial for the breakdown or removal of DNAPL contaminants in both saturated and unsaturated subsurface materials. Volatile and semivolatile contaminants are removed from the subsurface by a combination of direct volatilization and steam stripping. Recent reports also have claimed that organic contaminants degrade in situ due to heat-accelerated abiotic (e.g., hydrolysis, oxidation) and/or biotic processes (Battelle, 2001d and 2001e).

An aboveground treatment system may consist of a heat exchanger/cooling tower, wastewater transfer and processing tanks, NAPL/water separator, vacuum blower, and wastestream treatment equipment. Multiphase extraction wells are used to extract fluids and vapors from the subsurface. For near-surface deployments a surface plenum can be installed to control vapor migration.

In general, wastestream treatment depends on contaminant type, regulatory discharge limits, and the extent of existing wastestream treatment equipment at the site. For VOC-contaminated sites, the treatment equipment typically will consist of a thermal oxidizer for contaminant vapor destruction, and an air stripper, with or without GAC for polishing for wastewater treatment. Off-gas from the air stripper is sent to the thermal oxidizer for contaminant destruction. The treated vapor from the thermal oxidizer by a caustic scrubber is discharged to the atmosphere. The only wastestreams generated are spent granular activated carbon (GAC) and nonaqueous-phase liquid (NAPL) recovered in the NAPL/water separator. All other wastestreams can be treated to below regulatory discharge limits.

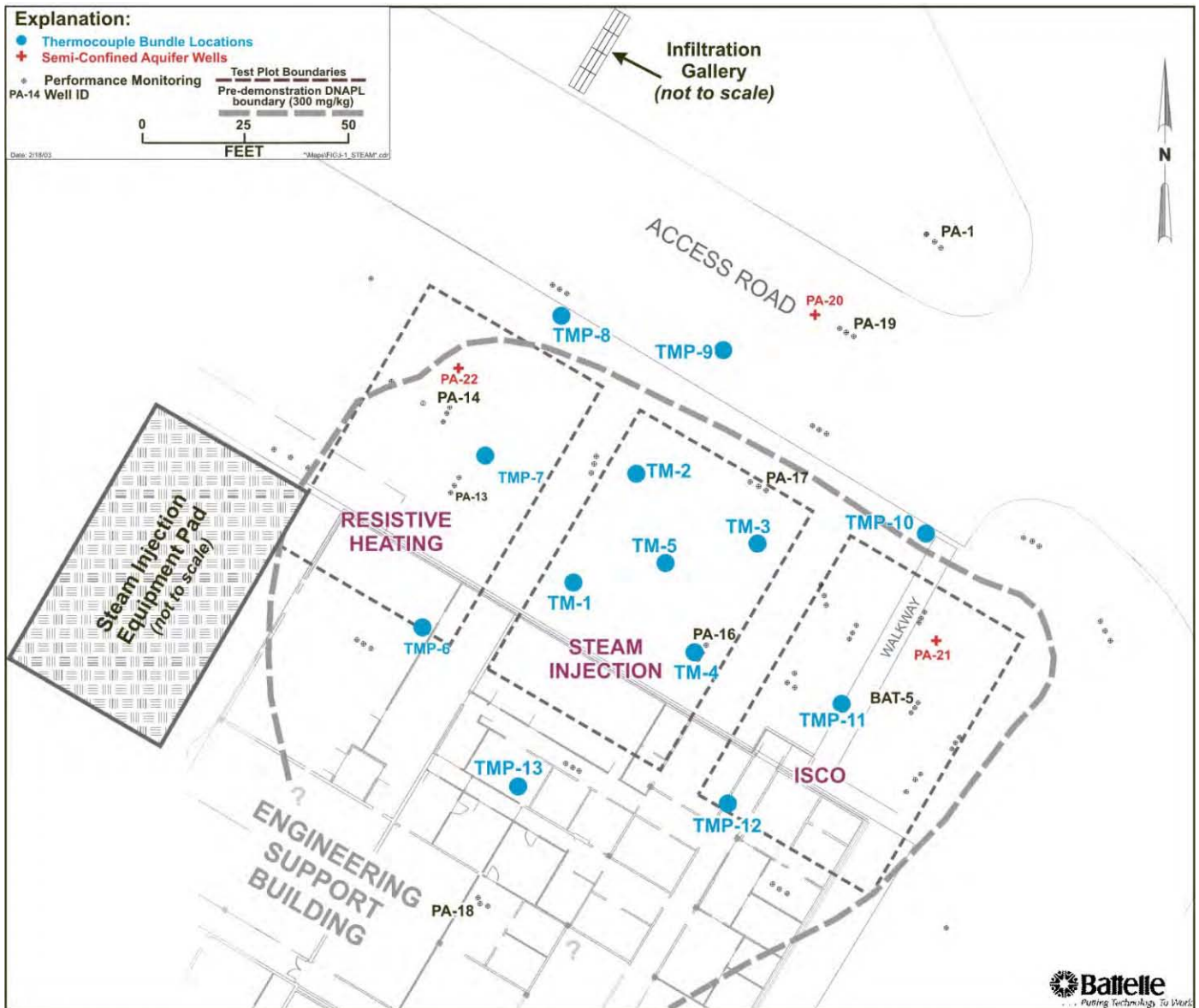
### 3.2 Application of SI/E Technology

For this IDC demonstration, SI/E was used to heat a DNAPL source zone in the aquifer at the Launch Complex 34 site. The source zone consisted primarily of TCE, although lesser amounts of *cis*-1,2-DCE also were present. For the purpose of the demonstration, the relatively large source zone was divided into three demonstration plots for three different technology applications. The 75-ft × 50-ft demonstration plot assigned to the SI/E demonstration is shown in Figure 3-1 and is referred to as the SI/E plot. The demonstrations of ISCO and electrical resistive heating were conducted concurrently in the two outer plots, before the SI/E demonstration began.

A summary description of the SI/E process implemented by the vendor at Launch Complex 34 follows in this section. Table 3-1 includes a chronology of events constituting the SI/E demonstration. The field application of the technology was conducted over a period of 6 months from July to December 2001. Some periods of downtime occurred during the application.

#### 3.2.1 SI/E Equipment and Setup

Figure 3-2 is a picture of the SI/E system installed at Launch Complex 34. As shown in the equipment layout in Figure 3-3, the SI/E scheme at Launch Complex 34 included two injection well clusters (SI-1 and SI-2); 8 deep and 7 shallow extraction wells (VE-1 to VE-3, VE-6 to VE-9, and VE-13D); and three shallow vapor extraction wells (VE-12 to VE-14), which were located within the Engineering Support Building. Two injection well clusters were installed in the Upper Sand Unit and Lower Sand Unit in the middle of the demonstration plot. The screen depths were between 7 and 22 ft bgs and 32 and 46 ft bgs for the Upper Sand Unit and Lower Sand Unit, respectively. To monitor the steam and heat distribution, a total of 13 strand thermocouples were installed inside and outside the demonstration plot, from surface to approximately 45 ft bgs. Of these, five temperature



**Figure 3-1.** The SI/E Plot and Monitoring Well Layout for Performance Assessment

thermocouples were installed in the plot and eight thermocouples were installed outside the plot. Air was co-injected with steam during the initial stages of the application to mitigate potential downward migration of TCE that was above the Lower Clay Unit.

The following system overview describes the fundamental SI/E system and major system components.

**Vapor Extraction** – The SI/E process utilized a combination of groundwater and vapor extraction as the contaminant removal mechanism. The groundwater and vapor extraction system utilized vertical extraction wells, in addition to vapor removal from the horizontal extraction wells.

Hot extracted vapor stream was cooled in a heat exchanger/condenser. This was necessary to condense contaminated liquids from the vapor stream prior to entering the extraction blower. Cooling water was recirculated through the heat exchanger from an evaporative cooling tower with a nominal rating of 375 tons of cooling capacity (5 MBTU/hr). The cooling stage resulted in the condensation of steam, which was then separated from the vapor stream.

After leaving the heat exchanger, entrained moisture was removed in a 500-gal water knockout tank (WKO). Vapor entered the knockout tank at a high tangential velocity allowing separation of entrained liquid droplets, which accumulated in the tank bottom. The condensate

**Table 3-1.** Timeline for Steam Injection Demonstration

Start Date	End Date	Number of Days	Events/Heat Application Stage	Cumulative Steam Injected <sup>(a)</sup> (kg)	Temperature (°C) at Top/Mid/Bottom of Aquifer <sup>(b)</sup>		Comments
					Start of Period	End of Period	
06/18/98	06/18/98	—	Solicitation Received from IDC	—	—	—	—
10/1/00	03/02/01	150	Design/Modeling/Treatability Tests	—	—	—	—
03/02/01	03/02/01	—	IDC Approval to Proceed	—	—	—	—
11/27/00	12/16/00	20	Pre-Demonstration Characterization of Steam Plot	—	—	—	—
01/22/01	06/15/01	145	Test Plan/QAPP	—	—	—	—
04/23/01	07/06/01	79	Mobilization to Site and Setup	—	—	26.5°/27°/27°	—
06/28/01	07/13/01	9	Helium Tracer Test	—	—	26.5°/27°/27°	Helium Tracer Test Conducted Three Times
07/19/01	07/26/01	9	Initial Steaming	95,710	26.5°/27°/27°	31°/57°/121°	Steam Injection 6-24 hr/day
07/27/01	08/26/01	31	Irregular Vapor Extraction and Steaming	131,667	33°/66°/116°	37°/73°/119°	Groundwater Extraction System Malfunction; Steam Injection 6-9 hr/day
08/27/01	11/30/01	95	Regular Steaming	1,131,123	37°/73°/119°	110°/114°/115°	Began Steam Injection 24 hr/day on 10/17/01
12/01/01	12/09/01	9	Irregular Vapor Extraction Only	Not Applicable	111°/115°/116°	111°/116°/115°	Thermox <sup>®</sup> Burner Control Malfunction
12/10/01	12/20/01	11	Regular Steaming	1,409,810	111°/115°/116°	109°/114°/115°	Total Steaming = 1,248 hr (52 days)
12/21/01	12/28/01	8	Vapor Extraction Only	Not Applicable	110°/114°/115°	111°/114°/116°	System Shutdown on 12/20/01 Total Demonstration Time = 3,936 hr (164 days)
01/07/02	01/25/02	24	System Demobilization	—	109°/113°/109°	93°/100°/94°	—
02/04/02	02/23/02	20	Post-Demonstration Characterization of Steam Plot	—	—	—	—

(a) Based on IWR operational data.

(b) Based on available readings in thermocouple TM-5 in center of plot.

Top: from Upper Sand Unit.

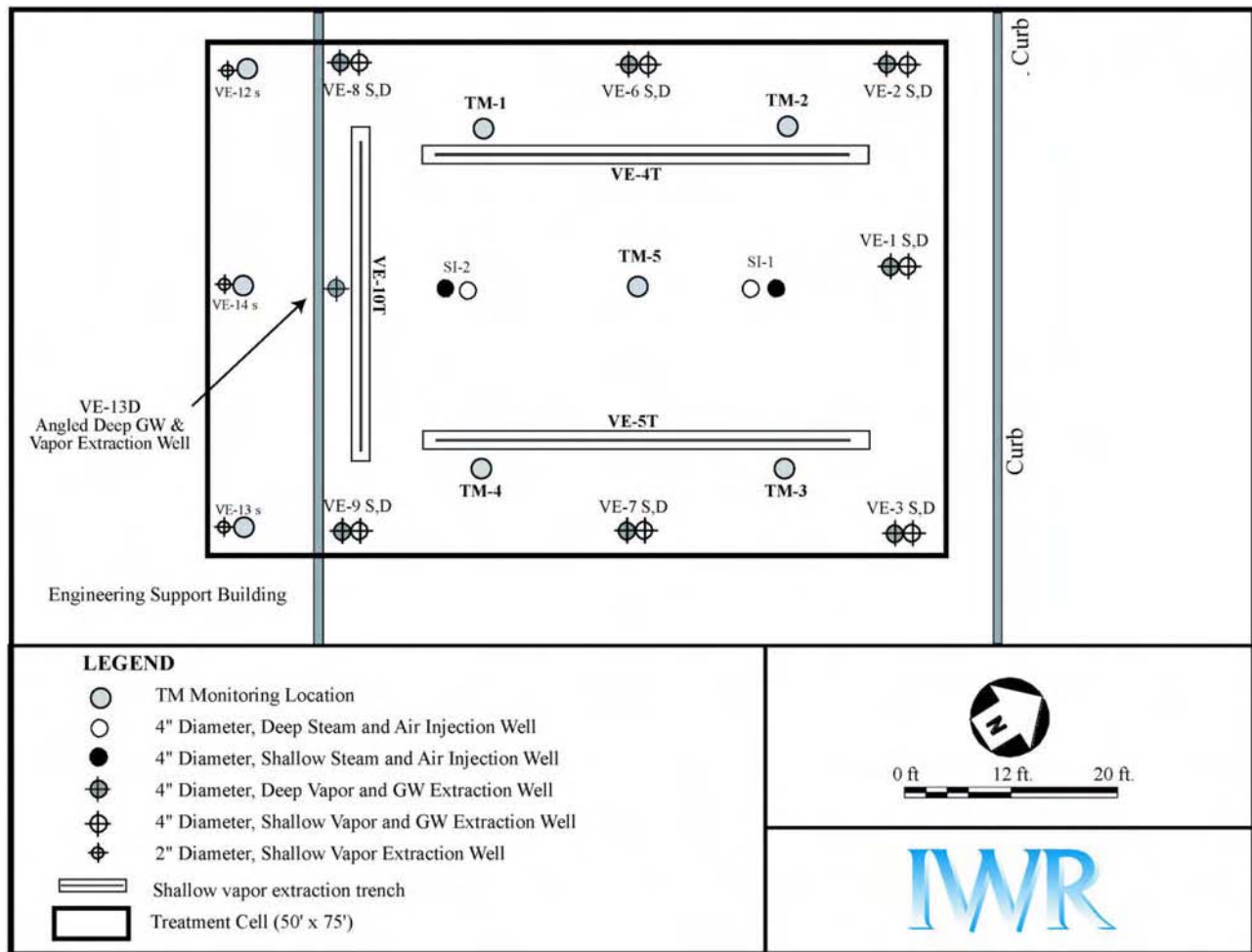
Mid: from Middle Fine-Grained Unit.

Bottom: from Lower Sand Unit.





**Figure 3-2.** Steam Injection System in Operation at Launch Complex 34



**Figure 3-3.** Layout of Steam Injection System at Launch Complex 34

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was transferred from the knockout tank to a DNAPL separator. The remaining vapor flowed into the thermal oxidizer at flowrates ranging from 300-400 standard cubic feet per minute (scfm).

**Vapor Treatment** – After exiting the water knockout tank, the extracted vapors were directed to a thermal oxidizer for destruction prior to atmospheric discharge. The oxidizer was designed to provide 98.5% VOC destruction efficiency. Sampling ports were used to monitor influent and effluent concentrations. The thermal oxidizer also was equipped with a caustic scrubber to neutralize hydrochloric acid (HCl) produced in the destruction of TCE. The blowdown from the caustic scrubber and the blowdown from a steam boiler were two effluent streams produced by the vapor treatment components of the SI/E technology. The effluents were combined and trucked from the demonstration site by NASA to a treatment plant.

**Groundwater Extraction** – Groundwater extraction utilized eductors positioned at the surface for each extraction well cluster. A water recirculation system provided the motive supply for the eductors. Extracted groundwater was discharged from the wellhead into the recirculation tank. As the water level increased in the tank, an overflow line with a gravity drain piped the extracted water to the transfer tank, where it was combined with effluent from the DNAPL/water separator. The water transfer tank was required as a reservoir from which to pump the water stream to the top of the air stripper.

**Water Treatment** – Water with dissolved contaminants from the water transfer tank was processed through an air stripper and liquid-phase carbon canisters to reduce the concentrations prior to discharge. After the carbon canisters water was directed to a 20,000-gal process container, where the water was held to test the contaminant levels prior to disposal. Contaminated vapors from the air stripper were directed to the thermal oxidizer, and the clean effluent water from the carbon canisters was directed to the infiltration gallery.

### **3.2.2 Steam Injection Field Operation**

This section summarizes the steam injection operation of the demonstration reported by the vendor. As shown in

Table 3-1, the vendor began the steam injection on July 19, 2001 for approximately a week and resumed the injection on August 27 until December 20, 2001. There was a 10-day downtime between December 1 to 9 due to a malfunction of the thermal oxidizer burner control unit. The vapor extraction system was operated until December 28, 2001 to ensure the capture of vapors emanating from the hot aquifer, after the steam injection had stopped. Over the course of the demonstration, a total of 1,409,810 kg of steam was applied to the subsurface.

During the demonstration, the vendor monitored volatile organic compound (VOC) levels and flowrate of the extracted vapor stream, and temperatures from five thermocouple bundles inside the plot (TM-1 through TM-5, shown in Figure 3-1). The temperature monitoring was also incorporated with temperature monitoring from the other thermocouples installed by Battelle and TetraTech EM (TMP-6 through TMP-13), to evaluate the temperature distribution in and around the plot. Separately, discharge water was collected from the discharge infiltration gallery to ensure that the water treatment system treated the wastewater before discharge.

### **3.2.3 Health and Safety Issues**

One initial concern with the steam injection technology was safe delivery of the high temperature steam to the subsurface. The vendor implemented the steam treatment without any damage to equipment or injury to workers. The monitoring wells in the steam injection plot and perimeter were sealed during the entire steam injection period and no samples were collected through these wells during the operation. The monitoring wells were sealed to prevent any possible dangers associated with opening wells that could possibly release strong jets of steam under pressure.

System operators and sampling personnel wore Level D personal protective equipment at the site. Heavy equipment movement during mobilization and demobilization and handling of hot fluids were hazards that were recognized in the QAPP prepared at the beginning of the demonstration (Battelle, 2001c). No injuries were encountered during the demonstration.



## 4. Performance Assessment Methodology

Battelle, in conjunction with the U.S. EPA SITE Program, conducted an independent performance assessment of the SI/E technology demonstration at Launch Complex 34 (see Figure 4-1). The objectives and methodology for the performance assessment were outlined in a QAPP prepared before the field demonstration and reviewed by all stakeholders (Battelle, 2001c). The objectives of the performance assessment were to:

- Estimate the reduction in TCE-DNAPL mass
- Evaluate changes in aquifer quality due to the treatment
- Evaluate the fate of TCE-DNAPL mass in the SI/E plot
- Verify the operating requirements and costs of SI/E technology.

The first objective, estimating the reduction in TCE-DNAPL mass, was the primary objective. The rest were secondary objectives, in terms of demonstration focus



**Figure 4-1.** Sampling for Performance Assessment at Launch Complex 34

and resources expended. Table 4-1 summarizes the four objectives of the performance assessment and the methodologies used to achieve them.

### 4.1 Estimate the Reduction in TCE-DNAPL Mass

The primary objective of the performance assessment was to estimate the mass reduction of total TCE and TCE-DNAPL. Total TCE includes both dissolved- and free-phase TCE present in the aquifer soil matrix. DNAPL refers to free-phase TCE only and is assumed to include all TCE detected in soil samples in excess of the calculated threshold concentration of 300 mg/kg described in Section 2.3. Soil sampling in the SI/E plot before and after the demonstration was the method used for estimating any reduction in TCE/DNAPL mass.

At the outset of the demonstration, the Technical Advisory Group proposed at least 90% DNAPL mass reduction as a target for the three remediation technologies being demonstrated. Soil sampling was the method selected in the QAPP for determining percent TCE-DNAPL reduction at this site. Previous soil coring, sampling, and analysis at Launch Complex 34 (Battelle, 1999b; Eddy-Dilek, 1998) had shown that this was a viable technique for identifying the boundaries of the DNAPL source zone and estimating the DNAPL mass. The advantage of soil sampling was that relatively intensive horizontal and vertical coverage of the SI/E plot, as well as of the dissolved-phase TCE and DNAPL distribution, could be achieved with a reasonable number of soil samples.

Although TCE was the primary focus of the performance assessment, the TCE breakdown products *cis*-1,2-DCE, *trans*-1,2-DCE, and vinyl chloride also were measured in the soil samples; however, high TCE levels often masked the other compounds and made their detection difficult.

The statistical basis for determining the number of soil coring locations and number of soil samples required to

**Table 4-1. Summary of Performance Assessment Objectives and Associated Measurements**

Objective	Measurements	Frequency	Sampling Locations <sup>(a)</sup>
Estimate TCE mass reduction percentage	CVOCs <sup>(b)</sup> in soil	Before and after treatment	12 locations spaced horizontally across the plot, every 2-ft depth interval sampled vertically
Evaluate changes in aquifer quality	CVOCs, field parameters <sup>(c)</sup> , inorganics <sup>(d)</sup> , BOD, TDS, TOC, and alkalinity in groundwater	Before and after treatment	Well clusters PA-16 and PA-17
	CVOCs, field parameters, TDS, alkalinity, and inorganics (Fe, Mn, Ca, K, Cl only) in groundwater	Before, during, and after treatment	Perimeter wells (PA-14, PA-18, PA-19, and BAT-5)
	TOC in soil	Before and after treatment	Two locations, three depths inside plot
	Hydraulic conductivity of the aquifer	Before and after treatment	Well clusters PA-16 and PA-17
	Temperature in soil and groundwater	Before, during, and after treatment	Thermocouples at five (5) locations inside the demonstration plot, and at eight (8) locations around the plot perimeter
Evaluate potential TCE migration to surrounding regions	CVOCs in vadose zone soil	Before and after treatment	As part of the 12 soil cores collected from the plot before and after treatment, soil samples were collected from the top portion (vadose zone soils) of the cores.
	CVOCs in groundwater	Before, twice during, and after treatment	Perimeter wells (PA-14, PA-18, PA-19, and BAT-5)
	Water levels	Twice during treatment	Perimeter wells (PA-14, PA-18, PA-19, and BAT-5) and one distant well (PA-1)
	CVOCs in surface emissions	Before, twice during, and after treatment	Multiple locations inside plot or around the plenum; two (2) ambient air sample locations
Verify operating requirements and costs of the SI/E technology	Field observations; tracking materials consumption and costs	Before, during, and after treatment	Field observations by vendor and Battelle; materials consumption and costs reported by vendor to MSE

(a) Monitoring well locations inside and outside the steam injection plot are shown in Figure 3-1. Soil coring locations are shown in Figure 4-2.

Surface emission sampling locations are shown in Figure 4-3.

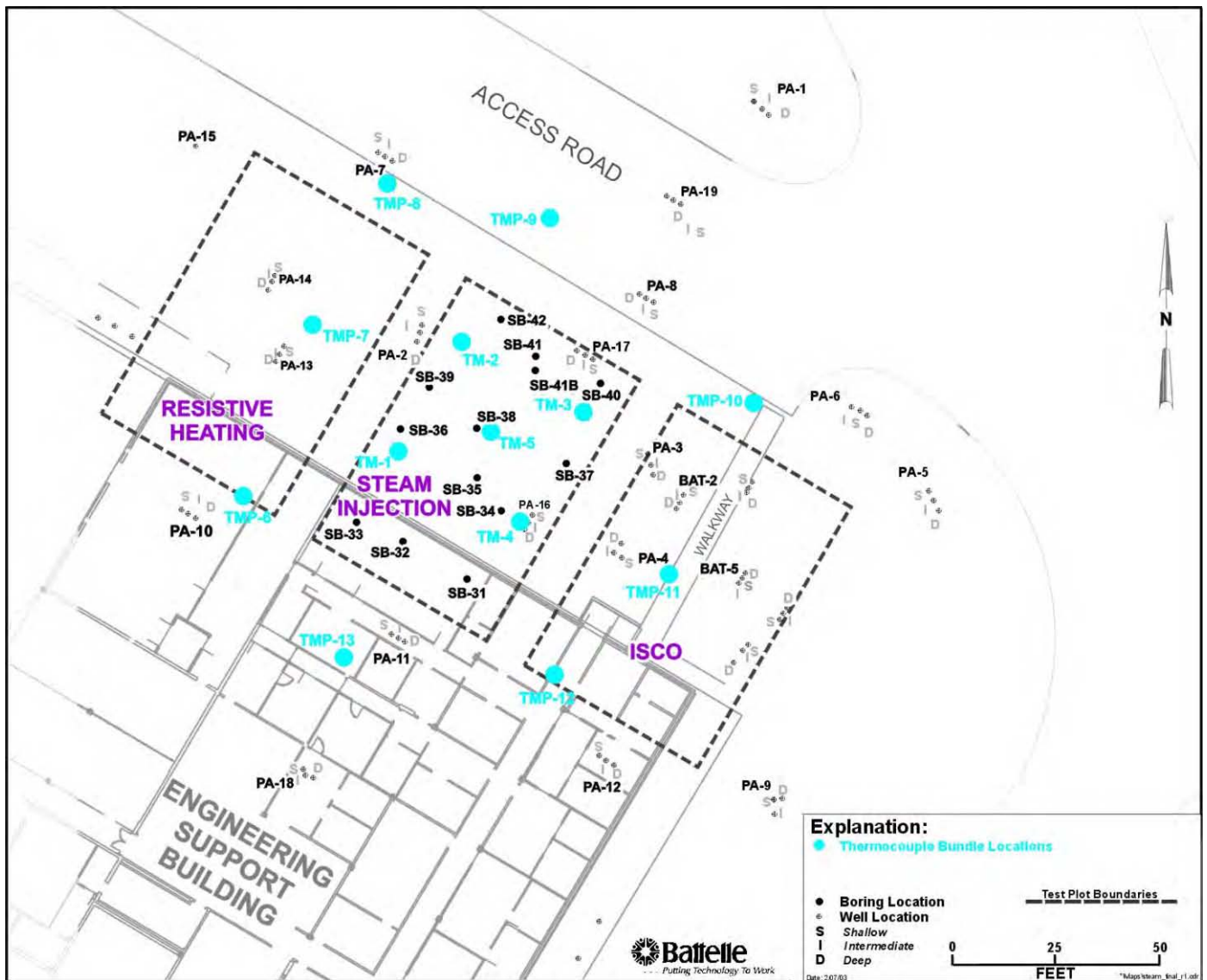
(b) The chlorinated VOCs of interest are TCE, *cis*-1,2-DCE, *trans*-1,2-DCE, and vinyl chloride.

(c) Field parameters are pH, DO, ORP, temperature, and conductivity.

(d) Inorganics include cations (Ca, Mg, Fe, Mn, Na, K) and anions (Cl, SO<sub>4</sub>, NO<sub>3</sub>/NO<sub>2</sub>).

be collected in the SI/E plot is described in Appendix A.1. Based on the horizontal and vertical variability observed in the TCE concentrations in soil cores collected during the pre-demonstration characterization in December 2000, a systematic unaligned sampling approach was used to divide the plot into a 4 × 3 grid and collect one soil core in each grid cell for a total of 12 soil cores (Figure 4-2). The resulting 12 cores (and one duplicate) provided good spatial coverage of the 75-ft × 50-ft SI/E plot and included three cores inside the Engineering Support Building. For each soil core, the entire soil column from ground surface to aquitard was sampled and analyzed in 2-ft sections. Another set of 12 cores (and one duplicate) was similarly collected after the demonstration in February 2002, in the same grid cells (see the post-demonstration coring locations in Figure 4-3). Each sampling event, therefore, consisted of nearly 300 soil samples (12 cores, 23 2-ft intervals per core, plus duplicates). No soil sampling was conducted outside or beneath the treatment plot. Therefore, displacement of DNAPL by the SI/E application could not be evaluated.

The soil coring, sampling, and extraction methods are described in Appendix A.2 and summarized in this section. Figures 4-4 and 4-5 show the outdoor and indoor rigs used for soil coring outside and inside the Engineering Support Building. A direct-push rig with a 2-inch-diameter, 4-ft-long sample barrel was used for coring. As soon as the sample barrel was retrieved, the 4-ft section of core was divided into two 2-ft sections and then split vertically. Approximately 125 g of wet soil was deposited into a predetermined volume (250 mL) of methanol for extraction in the field. The methanol extract was transferred into 20-mL volatile organic analysis (VOA) vials, which were shipped to an off-site laboratory for analysis. As compared to the more conventional method of collecting and analyzing small soil samples at discrete depths, the sampling and extraction technique used at this site provided better coverage of a heterogeneously distributed contaminant. The entire vertical depth of the soil column at the coring location could be analyzed. Preliminary site characterization had shown that the vertical variability of the TCE distribution was greater

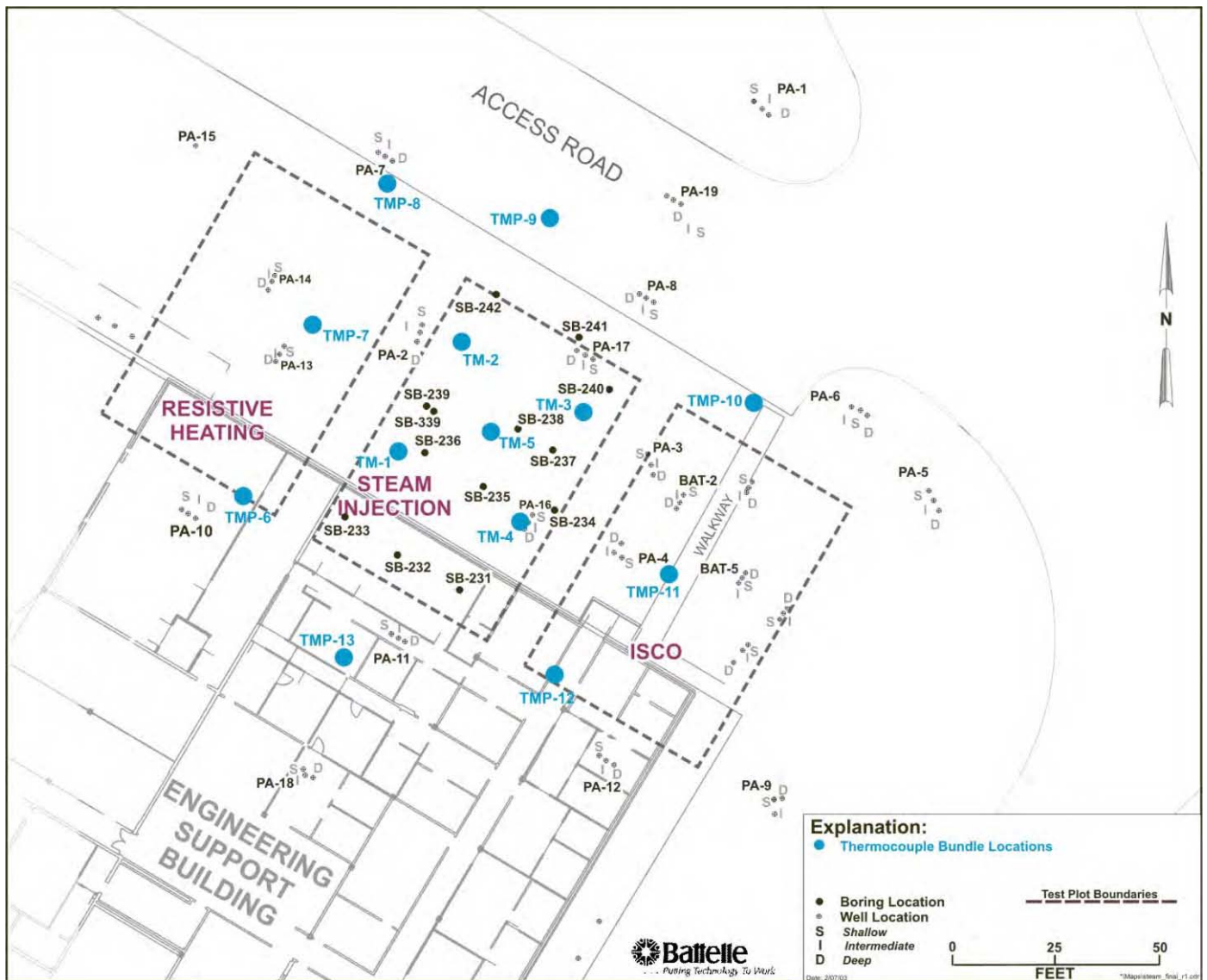


**Figure 4-2.** Pre-Demonstration Soil Coring Locations (SB-31 to SB-42) in the SI/E Plot (December 2000)

than the horizontal variability, and this sampling and extraction method allowed continuous vertical coverage of the soil column. The TCE recovery efficiency was tested using the same sampling and extraction procedure (modified U.S. EPA Method 5035; see Appendix A.2) on a surrogate compound spiked into soil samples. The surrogate recovery in soil ranged from 84 to 113%, with an average recovery of 92%. Appendix G, Table G-1 contains detailed results.

One challenge during post-demonstration soil coring in the SI/E plot was the handling of hot soil cores. The following steps were taken to minimize VOC losses due to volatilization from the extracted soil with elevated temperatures, and prevent work-related injuries to personnel handling the cores:

- Post-demonstration coring was delayed until all parts of the plot were below 90°C.
- Personnel were given special thermal-resistant gloves to use during coring activities.
- Butyrate sleeves were placed inside the coring barrel before drilling so that the soil core was collected and contained within the sleeve. This minimized soil contact with the hot (metal) core barrel, and also minimized the amount of time that personnel spent handling the metal core barrel while retrieving the soil samples.
- As soon as the soil core barrel was withdrawn, both ends of the butyrate sleeve were capped or bagged and the entire sleeve was placed in an ice bath to



**Figure 4-3.** Post-Demonstration Soil Coring Locations (SB-231 to SB-242) in Steam Injection Plot (February 2002)

cool. The end caps were used to prevent VOC losses and avoid ice water intrusion into the sleeve during the ice bath. Once the soil in the sleeve had cooled to ambient temperature (about 20°C), the sleeve was removed from the ice bath and the soil core was sampled.

- The potential for CVOC losses during cooling of the core was evaluated through a separate experiment whereby a surrogate compound (1,1,1-TCA) was spiked into a soil core. The results of the experiment indicated that significant VOC loss was not occurring during the cooling and sampling period. Appendix G contains details and results of the surrogate spike evaluation.

Two data evaluation methods were used for estimating TCE/DNAPL mass reduction in the SI/E plot: linear interpolation (or contouring), and kriging.

The spatial variability or spread of the TCE distribution in a DNAPL source zone typically is high, because small pockets of residual solvent may be distributed unevenly across the source region. The two methods address this spatial variability in different ways, and therefore the resulting mass removal estimates differ slightly. Because it is impractical to sample every single point in the SI/E plot and obtain a true TCE mass estimate for the plot, both methods address the practical limitations of estimating the TCE concentrations at unsampled points by



**Figure 4-4.** Outdoor Cone Penetrometer Test Rig for Soil Coring at Launch Complex 34



**Figure 4-5.** Indoor Direct Vibra-Push™ Rig (LD Geoprobe® Series) Used in the Engineering Support Building

interpolating (estimating) between sampled points. The objective in both methods is to use the information from a limited sample set to make an inference about the entire population (the entire plot or a stratigraphic unit).

#### **4.1.1 Linear Interpolation by Contouring**

Linear interpolation (by contouring) is the most straightforward and intuitive of the two methods for estimating TCE concentration or mass in the entire plot, based on a limited number of sampled points. TCE concentrations

are assumed to be linearly distributed between sampled points. A software program, such as EarthVision™ can be used to conduct the linear interpolation in three dimensions. In contouring, the only way to address the spatial variability of the TCE distribution is to collect as large a number of samples as is practical so that good coverage of the plot is obtained; the higher the sampling density, the smaller the distances over which the data need to be interpolated. Nearly 300 soil samples were collected from the 12 coring locations in the plot during each event (pre-demonstration and post-demonstration), which was the highest number practical for this project. Appendix A (Section A.1.1) describes how the number and distribution of these sampling points were determined to obtain good coverage of the plot.

The contouring software EarthVision™ uses the same methodology that is used for drawing water-level contour maps based on water-level measurements at discrete locations in a region. The only difference with this software is that the TCE concentrations are mapped in three dimensions to generate isoconcentration shells. The TCE concentration in each shell is multiplied by the volume of the shell (as estimated by the volumetric package in the software) and the bulk density of the soil ( $1.59 \text{ g/cm}^3$ , estimated during preliminary site characterization) to estimate a mass for each shell. The TCE mass in each region of interest (Upper Sand Unit, Middle Fine-Grained Unit, Lower Sand Unit, and the entire plot) is obtained by adding up the portion of the shells contained in that region. The DNAPL mass is obtained by adding up the masses in only those shells that have TCE concentrations above  $300 \text{ mg/kg}$ . Contouring provides a single mass estimate for the region of interest by interpolating data points. The interpolation is controlled primarily by gridding method and grid cell size. The gridding method employed by EarthVision™ is called minimum tension gridding. Minimum tension gridding is a method that very closely honors the values of the input data. This method also uses a biharmonic cubic spline function that has the effect of creating grid cell values that form a natural looking contoured surface. The curvature is distributed in between data based on the overall data distribution rather than being concentrated at the data points. Grid cell size also influences the interpolation of the contouring. The overall distribution of the data is the primary factor in determining the size of the grid cells. For a typical scattered data set that does not have dense clusters of data, a general rule is to choose a cell size that is one-half the distance between the closest adjacent data points.

#### **4.1.2 Kriging**

Kriging is a geostatistical interpolation tool that takes into consideration the spatial correlations among the TCE data in making inferences about the TCE concentrations



at unsampled points. Spatial correlation analysis determines the extent to which TCE concentrations at various points in the plot are similar or different. Generally, the degree to which TCE concentrations are similar or different is a function of distance and direction. Based on these correlations, kriging determines how the TCE concentrations at sampled points can be optimally weighted to infer the TCE concentrations at unsampled points in the plot or the TCE mass in an entire region of interest (entire plot or stratigraphic unit). Kriging accounts for the uncertainty in each point estimate by calculating a standard error for the estimate. Therefore, a range of TCE mass estimates is obtained instead of a single estimate; this range is defined by an average and a standard error or by a confidence interval. The confidence or level of significance required by the project objectives determines the width of this range. A level of significance of 0.2 (or 80% confidence) was determined as described in the QAPP (Battelle, 2001c).

#### **4.1.3 Interpreting the Results of the Two Mass Reduction Estimation Methods**

The two methods for estimating mass reduction address the spatial variability of the TCE distribution in different ways and, therefore, the resulting mass reduction estimates differ slightly between the two methods. Between linear interpolation (by contouring) and kriging, kriging provides a more informed inference of the TCE mass reduction because it takes into account the spatial correlations in the TCE distribution and the uncertainties (errors) associated with the estimates. At the same time, because a large number of soil samples were collected during each event, the results in Section 5.1 show that linear interpolation was able to overcome the spatial variability to a considerable extent and provides a mass estimate that is close to the range provided by kriging. Further, because no soil sample data was collected from outside or beneath the plot, displacement of DNAPL was not considered or included.

## **4.2 Evaluate Changes in Aquifer Quality**

A secondary objective of the performance assessment was to evaluate any short-term changes in aquifer quality due to the treatment. SI/E may affect both the contaminant and the native aquifer characteristics. Pre- and post-demonstration measurements conducted to evaluate the short-term impacts of the technology application on the aquifer included:

- CVOC measurements in the groundwater inside the SI/E plot

- Field parameter measurements in the groundwater
- Inorganic measurements (common cations and anions) in the groundwater
- Geochemical composition of the aquifer
- TDS, TOC, and BOD in the groundwater
- TOC measurements in the soil
- Hydraulic conductivity of the aquifer
- Microbiology of the soil and groundwater in the aquifer.

These measurements were conducted primarily in monitoring wells within the plot, but some measurements also were made in the perimeter and distant wells because the monitoring wells inside the plot were under the plenum and inaccessible during the application of SI/E

## **4.3 Evaluate the Fate of the TCE-DNAPL Mass in the Steam Injection Plot**

Another secondary objective was to evaluate the fate of the TCE removed from the plot by the SI/E application. Possible pathways for the decrease in TCE-DNAPL mass from the plot include recovery in the aboveground treatment systems, degradation, and migration from the SI/E plot (to the surrounding regions). These pathways were evaluated by the following measurements:

- Chloride (mineralization of CVOCs leads to formation of chloride) and other inorganic constituents in groundwater
- Hydraulic gradients (gradients indicative of groundwater movement)
- Surface emission tests, which were conducted as described in Appendix F to evaluate the potential for CVOC losses to the vadose zone and atmosphere (see Figures 4-6 and 4-7)
- CVOC concentrations in the semi-confined aquifer below the demonstration plots.

### **4.3.1 Potential for Migration to the Semi-Confined Aquifer**

During the week of April 2, 2001, Battelle installed three wells into the semi-confined aquifer beneath the demonstration plot with a two-stage (dual-casing) drilling and completion process with a mud rotary drill rig provided



**Figure 4-6.** Surface Emissions Testing at Launch Complex 34

by Environmental Drilling Services, Inc., from Ocala, FL. Figure 4-8 shows the location of these wells (PA-20, PA-21, and PA-22). The semi-confined aquifer is approximately 50 to 120 ft thick below the aquitard; three monitoring wells were installed to total depths of approximately 60 ft bgs. The objectives of installing these wells were to characterize the groundwater of the semi-confined aquifer before, during and after the demonstration, to evaluate the potential presence of CVOC contamination in the semi-confined aquifer, and to assess the effect of the SI/E demonstration on the semi-confined aquifer.

These wells were first proposed in 1999, but the IDC and Battelle decided to forgo their construction because of NASA's concerns over breaching the thin aquitard (Lower Clay Unit). However, a nonintrusive geophysical test conducted at the SI/E plot indicated the possible existence of DNAPL through preferential flowpaths between the surficial and semi-confined aquifer (Resolution Resources, 2000). It was not clear if DNAPL existed in the semi-confined aquifer, or what effect the SI/E demonstration would have on the semi-confined aquifer. The IDC and Battelle decided that there were enough questions about the status of this semi-confined aquifer that it would be worthwhile taking the risk to characterize the deeper aquifer.

Suitable precautions were taken to mitigate any risk of downward migration of contamination during the well installation.

WSRC sent an observer to monitor the field installation of the wells. The observer verified that the wells were installed properly and that no drag-down of contaminants was created during their installation.

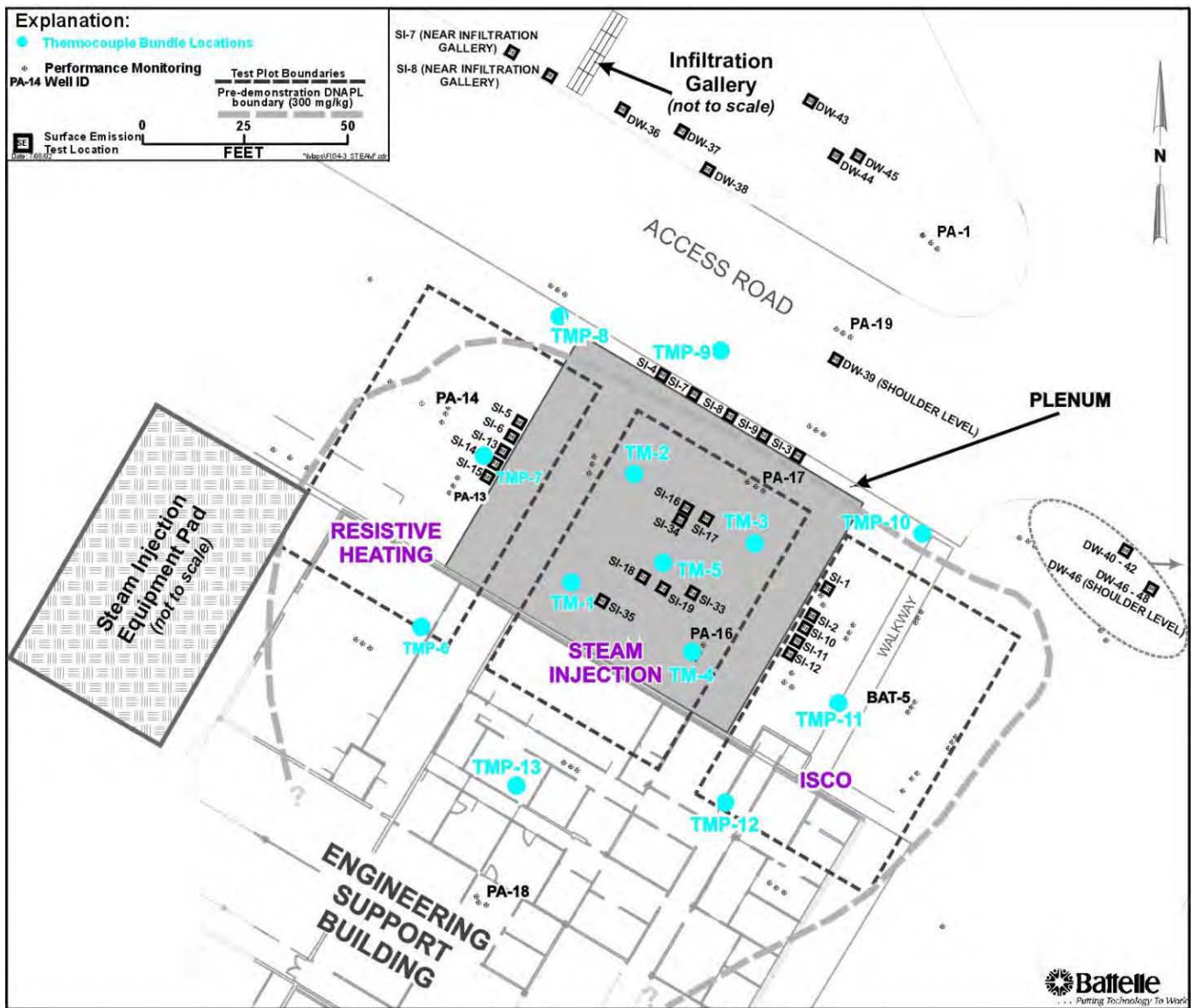
### 4.3.2 Geologic Background at Launch Complex 34

Several aquifers are present at the Launch Complex 34 area, reflecting a barrier island complex overlying coastal sediments (Figure 4-9). The surficial aquifer is comprised of layers of silty sand and shells. It extends down to about 45 ft bgs, where the Lower Clay Unit (aquitard) is encountered. Previous logging suggested that the Lower Clay Unit is 3 ft thick and consists of gray clay with low to medium plasticity. A 40- to 50-ft-thick semi-confined aquifer (Caloosahatchee Marl formation or equivalent) resides under the Lower Clay Unit and is composed of silty to clayey sand and shells. Underlying the semi-confined aquifer is the Hawthorne formation, a clayey sand-confining layer. The limestone Floridan Aquifer underlies the Hawthorne formation and is a major source of drinking water for much of Florida. Table 4-2 summarizes the character and water-bearing properties of the hydrostratigraphic units in the area.

### 4.3.3 Semi-Confined Aquifer Well Installation Method

Figure 4-10 shows the well completion diagram for the three semi-confined aquifer wells. In the first stage of well installation, a 10-inch borehole was advanced to about 45 ft bgs and completed with 6-inch blank stainless steel casing. The surface casing was advanced until it established a key between the "surface" casing and the Lower Clay Unit. The borehole was grouted around the surface casing. Once the grout around the 6-inch surface casing had set, in the second stage, a 5 $\frac{7}{8}$ -inch borehole was drilled through the inside of the surface casing to a depth of 61 ft bgs. A 2-inch casing with screen was advanced through the deeper borehole to set the well. This borehole also was grouted around the 2-inch casing. These measures were undertaken to prevent any DNAPL from migrating to the semi-confined aquifer. Figure 4-11 shows the surface casing and inner (screened well) casing for the dual-casing wells installed at Launch Complex 34. The detailed installation method for these wells is described below.

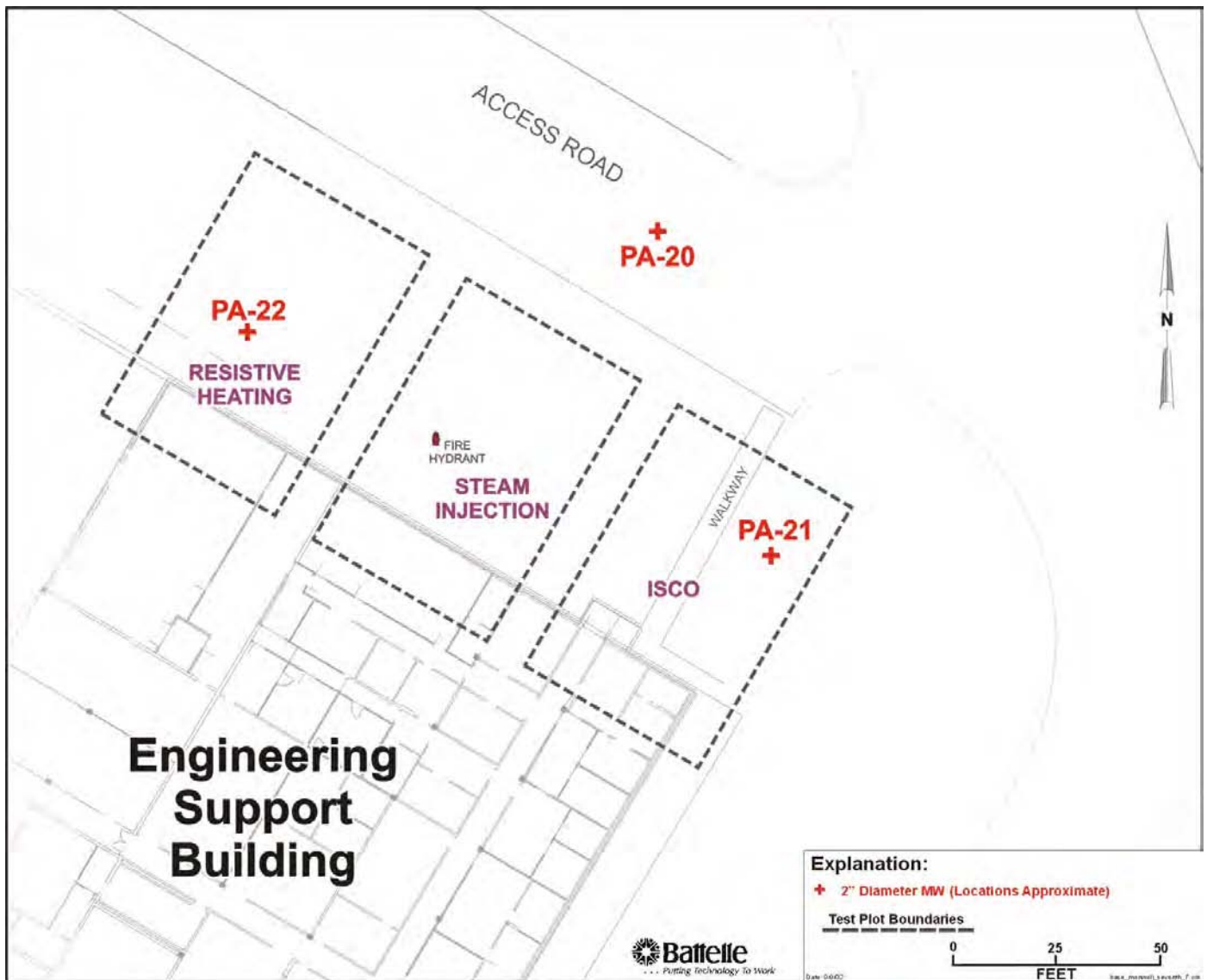
To verify the depth of the Lower Clay Unit (the semi-confining unit) at each well location, a 3 $\frac{7}{8}$ -inch pilot hole first was installed to a depth of 40 ft using a tricone roller bit. After this pilot hole was drilled, split-spoon samples were collected in 2-ft (or 1-ft) intervals as soils were observed and logged in search of the top interface of the Lower Clay Unit or aquitard. Upon retrieval of a 2-ft split-spoon sample, the borehole was deepened to the bottom of the previously spooned interval. Once the previously spooned interval was drilled, the drilling rods



**Figure 4-7.** Pre-Demonstration (SI-33 to SI-35), Demonstration (SI-1 to SI-15), and Post-Demonstration Soil Coring Locations (SI-16 to SI-19) Surface Emission Test Locations

and bit were pulled out of the hole and replaced with a new split spoon that was driven another 2 ft ahead of the borehole. Standard penetration tests (i.e., blow counts) were conducted and logged during each split-spoon advance. The blow counts were useful in identifying the soil types that are penetrated during spooning. They also were useful in helping to determine the exact interval of soil recovered from spoons that lacked total recovery. The split-spoon soil samples were logged. The soils were visually logged for soil type and description, photo-ionization detector (PID) scans were run, and at least one soil sample per 2-ft spoon interval was collected for methanol extraction and analysis.

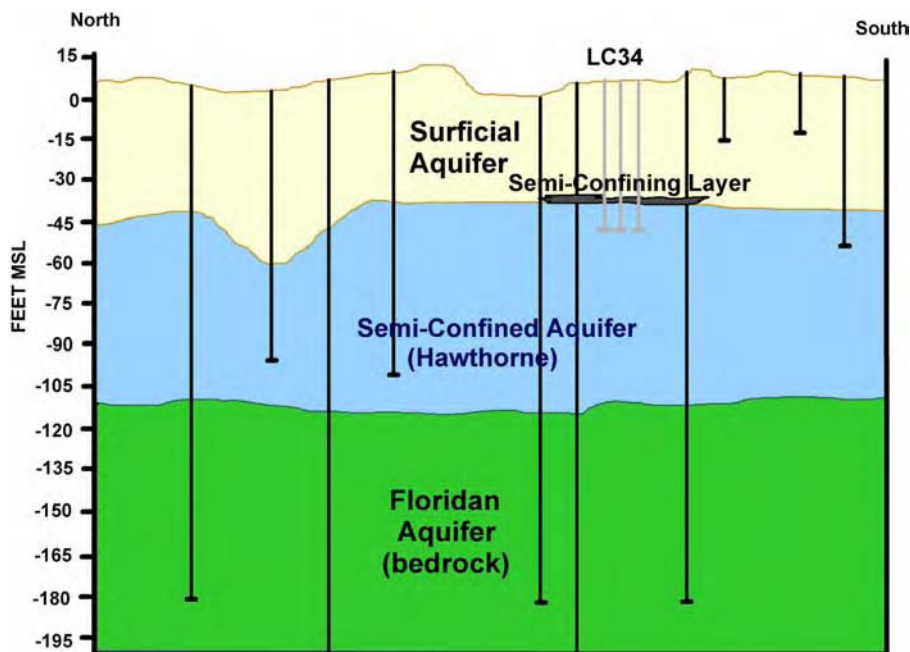
Once the top portion (approximately the first 1.5 ft) of the Lower Clay Unit was retrieved by split spoons in each borehole, the spoon and rods were pulled out of the borehole and the hole was reamed with a 10-inch tricone rotary drill bit to the depth of the lowest spooned interval. Before the 6-inch diameter casing was set in the hole, a polyvinyl chloride (PVC) slipcap was placed on the bottom of the casing to keep it free of drilling mud and soil. Use of slipcaps was an added precaution to prevent any possibility of downward contamination. As the casing was lowered in the hole, it was filled with clean water to prevent it from becoming buoyant. When the casing was set to the drilled depth of about 45 ft, it was grouted in place.



**Figure 4-8.** Location of Semi-Confined Aquifer Wells at Launch Complex 34. PA-20, PA-21, and PA-22 were drilled to approximately 60 ft bgs.

After the grout was allowed to set for at least 24 hours, the split cap was drilled through with a 5 $\frac{7}{8}$ -inch roller bit. Then split-spoon sampling progressed through the remainder of the Lower Clay Unit and into the semi-confined aquifer. Split-spoon samples were collected totaling 4 ft of lifts before the hole was reamed with the 5 $\frac{7}{8}$  bit as fresh drilling mud was circulated in the hole. Split-spooning progressed to a depth of 60 ft. Each hole was reamed an extra foot, to 61 ft, before the screen and casing were set. A sand pack was tremied into place from total depth to 2 ft above the top of the well screen (about 53 ft bgs). A bentonite seal (placed as a slurry) then was tremied in about the sand pack before the remainder of the casing was tremie-grouted into place with a Type G cement and silica flour slurry.

Once the split-spoon samples showed that the Lower Clay Unit had been reached, the 6-inch-diameter surface casing was set and grouted into place with a Type G (heat-resistant) cement and silica flour grout slurry. The drilling mud used for advancing the boreholes consisted of a product called "Super Gel-X bentonite". This powdered clay material was mixed with clean water in a mud pit that was set and sealed to the borehole beneath the drilling platform. The drilling mud was mixed to a density and viscosity that is greater than both groundwater and the bulk density of soil. This mud was pumped down through the drill pipe, out through the drill bit, and then pushed upward (circulated) through the borehole annulus into the mud pit (open space between the drilling rods and borehole wall). Use of the mud stabilized



**Figure 4-9.** Regional Hydrogeologic Cross Section through the Kennedy Space Center Area (after Schmalzer and Hinkle, 1990)

the borehole, even in sandy soils, enabling advancement of the borehole in depths well below the water table without heaving or caving. The mud sealed the borehole walls, preventing the borehole from being invaded by groundwater and contaminants. The mud also lifted all of the cuttings created by the drill bit as the hole was advanced. Once the drilling mud rose to the top of the annulus, it was captured in the mud pit where cuttings were removed by a series of baffles through which the mud was circulated.

The mud pit was monitored with a PID throughout the drilling process. At no time did the PID detect VOCs in the drilling mud, indicating that no significant levels of contamination were entering the borehole and being carried downward into deeper aquifer intervals as the drilling advanced.

After each well was installed, the well was developed using a 3-ft-long stainless steel bailer and a small submersible pump. A bailer was used to surge each well

and lift the coarsest sediments. A submersible pump then was used to lift more fines that entered the well as development progressed. A total of at least three well volumes (approximately 27 gal) were lifted from each well. Groundwater sampling was performed following well development. Standard water quality parameters were measured during sampling, and groundwater samples were collected after these parameters became stable.

#### 4.4 Verify Operating Requirements and Costs of Steam Injection Technology

Another secondary objective of the demonstration was to verify the vendor's operating requirements and cost for the technology application. An operating summary is provided in Section 3.2. Costs of the technology application also were tracked by MSE, the DOE contractor who subcontracted the steam injection vendor. Site characterization costs were estimated by Battelle and TetraTech EM, Inc.

**Table 4-2.** Hydrostratigraphic Units of Brevard County, FL<sup>(a)</sup>

Geologic Age	Stratigraphic Unit		Approximate Thickness (ft)	General Lithologic Character	Water-Bearing Properties
Recent (0.1 MYA-present)	Pleistocene and Recent Deposits		0-110	Fine to medium sand, coquina and sandy shell marl.	Permeability low due to small grain size, yields small quantities of water to shallow wells, principal source of water for domestic uses not supplied by municipal water systems.
Pleistocene (1.8-0.1 MYA)					
Pliocene (1.8-5 MYA)	Upper Miocene and Pliocene Deposits (Caloosahatchee Marl)		20-90	Gray to greenish gray sandy shell marl, green clay, fine sand, and silty shell.	Permeability very low, acts as confining bed to artesian aquifer, produces small amount of water to wells tapping shell beds.
Miocene (5-24 MYA)	Hawthorne Formation		10-300	Light green to greenish gray sandy marl, streaks of greenish clay, phosphatic radiolarian clay, black and brown phosphorite, thin beds of phosphatic sandy limestone.	Permeability generally low, may yield small quantities of fresh water in recharge areas, generally permeated with water from the artesian zone. Contains relatively impermeable beds that prevent or retard upward movement of water from the underlying artesian aquifer. Basal permeable beds are considered part of the Floridan aquifer.
Eocene (37-58 MYA)	Ocala Group	Crystal River Formation	0-100	White to cream, friable, porous coquina in a soft, chalky, marine limestone.	Floridan aquifer: Permeability generally very high, yields large quantities of artesian water. Chemical quality of the water varies from one area to another and is the dominant factor controlling utilization. A large percentage of the groundwater used in Brevard County is from the artesian aquifer. The Crystal River Formation will produce large quantities of artesian water. The Inglis Formation is expected to yield more than the Williston Formation. Local dense, indurate zones in the lower part of the Avon Park Limestone restrict permeability but in general the formation will yield large quantities of water.
		Williston Formation	10-50	Light cream, soft, granular marine limestone, generally finer grained than the Inglis Formation, highly fossiliferous.	
		Inglis Formation	70+	Cream to creamy white, coarse granular limestone, contains abundant echinoid fragments.	
	Avon Park Limestone		285+	White to cream, purple tinted, soft, dense chalky limestone. Localized zones of altered to light brown or ashen gray, hard, porous, crystalline dolomite.	

(a) Source: Schmalzer and Hinkle (1990) and originally modified from Brown et al. (1962).  
MYA = million years ago.

Project #: G004065-31	Site: LC34, Cape Canaveral	Well #: PA-20/21/22
Drilling Contractor: EDS (SBC)	Rig Type and Drilling Method: Rotary	Date: 4/5/01
Reviewed By: S. Yoon	Driller: R. Hutchinson	Hydrologist: C. J. Perry

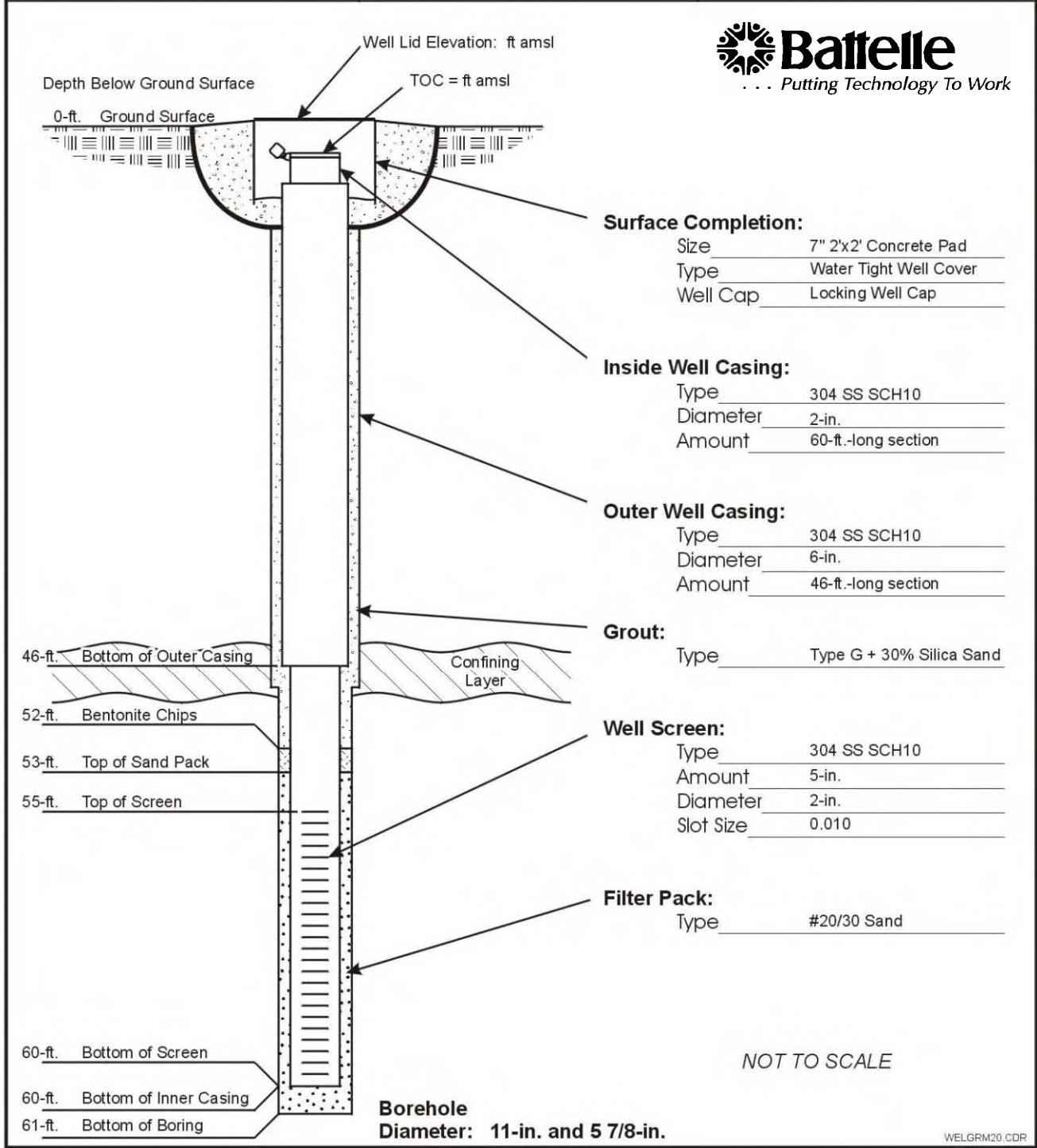


Figure 4-10. Well Completion Detail for Confined Aquifer Wells



**Figure 4-11.** Pictures Showing (a) Installation of the Surface Casing and (b) the Completed Dual-Casing Well





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## 5. Performance Assessment Results and Conclusions

The results of the performance assessment methodology outlined in Section 4 are described in this section.

### 5.1 Change in TCE-DNAPL Mass in the Plot

Section 4.1 describes the methodology used to estimate the mass reduction of total TCE and DNAPL in the plot after the SI/E application at Launch Complex 34. Intensive soil sampling was the primary tool for estimating total TCE and DNAPL mass reduction. Total TCE refers to both dissolved-phase and DNAPL TCE. DNAPL refers to that portion of total TCE in a soil sample that exceeds the threshold concentration of 300 mg/kg (see Section 2.3). Pre- and post-demonstration concentrations of TCE at 12 soil coring locations (approximately 300 soil samples) inside the steam injection plot were tabulated and graphed to *qualitatively* identify the changes in TCE-DNAPL mass distribution and the efficiency of the SI/E application in different parts of the plot (Section 5.1.1). In addition, TCE-DNAPL mass reduction was *quantified* by two methods:

- Linear interpolation by contouring (Section 5.1.2)
- Kriging (Section 5.1.3)

These quantitative techniques for estimating TCE-DNAPL mass reduction due to the SI/E application are described in Section 4.1; the results are described in Sections 5.1.2 through 5.1.4.

#### 5.1.1 Qualitative Evaluation of Changes in TCE-DNAPL Distribution

Figure 5-1 charts the pre- and post-demonstration concentrations of TCE in the soil samples from the 12 coring locations in the SI/E plot. This chart allows a simple numerical comparison of the pre- and post-demonstration TCE concentrations at paired locations, as well as the soil sample color observed at each 2-ft interval.

The chart in Figure 5-1 shows that, at several locations in the plot, TCE concentrations were reduced consider-

ably in all three units. The thicker horizontal lines in the chart indicate the depths at which the Middle Fine-Grained Unit was encountered at each location. As seen in Figure 5-1, the highest pre-demonstration contamination detected was in the deep samples from soil cores SB-36 (30,593 mg/kg in the Middle Fine-Grained Unit and 21,402 mg/kg and 25,433 mg/kg in the Lower Sand Unit) and SB-38 (24,548 mg/kg in the Lower Sand Unit).

Figures 5-2, 5-3, and 5-4 show representative pre- and post-demonstration distributions of TCE in soil from the Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit, respectively, in the SI/E plot and surrounding aquifer. A graphical representation of the TCE data illustrates the horizontal and vertical extent of the initial contaminant distribution and the subsequent changes in TCE concentrations. The yellow and red colors indicate DNAPL (TCE >300 mg/kg). In general, the portions of the aquifer in the center of the plot (SB-36, SB-37, and SB-38) had the highest pre-demonstration contamination generally occurring right on top of the Lower Clay Unit.

Figure 5-5 depicts pre- and post-demonstration three-dimensional (3-D) DNAPL distributions across all depths of the SI/E plot. The post-demonstration coring showed that the SI/E process caused considerable decline in TCE concentrations in several parts of the plot and in all three stratigraphic units. However, some sections of cores SB-232 and SB-233, collected under the Engineering Support Building, contained considerable post-demonstration levels of both total TCE and DNAPL. These results indicate that obtaining good steam distribution under the building may have been difficult. In addition, there was no steam extraction along the southern boundary of the demonstration plot under the building, which may have contributed to the residual TCE concentrations found in soil cores under the building following SI/E treatment.

In the portion of the demonstration plot outside the building, much of the aquifer was free of DNAPL after treatment. SI/E appears to have reduced DNAPL from some difficult regions to access, such as the Middle Fine-Grained Unit. Some DNAPL remained at the base of the

Top Depth (ft bgs)	Bottom Depth (ft bgs)	Pre-Demo SB-31 (mg/kg)	Post-Demo SB-231 (mg/kg)	Pre-Demo SB-32 (mg/kg)	Post-Demo SB-232 (mg/kg)	Pre-Demo SB-33 (mg/kg)	Post-Demo SB-233 (mg/kg)	Pre-Demo SB-34 (mg/kg)	Post-Demo SB-234 (mg/kg)
0	2	39	ND	ND	ND	5	0	ND	ND
2	4	4	ND	ND	ND	0.39	ND	42	1
4	6	8	ND	0.43	ND	3	ND	6	0
6	8	ND	0	ND	ND	3	0	1	ND
8	10	ND	1	ND	7	ND	13	1	1
10	12	1	7	8.8	12	1.6	19	ND	ND
12	14	5	9	ND	6	ND	18	ND	0
14	16	1	1	ND	6	ND	15	ND	1
16	18	ND	1	ND	6	ND	5	1	1
18	20	ND	2	5.7	7	13	4	4	2
20	22	ND	1	84	30	46	9	9	5
22	24	ND	4	7,803	48	146	59	2.8	4
24	26	ND	7	1,684	323	153	126	7,183	7
26	28	1	11	1,650	8,083	167	338	69	35
28	30	16	19	1,541	241	475	466	217	26
30	32	106	11	2,339	1,204	2,840	9,233	122	45
32	34	77	12	5,983	560	462	1,341	46	22
34	36	54	55	3,284	607	244	1,079	225	27
36	38	140	289	9,779	408	8,852	1,624	132	38
38	40	220	434	2,465	564	3,686	69	81	243
40	42	95	378	1,318	329	310	352	27	64
42	44	72	274	1,912	321	2,306	892	598	166
44	46	320	801	9,287	312	19,075	2,152	NA	112

Figure 5-1. Distribution of Pre- and Post-Demonstration TCE Concentrations (mg/kg) in the Steam Injection/Extraction Plot Soil

Top Depth (ft bgs)	Bottom Depth (ft bgs)	Pre-Demo SB-35 (mg/kg)	Post-Demo SB-235 (mg/kg)	Pre-Demo SB-36 (mg/kg)	Post-Demo SB-236 (mg/kg)	Pre-Demo SB-37 (mg/kg)	Post-Demo SB-237 (mg/kg)	Pre-Demo SB-38 (mg/kg)	Post-Demo SB-238 (mg/kg)
0	2	0.7	0	ND	0	0.9	ND	0.6	0
2	4	0.38	0	ND	0	ND	ND	0.6	1
4	6	0.46	0	ND	0	ND	9	0.9	17
6	8	ND	23	0.40	2	ND	2	ND	0
8	10	8.5	16	10.0	2	0.8	1	1.3	0
10	12	1.5	NA	6.9	8	3.5	1	0.47	29
12	14	0.7	NA	1.8	3	32	1	ND	25
14	16	5.8	30	0.44	2	27	1	7	31
16	18	6.3	25	8.8	8	1,061	3	14	34
18	20	32	56	11	4	65	6	66	33
20	22	47	46	10,013	6	45	9	159	30
22	24	30	97	1,166	6	83	14	4,695	11
24	26	116	120	438	6	394	13	467	14
26	28	260	117	197	13	343	99	5,228	18
28	30	4,920	167	4,306	9	3,936	83	NA	31
30	32	4,367	44	9,373	26	604	39	624	47
32	34	4,409	237	30,593	35	6,653	23	2,121	14
34	36	301	58	14,854	73	10,262	NA	525	36
36	38	394	NA	4,143	91	837	NA	337	55
38	40	432	33	1,595	108	429	29	17,976	30
41	43	4,229	47	21,402	176	12,835	40	7,046	8
43	45	8,276	49	25,433	147	12,184	2,420	24,548	7
45	46	NA	46	NA	156	NA	4,403	NA	5

Figure 5-1. Distribution of Pre- and Post-Demonstration TCE Concentrations (mg/kg) in the Steam Injection/Extraction Plot Soil (Continued)

Top Depth (ft bgs)	Bottom Depth (ft bgs)	Pre-Demo SB-39 (mg/kg)	Post-Demo SB-239 (mg/kg)	Post-Demo SB-339 (mg/kg)	Pre-Demo SB-40 (mg/kg)	Post-Demo SB-240 (mg/kg)	Pre-Demo SB-41 (mg/kg)	Pre-Demo SB-41B (mg/kg)	Post-Demo SB-241 (mg/kg)	Pre-Demo SB-42 (mg/kg)	Post-Demo SB-242 (mg/kg)
0	2	3	0	ND	5	ND	1	ND	ND	5	ND
2	4	1	0	ND	0.45	ND	1	ND	ND	1	ND
4	6	7	2	ND	ND	16	1	ND	15	8	6
6	8	2	7	9	ND	15	ND	ND	11	5	10
8	10	1	6	8	4	4	1	ND	12	ND	3
10	12	2	8	10	2	9	ND	ND	2	ND	ND
12	14	1	4	5	13	6	ND	ND	2	ND	ND
14	16	7	3	4	11	0	ND	ND	1	ND	ND
16	18	8	2	10	ND	1	ND	3.3	3	ND	ND
18	20	14	5	6	18	9	ND	ND	4	ND	ND
20	22	130	7	11	51	14	116	269	6	48	4
22	24	150	13	12	85	2	203	3,050	2	149	5
24	26	455	16	14	256	29	409	305	ND	209	44
26	28	356	15	24	215	55	394	245	4	163	48
28	30	331	9	14	183	81	360	260	9	323	27
30	32	240	121	112	111	41	236	314	31	175	1,654
32	34	275	191	133	ND	104	435	460	15	7,348	1,336
34	36	346	NA	121	73	220	332	546	163	1,712	712
36	38	474	NA	90	100	124	210	274	176	409	1,920
38	40	272	77	78	6	332	182	392	NA	277	73
40	42	3,649	173	94	133	278	0	13,140	NA	348	9
42	44	7,463	366	830	285	440	8,621	23,976	5,369	16,700	11,446
44	46	NA	2,997	12,129	NA	660	NA	NA	1,973	NA	6,487

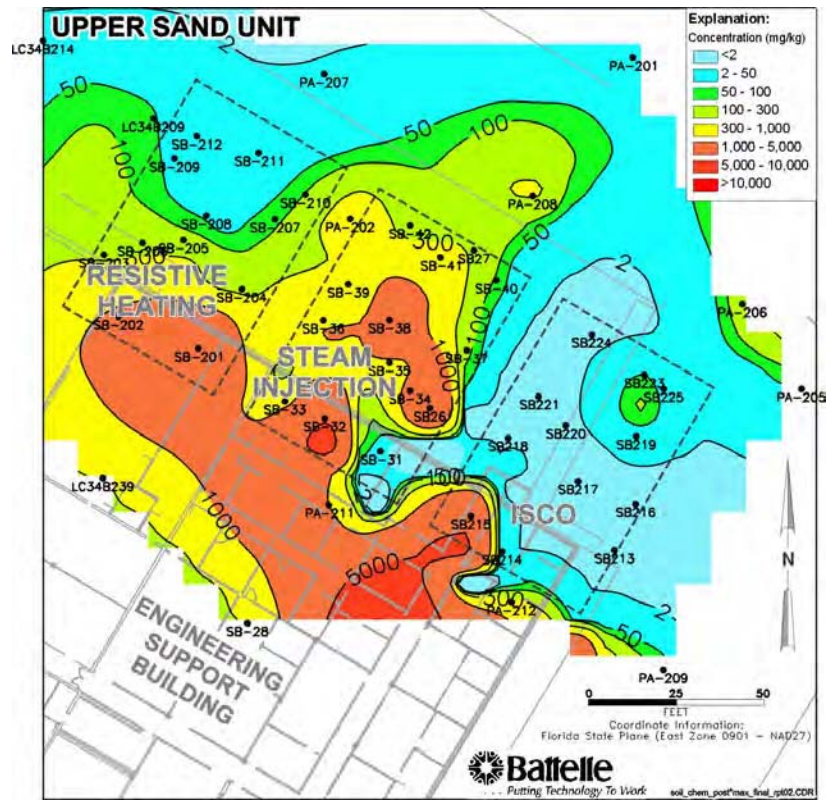
NA: Not available due to poor recovery.

ND: Not detected.

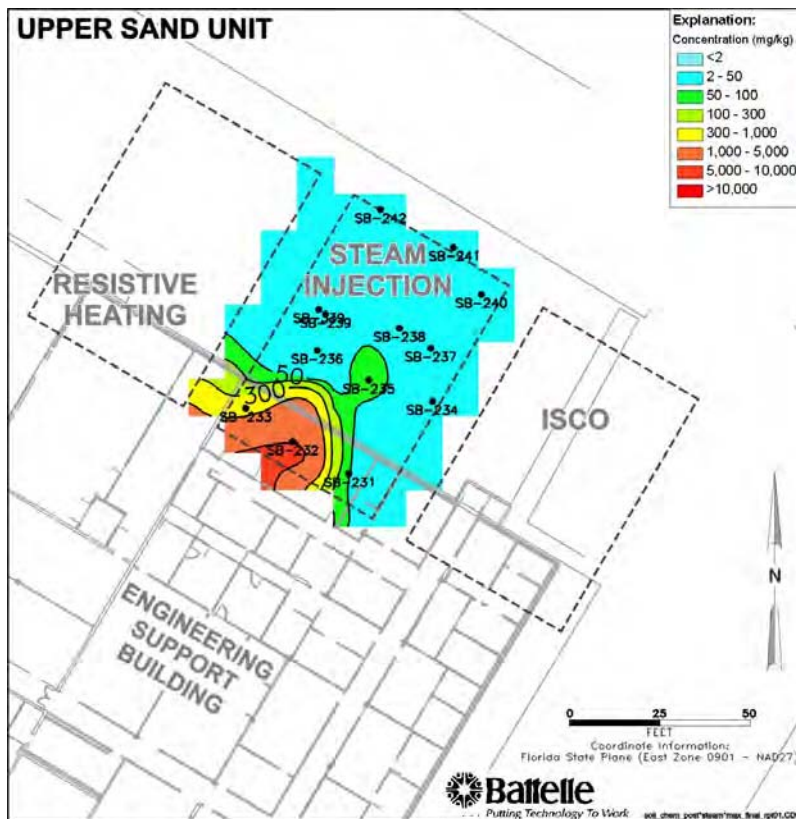
Solid Horizontal Lines demarcate the Middle Fine-Grained Unit.

Indicated color denotes the observed soil color of the soil sample at the corresponding depth.

Figure 5-1. Distribution of Pre- and Post-Demonstration TCE Concentrations (mg/kg) in the Steam Injection/Extraction Plot Soil (Continued)

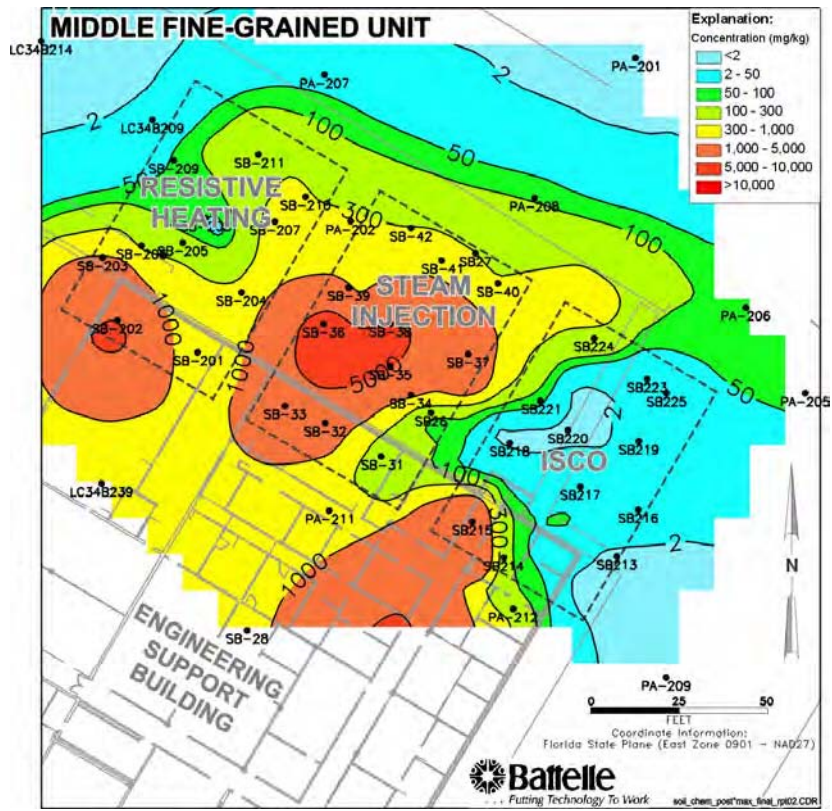


(a)

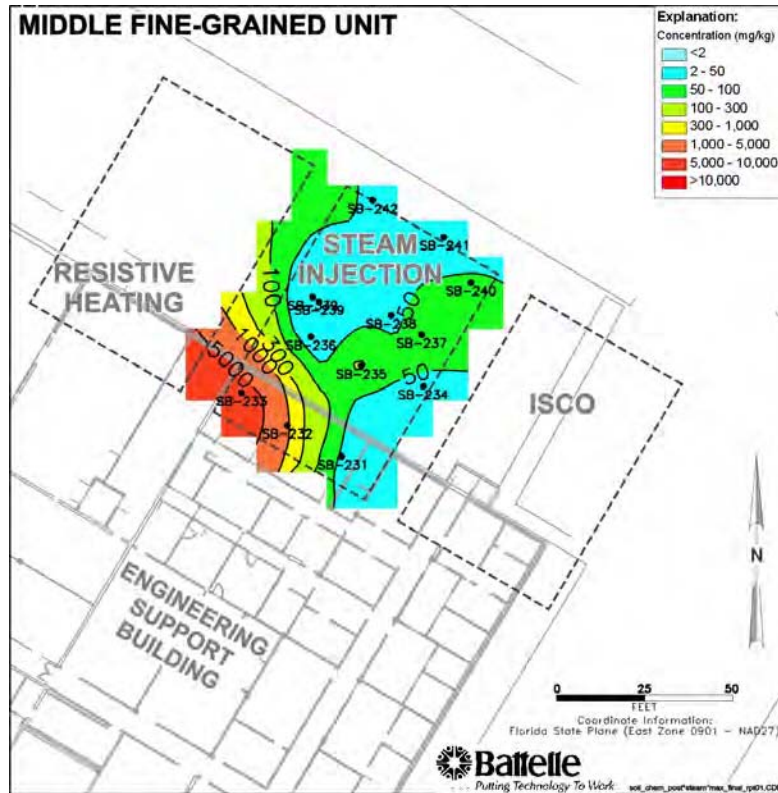


(b)

**Figure 5-2.** Representative Pre-Demonstration (a) and Post-Demonstration (b) Concentrations of TCE (mg/kg) in the Upper Sand Unit

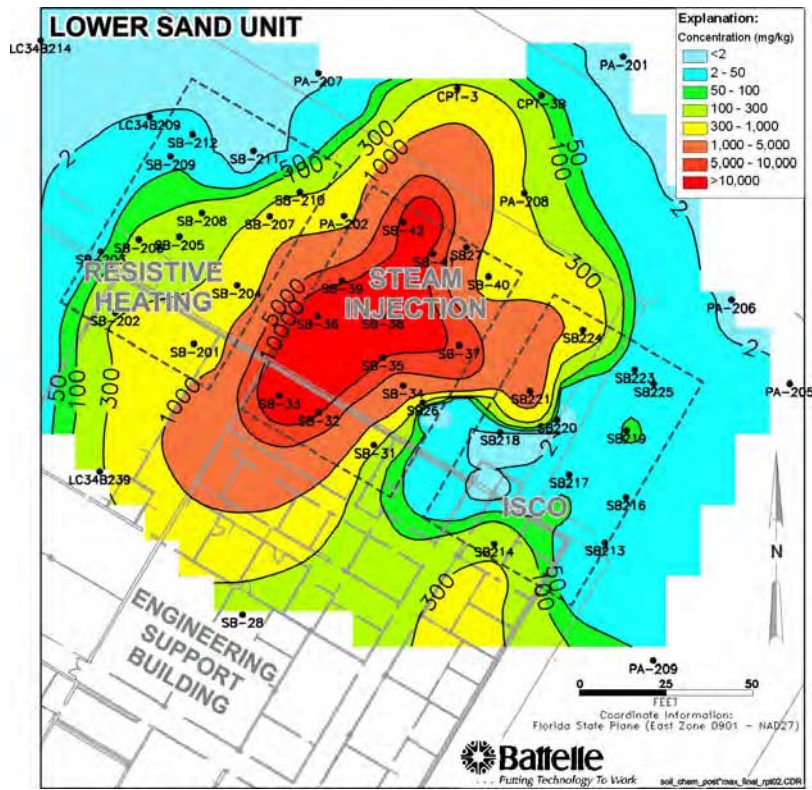


(a)

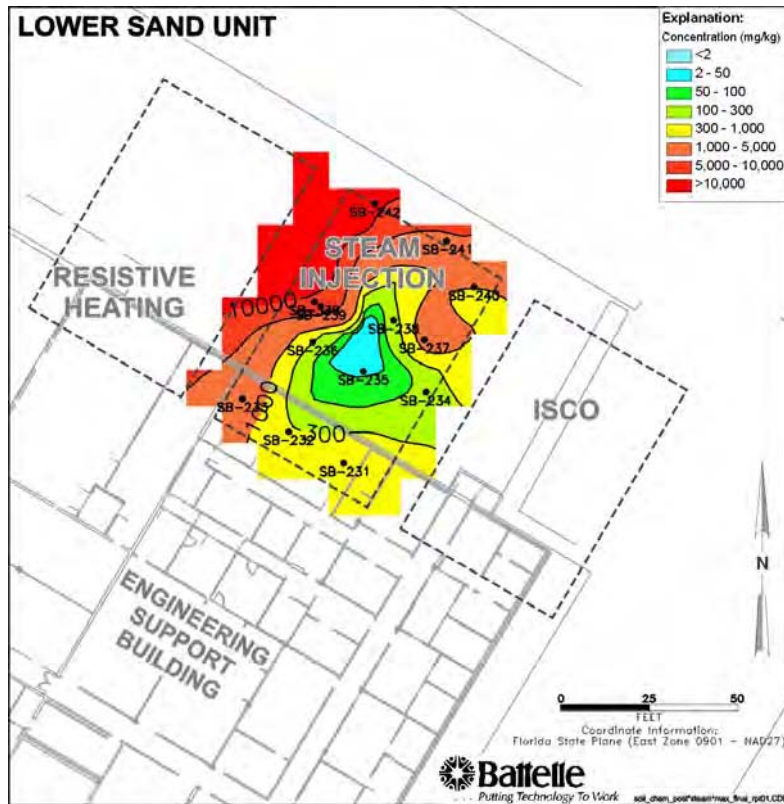


(b)

**Figure 5-3.** Representative Pre-Demonstration (a) and Post-Demonstration (b) Concentrations of TCE (mg/kg) in the Middle Fine-Grained Unit



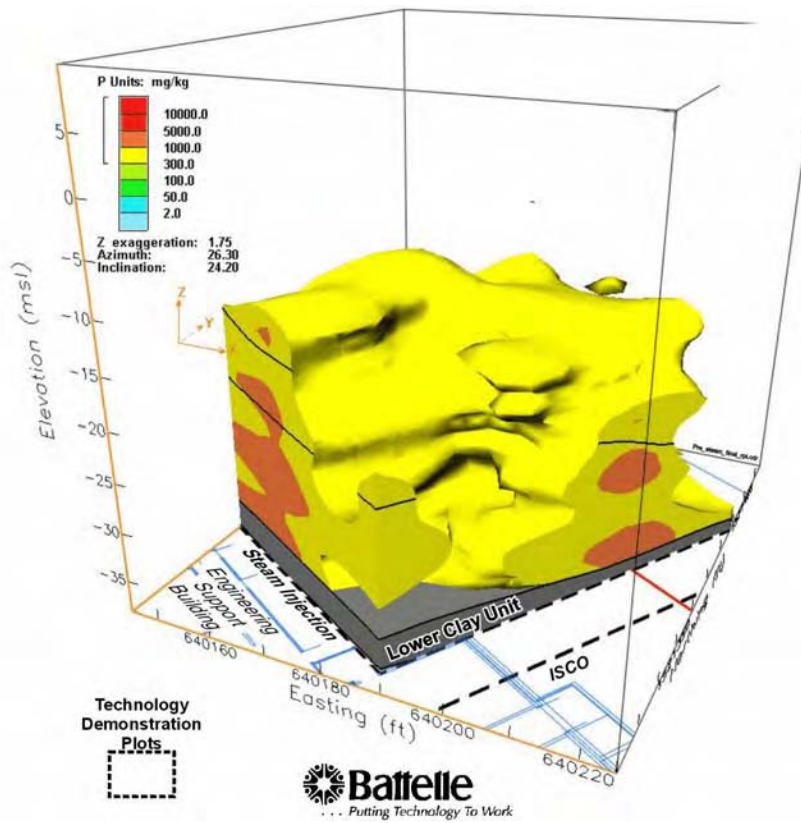
(a)



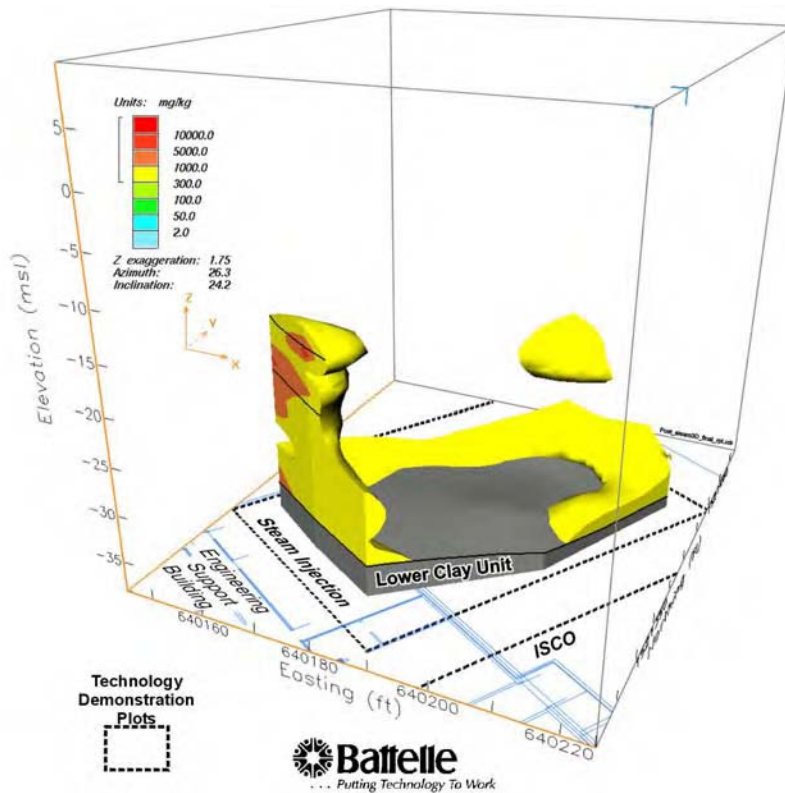
(b)

**Figure 5-4.** Representative Pre-Demonstration (a) and Post-Demonstration (b) Concentrations of TCE (mg/kg) in the Lower Sand Unit





(a)



(b)

**Figure 5-5.** Representative Pre-Demonstration (a) and Post-Demonstration (b) Presence of 3-D DNAPL (mg/kg) in the Entire Depths of the Steam Injection/Extraction Plot

Lower Sand Unit, which is a difficult region for the steam to access. (Steam, being lighter than water, has an upward trajectory after injection, and heating the base of the aquifer is typically difficult with steam injection.)

Figures 5-6, 5-7, and 5-8 show the distribution of temperature in the shallow, intermediate, and deep wells, respectively, in the Launch Complex 34 aquifer, as measured by downhole thermocouples in November 2001 during the demonstration, toward the end of the S/E application. The temperature levels in the monitoring wells are a measure of the aquifer temperature. These figures show that all three layers—shallow, intermediate, and deep—eventually were heated well and probably achieved the desired boiling temperatures during the demonstration. However, the temperatures along the southern boundary of the plot under the building were not as high as the other portions of the plot. A comparison of the temperatures in Figures 5-6, 5-7 and 5-8 and the 3-D distribution of DNAPL in Figure 5-5(b) suggests that the S/E treatment was not as effective at reducing DNAPL concentrations in zones that were not heated to the target temperature, such as the southern plot boundary under the Engineering Services Building.

In summary, a qualitative examination of the TCE-DNAPL and temperature data indicates that the S/E treatment generally achieved reasonably good heating in most parts of the plot, even in the relatively low-permeability Middle Fine-Grained Unit. Heating was not as thorough under the building and at the base of the Lower Sand Unit (just above the Lower Clay Unit). The highest post-demonstration TCE concentration was found in the north-western corner of the plot in the Lower Sand Unit near the clay aquitard, indicating that achieving sufficient steam distribution at deeper depths may have been difficult due to density differences. However, most regions of the demonstration plot showed significant reductions in TCE levels after steam treatment.

### 5.1.2 TCE-DNAPL Mass Reduction Estimation by Linear Interpolation

Section 4.1.1 describes the use of contouring to estimate pre- and post-demonstration TCE-DNAPL masses and calculate TCE-DNAPL mass reduction within the treatment plot. In this method, EarthVision™, a 3-D contouring software, is used to group the TCE concentration

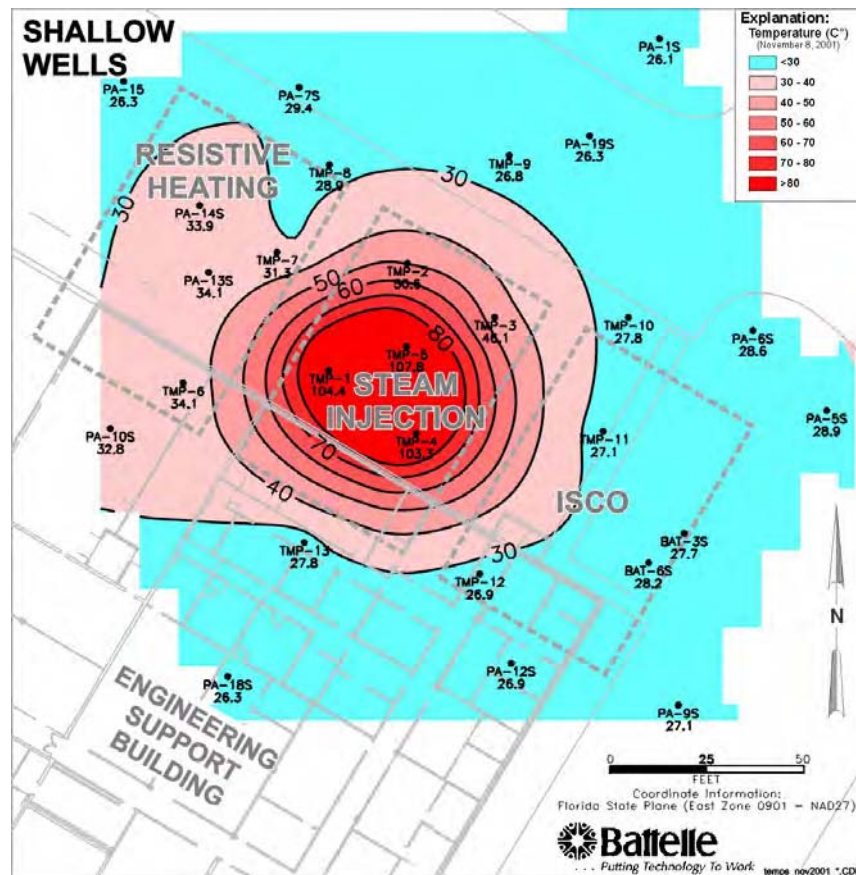
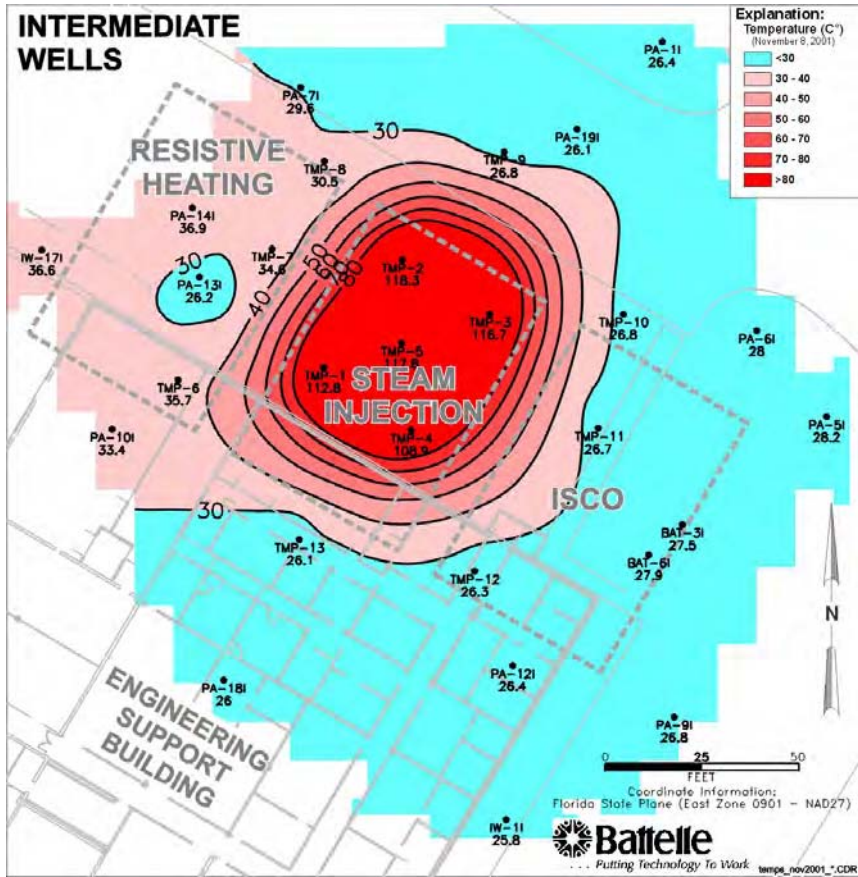
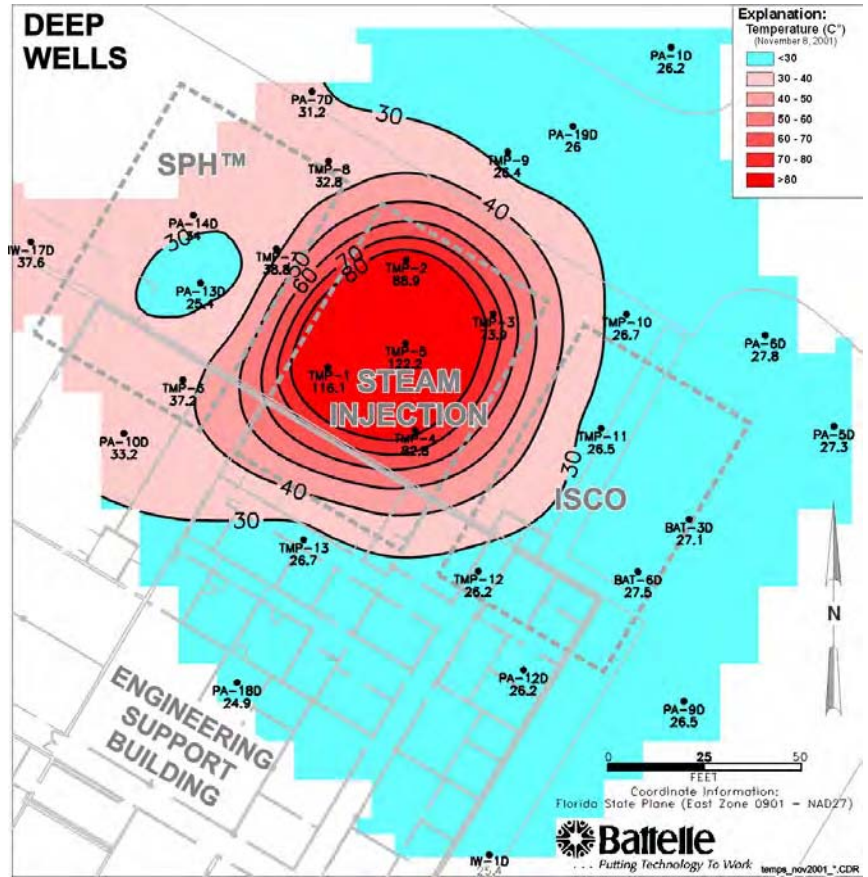


Figure 5-6. Distribution of Temperature in Shallow Wells (November 2001)



**Figure 5-7.** Distribution of Temperature in Intermediate Wells (November 2001)



**Figure 5-8.** Distribution of Temperature in Deep Wells (November 2001)

distribution in the SI/E plot into 3-D shells (or bands) of equal concentration. The concentration in each shell is multiplied by the volume of the shell and the bulk density of the soil to arrive at the TCE mass in that shell. The masses in the individual shells are added to arrive at a TCE mass for the entire plot; this process is conducted separately for the pre- and post-demonstration TCE distributions in the SI/E plot. The pre-demonstration TCE-DNAPL mass in the entire plot then can be compared with the post-demonstration mass in the entire plot to estimate TCE-DNAPL reduction. The results of this evaluation are described in this section.

Table 5-1 presents the estimated masses of total TCE and DNAPL in the SI/E plot and the three individual stratigraphic units. Under pre-demonstration conditions, soil sampling indicated an estimated 10,435 kg of total TCE (dissolved and free phase), approximately 9,301 kg of which was DNAPL. Following the demonstration, the soil sampling results indicated an estimated 1,546 kg of total TCE remained in the plot; approximately 984 kg of this remnant TCE was DNAPL. Therefore, the overall mass reduction estimated by linear interpolation (contouring) was 85% of total TCE and 89% of DNAPL.

Using linear interpolation, the highest estimated total mass reduction (88% of total TCE and 94% of DNAPL) was achieved in the Upper Sand Unit (Table 5-1). More than 89% of the pre-demonstration DNAPL mass was located in the Lower Sand Unit, and this unit also had the greatest amount (779 kg) of DNAPL remaining after SI/E treatment (see Figure 5-5b).

### 5.1.3 TCE Mass Reduction Estimation by Kriging

Section 4.1.2 describes the use of kriging to estimate the pre- and post-demonstration TCE masses in the aquifer. Whereas the contouring method interpolates the TCE measurements at discrete sampling points to estimate TCE concentrations at unsampled points in the plot, kriging takes into account the spatial variability and uncertainty of the TCE distribution when estimating TCE

concentrations (or masses) at unsampled points. Consequently, kriging provides a range of probable values rather than single TCE concentration estimates. Kriging is a good way of obtaining a global estimate (estimate for one of the three stratigraphic units or the entire plot) for the parameters of interest (such as pre- and post-demonstration TCE masses), when the parameter is heterogeneously distributed.

Appendix A.1.1 contains a description of the application of kriging to the TCE distribution in the SI/E plot. Table 5-2 summarizes the total TCE mass estimates obtained from kriging. This table contains an average and range for each global estimate (Upper Sand Unit, Middle Fine-Grained Unit, Lower Sand Unit, and the entire plot total). Because limiting the evaluation to DNAPL instead of total TCE constrains the number of usable data points to those with TCE concentrations greater than 300 mg/kg, kriging was conducted on total TCE values only.

The pre- and post-demonstration total TCE mass ranges estimated from kriging match the total TCE estimate obtained from contouring relatively well, probably because the high sampling density (almost 300 soil samples in the plot per event) allows linear interpolation by contouring to capture much of the variability of the TCE distribution in the plot. Kriging shows that an estimated 80 to 90% (85% on average) pre-demonstration TCE mass reduction was achieved from the entire plot after the SI/E application. Using kriging estimates, the TCE mass reduction was highest in the Lower Sand Unit, followed by the Middle Fine-Grained Unit. An interesting observation from Table 5-2 is that the estimated ranges for the pre- and post-demonstration TCE masses do not overlap, either for the entire plot or for the Lower Sand or Middle Fine-Grained units. This result indicates that the mass reduction due to SI/E application is significant at the 80% confidence level (i.e., at least 80% of the pre-demonstration TCE mass is likely to have been reduced due to the SI/E treatment). The mass reduction estimates obtained in the SI/E plot by the two methods (contouring and kriging) are consistent with each other.

**Table 5-1.** Linear Interpolation (or Contouring) Estimates for the Steam Demonstration

Stratigraphic Unit	Pre-Demonstration		Post-Demonstration		Mass Removal	
	Total TCE (kg)	DNAPL <sup>(a)</sup> (kg)	Total TCE (kg)	DNAPL <sup>(a)</sup> (kg)	Total TCE (%)	DNAPL <sup>(a)</sup> (%)
Upper Sand Unit	838	555	97	32	88	94
Middle Fine-Grained Unit	1,962	1,674	273	173	86	90
Lower Sand Unit	7,635	7,072	1,176	779	85	89
<b>TOTAL</b>	<b>10,435</b>	<b>9,301</b>	<b>1,546</b>	<b>984</b>	<b>85</b>	<b>89</b>

(a) DNAPL includes only the TCE that is above 300 mg/kg of soil.

**Table 5-2.** Kriging Estimates for the SI/E Demonstration

Stratigraphic Unit	Pre-Demonstration Total TCE <sup>(a)</sup>			Post-Demonstration Total TCE <sup>(a)</sup>			Total TCE Mass Reduction <sup>(a)</sup>		
	Average (kg)	Lower Bound (kg)	Upper Bound (kg)	Average (kg)	Lower Bound (kg)	Upper Bound (kg)	Average (%)	Lower Bound (%)	Upper Bound (%)
Upper Sand Unit	1,069	722	1,416	357	2	713	67	32	100
Middle Fine-Grained Unit	3,234	2,600	3,868	478	109	847	85	73	97
Lower Sand Unit	8,349	7,028	9,671	1,099	776	1,422	88	83	92
TOTAL	12,652	11,145	14,159	1,934	1,328	2,540	85	80	90

(a) Average and 80% confidence intervals (bounds).

### 5.1.4 TCE-DNAPL Mass Reduction Summary

In summary, the evaluation of TCE concentrations in soil indicates the following:

- In the horizontal plane, the highest pre-demonstration DNAPL concentration was in the western half of the SI/E plot, especially under the Engineering Support Building.
- In the vertical plane, the highest pre-demonstration DNAPL concentration was immediately above the Lower Clay Unit.
- Linear interpolation (by contouring) of the pre- and post-demonstration TCE-DNAPL soil concentrations showed that approximately 89% of the estimated pre-demonstration DNAPL mass in the SI/E plot was reduced after the steam application. Therefore, the DNAPL reduction achieved by the SI/E technology was close to the targeted 90% mass removal goal.
- A statistical evaluation (kriging) of the pre- and post-demonstration TCE concentrations in soil showed that between 80 and 90% of the estimated pre-demonstration total TCE mass in the SI/E plot was reduced after the SI/E application. Total TCE includes both dissolved-phase TCE and DNAPL. The kriging results are generally consistent with the linear interpolation results and indicate a high probability (80% confidence level) that the mass reduction estimates are accurate.
- Kriging indicated that total TCE reduction was highest in the Lower Sand Unit with the average of 88% reduction, which contained the largest pre-demonstration TCE mass as shown in Figure 5-5. However, much of the TCE-DNAPL remaining after the SI/E application was near the base of the aquifer (immediately above the Lower Clay Unit), a location that may have been difficult for the steam to access because of density differences.

### 5.2 Changes in Aquifer Characteristics

This section describes the short-term changes in aquifer characteristics created by the application of steam the SI/E technology at Launch Complex 34, as measured by monitoring conducted before, during, and immediately after the demonstration. The affected aquifer characteristics that were measured during the demonstration include:

- Changes in aquifer CVOC levels (see Appendix C for detailed results)
- Changes in aquifer geochemistry (see Appendix D for detailed results)
- Changes in the hydraulic properties of the aquifer (see Appendix B for detailed results)
- Changes in the aquifer microbiology (see Appendix E for detailed results).

Table 5-3 lists the pre- and post-demonstration levels of various groundwater parameters that indicate aquifer quality and the impact of the SI/E treatment. Other important organic and inorganic aquifer parameters are discussed in the text. A separate microbiological evaluation of the aquifer is described in Appendix E.

One challenge with interpreting post-demonstration groundwater data is that the vendor extracted 4,013,588 gal of water from the aquifer during the SI/E treatment. After accounting for the 1,409,810 kg of steam (equivalent to 372,473 gal of water) injected in the aquifer, the amount of water extracted from the aquifer in and around the demonstration plot represents approximately 11 pore volumes of the demonstration plot. Because the groundwater extraction wells were located around the perimeter of the plot and therefore drew water toward the plot boundaries from both inside and outside of the plot, an assumption could be made that roughly half of the extracted groundwater came from inside the plot

**Table 5-3.** Pre- and Post-Demonstration Levels of Groundwater Parameters Indicative of Aquifer Quality

Groundwater Parameter	Applicable Groundwater Standard (if any) (mg/L)	Aquifer Depth <sup>(a)</sup>	Pre-Demonstration (mg/L) <sup>(b)</sup>	Post-Demonstration (mg/L) <sup>(b)</sup>
TCE	0.003	Shallow	<0.002 to 650	6.1 to 145
		Intermediate	0.081 to 210	1.8 to 14
		Deep	280 to 860	2.7 to 210
<i>cis</i> -1,2-DCE	0.070	Shallow	<0.002 to 21	1 to 19
		Intermediate	0.010 to 260	2 to 8
		Deep	35 to 38	0.2 to 52
Vinyl chloride	0.001	Shallow	<0.004 to <83	0.098 to <0.2
		Intermediate	<0.008 to <20	0.128 to 0.170
		Deep	<33 to <83	0.013 to 0.15
pH	Not applicable	Shallow	7.0 to 8.2	7.0 to 8.7
		Intermediate	7.0 to 9.1 <sup>(c)</sup>	6.6 to 6.9
		Deep	6.7 to 7.1	6.7 to 7.1
ORP	Not applicable	Shallow	-105 to 534 <sup>(c)</sup>	-95 to 102
		Intermediate	-152 to -163	49 to 89
		Deep	-105.8 to -159.7	-231 to 113
DO	Not applicable	Shallow	0.43 to 4.6 <sup>(c)</sup>	0.54 to 0.74
		Intermediate	0.36 to 0.52	0.41 to 0.45
		Deep	0.62 to 2.73	0.59 to 0.74
Calcium	Not applicable	Shallow	27.7 to 108	5.3 to 88
		Intermediate	30.5 to 92.6	63.4 to 93.5
		Deep	89.1 to 111	46.9 to 86.8
Magnesium	Not applicable	Shallow	<2 to 74	1.5 to 17
		Intermediate	3.7 to 101	16 to 20
		Deep	100 to 179	19.1 to 37.9
Alkalinity	Not applicable	Shallow	661 to 1,430	248 to 361
		Intermediate	380 to 422	193 to 468
		Deep	459 to 2,500	329 to 445
Chloride	250	Shallow	297 to <1,000	89 to 160
		Intermediate	42.8 to 448	86 to 93
		Deep	305 to 415	144 to 313
Manganese	0.050	Shallow	0.46 to 667	0.013 to 0.858
		Intermediate	0.64 to 5.3	0.1 to 1.03
		Deep	0.18 to 1.3	0.081 to 0.826
Iron	0.3	Shallow	<0.1 to 3.9	<0.1 to 2.47
		Intermediate	<0.1 to 3.4	<0.1 to 0.30
		Deep	0.28 to 0.63	0.813 to <0.1
Sulfate	Not applicable	Shallow	293 to <1,000	95.6 to 360
		Intermediate	104 to 120	90.9 to 466
		Deep	202 to 681	121 to 1,960
TDS	500	Shallow	1,740 to 2,470	728 to 1,250
		Intermediate	814 to 1,360	886 to 1,200
		Deep	1,200 to 4,510	1,070 to 4,650
BOD	Not applicable	Shallow	<3 to 70	<6 to 6.8
		Intermediate	7.4 to 13.8	4.2 to <6
		Deep	22.8 to 84.0	<6 to 16.6
TOC	Not applicable	Shallow	74.2 to 1,680	26.8 to 61.5
		Intermediate	2.1 to 30.5	29.2 to 56
		Deep	19.5 to 134	69.2 to 79.5

- (a) Shallow well screens are located in the Upper Sand Unit; intermediate wells screens are located in the Middle Fine-Grained Unit; and deep well screens are located in the Lower Sand Unit.
- (b) All reported quantities are in mg/L, except for pH, which is in log units, and ORP, which is in mV.
- (c) pH, DO, and ORP values for the pre-demonstration samples are questionable because of suspected interference from high levels of residual permanganate remaining in the water following the ISCO demonstration.

(i.e., approximately 5 pore volumes). The groundwater extraction rate was not measured for each individual well, but the overall extraction rate averaged 22 gpm during the demonstration. It is difficult to determine if any change in TCE mass measured in groundwater is attributable to the SI/E treatment or to the groundwater extraction. The vendor was not required to track any parameter other than VOCs in the extracted fluids and vapor, which otherwise may have provided information on the amount of degradation occurring as a result of the SI/E treatment. Even if the vendor had analyzed other parameters, such as chloride, uncertainty would still be associated with how much the surrounding aquifer contributed to any changes in dissolved parameters. Therefore, the soil analysis reported in Section 5.1 is probably a better indicator of system performance than the groundwater analysis.

### 5.2.1 Changes in CVOC Levels in Groundwater

CVOC levels were measured in the SI/E plot wells (PA-16 and -17) before and after the demonstration. Samples were not collected from these wells during the demonstration because of safety issues (e.g., high temperature-pressurized wells) and because the wells were covered by the plenum over the plot, and were therefore inaccessible. CVOC levels were measured in wells around the perimeter of the plot (PA-14, PA-18, PA-19, and BAT-5) and in one distant well cluster (PA-1) before, during, and after the demonstration to evaluate the short-term changes in CVOC levels in groundwater. Appendix C tabulates the levels of TCE, *cis*-1,2-DCE, and vinyl chloride found in groundwater collected from these wells.

Figures 5-9, 5-10, and 5-11 show the pre- and post-demonstration dissolved TCE concentrations in the shallow (approximately 22 ft bgs), intermediate (approximately 29 ft bgs), and deep wells (approximately 45 ft bgs), respectively, in the SI/E plot and around the perimeter of the plot. Pre-demonstration levels of TCE in wells inside the plot (PA-16 and -17) ranged from <2 to 650,000 µg/L in the shallow wells, 81 to 210,000 µg/L in the intermediate wells, and 280,000 to 860,000 µg/L in the deep wells. After the demonstration, TCE levels rose in some wells and declined in others. As tabulated in Appendix C, TCE levels rose in the PA-16 cluster, but declined in the PA-17 cluster. PA-16 is closer to the ISCO plot. TCE levels in PA-16 (S, I, and D) were relatively low before the steam injection demonstration, probably because of an influx of permanganate from the ISCO plot, but rose after the demonstration. The TCE concentrations in PA-16 and PA-17 may have been influenced by an influx of water from inside and outside

the test plot due to the groundwater extraction. The PA-17 cluster, which is closer to the northern boundary of the plot and further away from the neighboring demonstration plots than PA-16, showed a significant decrease in TCE levels. This could be due to a reduction in DNAPL from the demonstration plot either from the steam injection wells and/or from an influx of cleaner water from the north.

The TCE levels in the perimeter wells PA-19, BAT-5, and PA-14 on three sides of the plot generally declined. In PA-19, TCE levels declined from 130,000 µg/L to 93 µg/L in the shallow well, from 483,000 µg/L to 248,000 µg/L in the intermediate well, and from 306,000 µg/L to 2,280 µg/L in the deep well. Similar reductions were observed in perimeter well BAT-5. Even the distant well PA-1 on the north side showed a decline in TCE levels. The TCE levels in the perimeter well PA-18 on the south side of the SI/E plot (and inside the Engineering Support Building) remained persistently high. This may indicate that the perimeter wells that were on the cleaner (northern) or remediated (eastern and western) sides of the SI/E plot showed a decrease in TCE levels because most of the remaining TCE on these three sides was dissolved phase. On the other hand, PA-18 on the south side is inside the Engineering Support Building, where DNAPL is present and has not undergone any remediation. These results, as well as the general trend in the perimeter wells during interim sampling events, indicate that the vendor probably achieved good hydraulic control. Most of the groundwater flow during the SI/E demonstration occurred inward toward the steam plot. Except on the south side, where DNAPL already was present, none of the trends in the perimeter wells indicate that any TCE or DNAPL migrated out from the SI/E plot.

Inside the SI/E plot, concentrations of *cis*-1,2-DCE in groundwater increased at the PA-16 well cluster, although TCE levels also increased in this cluster. Both TCE and *cis*-1,2-DCE could have re-equilibrated in the eastern half of the cell after the permanganate from the neighboring plot dissipated due to groundwater extraction in the SI/E plot. The levels of *cis*-1,2-DCE decreased in the PA-17 well cluster. Vinyl chloride concentrations generally increased in the PA-16 wells (because of higher detection limits before the demonstration, it was difficult to compare vinyl chloride levels in PA-17). In the perimeter wells, there was no clear trend in concentrations of *cis*-1,2-DCE and vinyl chloride between pre- and post-demonstration sampling events, with levels both increasing and decreasing depending on the location and depth of the well. It is unclear whether there was a net accumulation or a redistribution of *cis*-1,2-DCE and vinyl chloride.

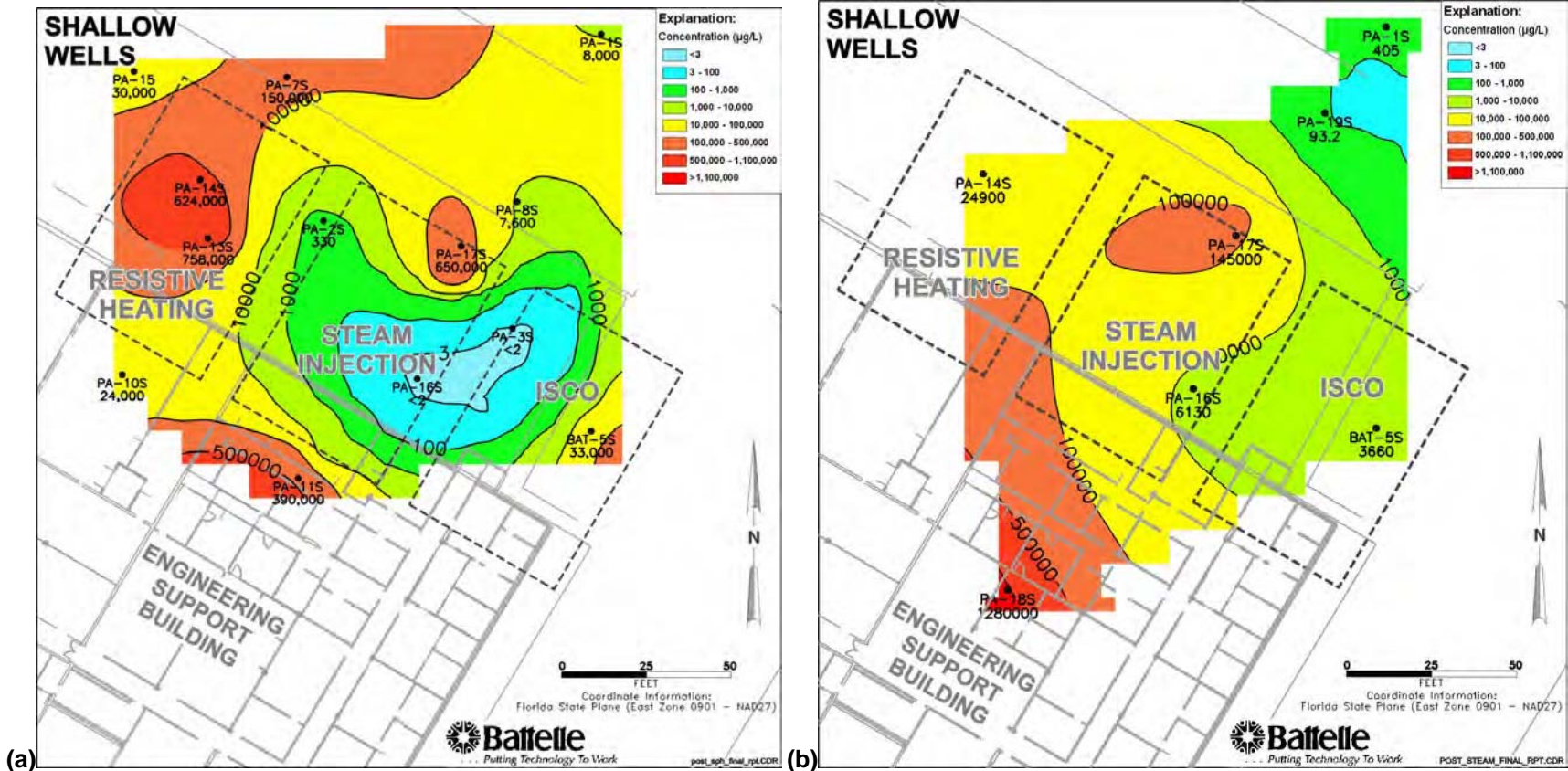


Figure 5-9. Dissolved TCE Concentrations (µg/L) during (a) Pre-Demonstration and (b) Post-Demonstration Sampling of Shallow Wells



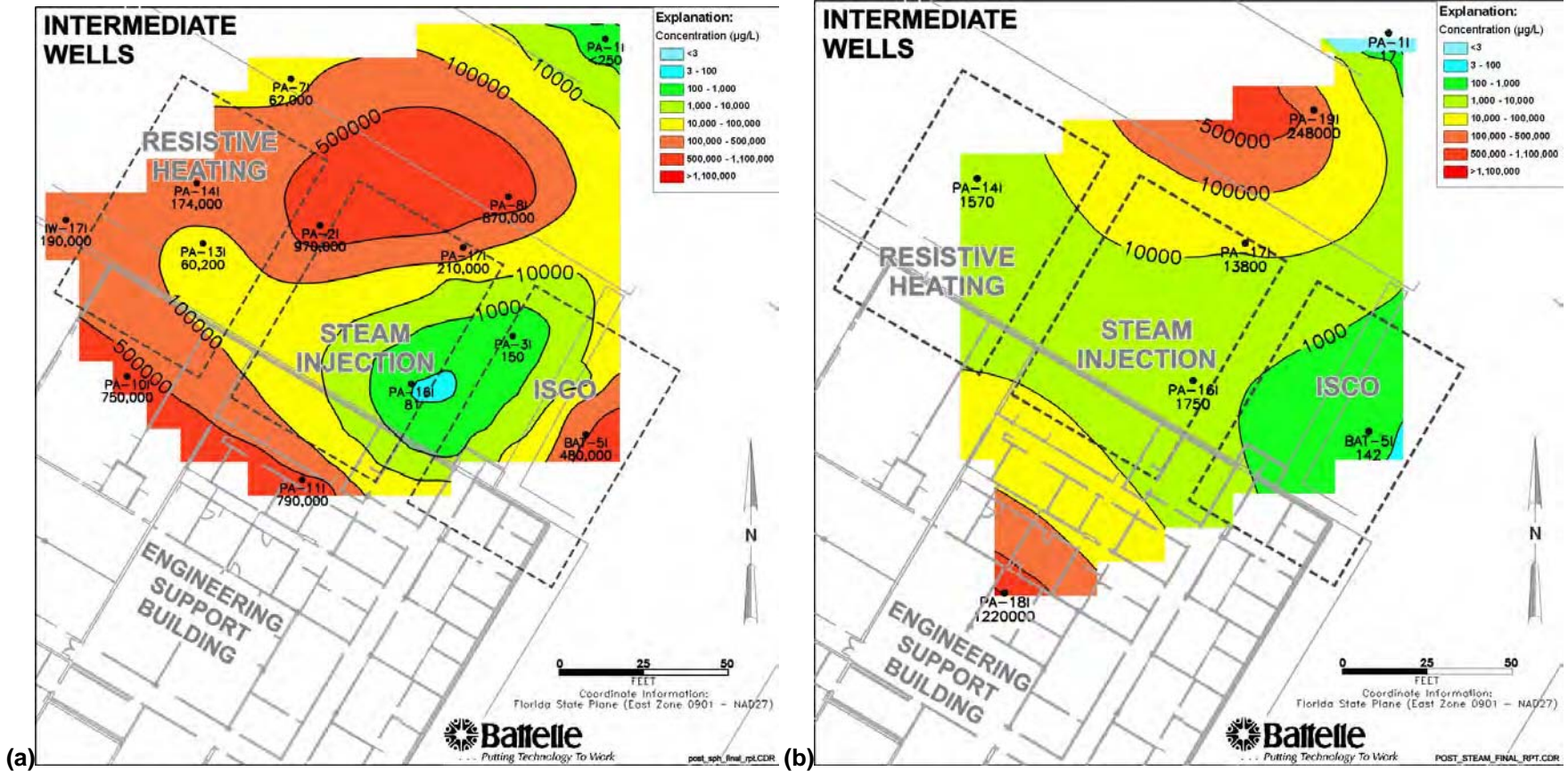


Figure 5-10. Dissolved TCE Concentrations (µg/L) during (a) Pre-Demonstration and (b) Post-Demonstration Sampling of Intermediate Wells

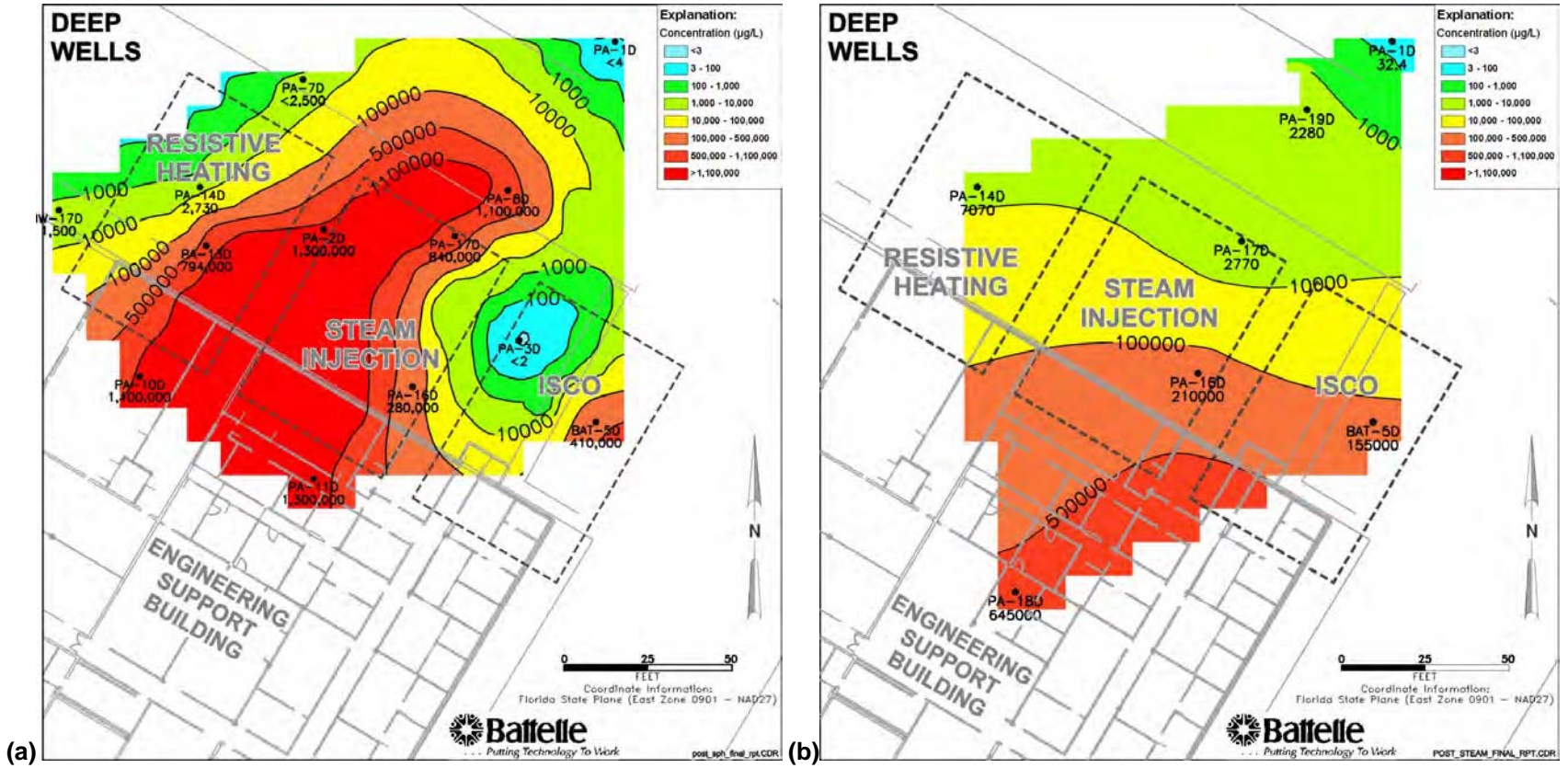


Figure 5-11. Dissolved TCE Concentrations (µg/L) during (a) Pre-Demonstration and (b) Post-Demonstration Sampling of Deep Wells

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## 5.2.2 Changes in Aquifer Geochemistry

The geochemical composition of both groundwater and soil were examined to evaluate the effects of the SI/E application.

### 5.2.2.1 Changes in Groundwater Chemistry

Among the field parameter measurements (tabulated in Appendix D) conducted in the affected aquifer before, during, and after the demonstration, the following trends were observed:

- Groundwater *pH* in the plot ranged from 6.7 to 9.1 before the demonstration to 6.6 to 8.7 after the demonstration.
- *ORP* varied, from -105 to -163 mV before the demonstration to -231 to +113 mV after the demonstration. The *ORP* in well PA-16S was measured at +534 mV before the demonstration; this value is suspect due to interference from residual permanganate remaining in the area from the ISCO demonstration in the neighboring plot.
- *DO* ranged from 0.36 to 2.73 mg/L before the demonstration to 0.41 to 0.74 mg/L after the demonstration. Due to the limitations of measuring *DO* with a flowthrough cell, groundwater with *DO* levels below 0.5 or even 1.0 is considered anaerobic. Except for the shallower regions, the aquifer was mostly anaerobic throughout the demonstration. It is difficult to determine why *DO* levels did not increase more after the co-air injection. The residence time of the steam may not have been long enough to significantly impact the *DO* levels in groundwater. The *DO* in well PA-16S measured 4.6 mg/L before the demonstration, which is questionable due to suspected interference from residual permanganate remaining in the area from the ISCO demonstration.

Other groundwater measurements indicative of aquifer quality included inorganic ions, BOD, and TOC. The results of these measurements are as follows:

- *Calcium* levels did not display a clear trend. Concentrations ranged from 28 to 111 mg/L before the demonstration to 5.3 to 94 mg/L after the demonstration. In the PA-16 cluster, calcium levels in groundwater increased in the shallow and intermediate depths but decreased at deep depths between pre- and post-demonstration sampling. In PA-17, calcium levels decreased in the shallow and deep depths, and remained relatively constant at the intermediate depth. Calcium and alkalinity levels can decrease after heating because calcium carbonate solubility decreases with increasing

temperature. No such clear trend was apparent at the site, probably because the constant pumping at 22 gpm from the extraction wells by the vendor caused considerable influx of water from outside the plot. In addition, carbon dioxide degassing may be a more important catalyst for calcite precipitation than the effect of temperature on calcite solubility.

- *Magnesium* levels also did not show a clear trend in the groundwater sampled from the plot before and after the demonstration. Magnesium levels in well PA-16 ranged from <2 to 179 mg/L prior to the demonstration and 17 to 38 mg/L after the demonstration, with an increase seen in the shallow and intermediate depths but a decrease at deep depth. In the PA-17 cluster, magnesium concentrations ranged from 73 to 101 mg/L before the demonstration to 1.5 to 20 mg/L after the demonstration. A decrease was seen at all depths for wells PA-17.
- Groundwater *alkalinity* in the plot generally decreased, with concentrations ranging from 380 to 2,500 mg/L before the demonstration to 193 to 468 mg/L after the demonstration. The alkalinity in the plot prior to the demonstration appears elevated compared to the distant well PA-1, and may be due to the influence of the ISCO and resistive heating technology demonstrations conducted in nearby plots.
- *Chloride* levels were already relatively high in the aquifer before the SI/E demonstration, especially in the deeper units. Chloride was generated in both the neighboring plots during the ISCO and resistive heating demonstrations. It is possible that some of this chloride was displaced into the SI/E plot and was measured during the pre-demonstration sampling. Following the SI/E application, chloride concentrations decreased considerably in the three stratigraphic units. In the shallow wells, chloride decreased from a range of 297 to <1,000 mg/L before the demonstration to 89 to 160 mg/L after the demonstration. In the intermediate wells, chloride decreased from 43 to 448 mg/L before the demonstration to 86 to 93 mg/L after the demonstration. In the deep wells, chloride levels decreased from 305 to 415 mg/L before the demonstration to 144 to 313 mg/L after the demonstration. Of the six wells sampled in the plot prior to the demonstration, four wells were above the 250-mg/L secondary drinking water limit for chloride. After the demonstration, only one well remained above that limit. Again, chloride levels in the plot probably were diluted by the constant groundwater extraction that resulted in the equivalent of 11 test plot pore volumes of water being extracted during the demonstration.

- *Manganese* levels in the plot generally decreased slightly from 0.18 to 5.3 mg/L before the demonstration to 0.01 to 1.03 mg/L after the demonstration. In PA-16S, manganese concentration level was 667 mg/L before the demonstration due to the influx of potassium permanganate from the ISCO plot. Thus, this level was not included in the concentration range. Manganese has a secondary drinking water limit of 0.05 mg/L, which was exceeded during and after the demonstration. Perimeter wells also showed relatively unchanged levels of manganese. Dissolved manganese consists of the species  $Mn^{7+}$  (from excess permanganate ion) and  $Mn^{2+}$  (generated when  $MnO_2$  is reduced by native organic matter); both species could have migrated into the SI/E plot before the demonstration.
- *Iron* levels in the SI/E plot increased in well PA-16, from pre-demonstration levels of <0.1 to 0.28 mg/L, to post-demonstration groundwater levels of 0.30 to 2.47 mg/L. Iron levels decreased in well PA-17, from pre-demonstration levels of 0.58 to 3.9 mg/L, to post-demonstration groundwater levels of <0.1 mg/L. The secondary drinking water limit for iron is 0.3 mg/L, which was exceeded in some of the wells both before and after the demonstration.
- *Sodium* levels decreased slightly in general across the plot, from 42 to 213 mg/L before the demonstration to 31 to 184 mg/L after the demonstration.
- *Potassium* levels generally decreased across the plot, from a range of 33 to 1,600 mg/L before the demonstration to 92 to 335 mg/L after the demonstration. However, potassium levels in the deep well PA-17D increased from 103 mg/L before the demonstration to 1,860 mg/L after the demonstration. This may indicate redistribution of the potassium that entered the plot during the ISCO demonstration.
- *Sulfate* levels remained relatively constant or increased slightly in groundwater sampled from the shallow and intermediate wells of PA-17, with concentrations of 104 to <1,000 mg/L before the demonstration to 91 to 466 mg/L after the demonstration. However, sulfate levels decreased sharply in the deep well PA-16D, from 681 mg/L to 121 mg/L, and increased sharply in the deep well PA-17, from 202 mg/L to 1,960 mg/L.
- *TDS* levels varied considerably in all three units between pre- and post-demonstration groundwater sampling. In the shallow wells, TDS levels fell from 2,470 mg/L to 728 mg/L in well PA-16S and from 1,740 mg/L to 1,250 mg/L in well PA-17S. In the intermediate wells, TDS remained fairly constant, from 815 mg/L to 886 mg/L in well PA-16I, and fell

slightly in well PA-17I from 1,360 to 1,200 mg/L. In the deep wells, TDS decreased in well PA-16D from 4,510 mg/L to 1,070 mg/L, and increased in well PA-17D from 1,200 mg/L to 4,650 mg/L. The secondary drinking water limit for TDS is 500 mg/L, which was exceeded both before and after the demonstration. TDS generally decreased after the demonstration in the perimeter wells surrounding the plot.

- *BOD* declined in the demonstration plot, with levels ranging from <3.0 to 84 mg/L before steam injection to 4.2 to 16.6 mg/L after the demonstration. Lower BOD levels suggest that the high temperatures caused by the steam injection may have promoted microbial activity that consumed available carbon sources. Section 5.2.4 and Appendix E contain details on the microbiology of the demonstration plot. Fresh steam condensate also may have contributed to reduced BOD levels.
- *TOC* in groundwater did not display any clear trends in the demonstration plot. In general, groundwater from PA-16S and PA-17S contained the highest levels of TOC before the demonstration (1,680 mg/L and 74 mg/L, respectively), and decreased after the demonstration (61.5 mg/L and 26.8 mg/L, respectively). At intermediate depths, TOC in groundwater increased from 30.5 mg/L to 56 mg/L in well PA-16I, and from 2.1 mg/L to 29.2 mg/L in well PA-17I. At deep depths, TOC in groundwater decreased from 134 mg/L to 73.5 mg/L in well PA-16D; however, TOC increased from 19.6 mg/L before the demonstration to 79.5 mg/L after the demonstration in groundwater collected from well PA-17D.

The effect of the SI/E application on the aquifer microbiology was evaluated in a separate study, as described in Appendix E.

In general, no strong trends were discernible in the groundwater during the SI/E demonstration. The extraction of groundwater by the vendor from in and around the demonstration plot to maintain hydraulic control most likely caused a sizable influx of groundwater from the surrounding aquifer that obscured the changes in the SI/E plot that could be attributable to the steam treatment.

#### 5.2.2.2 Changes in Soil Geochemistry

In addition to the groundwater monitoring of geochemical parameters, soil samples were collected before and after the demonstration for TOC measurements (Table 5-4). Soil TOC concentrations ranged from 5,390 to 47,800 mg/kg before the demonstration to 240 to 2,160 mg/kg after the demonstration. Although the data are limited, the results suggest that the high temperatures associated with SI/E resulted in significant consumption of the

**Table 5-4.** Total Organic Carbon Levels in Soil Before and After the Demonstration

Pre-Demonstration		Post-Demonstration		
Sample ID	U.S. EPA SW-846 9060 (mg/kg)	Sample ID	TOC <sup>(a)</sup> (wt% dry)	TOC <sup>(a)</sup> (mg/kg)
SB-32-20	5,390	SB-236-10	0.036	360
SB-32-30	9,450	SB-236-30	0.065	650
SB-32-46	17,700	SB-236-38	0.068	680
SB-38-20	16,000	SB-234-18	0.024	240
SB-38-26	15,400	SB-234-30	0.216	2,160
SB-38-39	47,800	SB-234-38	0.066	660

(a) See Appendix D-7 for further information on TOC analysis using LECO Corporation instrument.

total organic carbon available in the soil, due to microbial or abiotic processes. Appendix D contains further details on the soil TOC analysis.

### 5.2.3 Changes in the Hydraulic Properties of the Aquifer

Table 5-5 shows the results of pre- and post-demonstration slug tests conducted in the SI/E plot wells. The hydraulic conductivity of the aquifer remained relatively unchanged during the SI/E application. In PA-17S, the hydraulic conductivity dropped considerably, but no widespread trend was discernible in the demonstration plot. Details on the slug tests may be found in Appendix B.

**Table 5-5.** Pre- and Post-Demonstration Hydraulic Conductivity in the SI/E Plot Aquifer

Well	Hydraulic Conductivity (ft/day)	
	Pre-Demonstration	Post-Demonstration
PA-16S	0.14	0.11
PA-16I	4.9	8.8
PA-16D	2.7	7.8
PA-17S	13.7	1.8
PA-17I	2.1	3.1
PA-17D	3.3	5.1

### 5.2.4 Changes in the Microbiology of the SI/E Plot

Microbiological analysis of soil and groundwater samples was conducted to evaluate the effect of the steam injection application on the microbial community (see Appendix E for details). Samples were collected before and after (six months after) the SI/E technology demonstration. For each monitoring event, soil samples were

collected from five locations in the plot and five locations in a control (unaffected) area. At each location, four depths were sampled—capillary fringe, Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit. The results are presented in Appendix E.

Table 5-6 summarizes the soil analysis results. The geometric mean typically is the mean of the five samples collected in each stratigraphic unit in the plot. The six months of time that elapsed since the end of the SI/E application and collection of the microbial samples may have given time for microbial populations to reestablish. Because microbial counts can be highly variable, only order-of-magnitude changes in counts were considered significant. In the Middle Fine-Grained Unit and Lower Sand Unit, aerobic microbial populations decreased. In the capillary fringe and in the Lower Sand Unit, anaerobic microbial populations decreased. In other stratigraphic units, the populations appeared to be relatively constant. The microbial counts indicate that microbial populations may have declined during the steam treatment, although they could re-establish in the plot over time.

### 5.2.5 Summary of Changes in Aquifer Quality

In most groundwater parameters measured before, after, and during the steam injection demonstration, there were no strongly discernible trends. Due to the constraints of the demonstration plot geometry and the need to remediate a small part of a larger DNAPL source, the vendor extracted more than 4 million gallons of water (22 gpm average), or almost 11 pore volumes of the demonstration plot to maintain hydraulic control. This large influx of groundwater from surrounding regions of the aquifer may have masked many of the changes in the demonstration plot that could have resulted from the SI/E application. Because extraction was done along all four sides of the plot, the water drawn into the plot came from parts of the aquifer that were under different influences. On the east side of the SI/E plot is the ISCO plot that possibly had elevated levels of residual potassium permanganate, alkalinity, and chloride from the ISCO demonstration. On the west side of the SI/E plot is the resistive heating plot that possibly had elevated levels of chloride, sodium, and alkalinity. On the south side of the SI/E plot is the Engineering Support Building, under which lies more DNAPL. On the north side of the plot, the TCE contamination starts receding and the aquifer becomes progressively cleaner. Drawing water from all four sides, with different water chemistries on each side, makes it difficult to isolate the changes occurring within SI/E plot itself. Therefore, the groundwater chemistry in the SI/E plot that was tracked through the SI/E demonstration did not show any strongly discernible trends attributable to the steam injection/extraction.

**Table 5-6.** Geometric Mean of Microbial Counts in the Steam Injection Plot (Full Range of Replicate Sample Analyses Given in Parentheses)

Stratigraphic Unit	Pre-Demonstration Aerobic Plate Counts (CFU/g)	Post-Demonstration Aerobic Heterotrophic Counts <sup>(a)</sup> (6 months after) (MPN/g)	Pre-Demonstration Anaerobic Viable Counts (Cells/g)	Post-Demonstration Anaerobic Heterotrophic Counts <sup>(a)</sup> (6 months after) (MPN/g)
Capillary Fringe	73,564 (19,953 to 398,107)	91,525 (41,000 to 220,000)	199,526 (100,000 to 501,187)	8,055.6 (850 to 410,000)
Upper Sand Unit	690.9 (<316 to 15,849)	313.4 (1.8 to 300,000)	831.8 (39.8 to 100,000)	111.9 (0.3 to 550,000)
Middle Fine-Grained Unit	856.7 (<316 to 12,589)	32.2 (4.6 to 85)	276.4 (0.89 to 31,623)	466.6 (4.6 to 4,800,000)
Lower Sand Unit	8,409.0 (<316 to 158,489)	47.7 (8.5 to 150)	10,000 (251.2 to 501,187)	551 (8.5 to 410,000)

(a) Post-demonstration soil samples were analyzed with MPN technique. CFU = colony-forming units. MPN = most probable number.

In general though, there was no sign in the perimeter wells (outside the SI/E area) of any migration of TCE from the SI/E plot. TCE concentrations in the perimeter wells remained constant or declined. The decline was more noticeable on the north side where the groundwater extraction may have acted to retract the plume toward the source and pull more water from cleaner areas.

The soil parameters that were measured in the SI/E plot showed more discernible trends than the groundwater. As described in Section 5.1, TCE levels in the soil dropped significantly indicating removal of DNAPL mass. Microbial counts in the soil samples varied, but populations did seem to have dropped somewhat in many parts of the SI/E plot. Although microbial populations were reduced, much of the population survived the thermal treatment. In fact, the TOC content of the soil and BOD content of the water declined, indicating that there possibly may have been heightened microbial activity in some parts of the plot due to the steaming. TOC in the plot soil was potentially transformed or oxidized, biotically or abiotically, during the steam injection/extraction. These results are important because natural attenuation of the residual contamination is a key feature of any DNAPL source removal action.

Except for a sharp decrease in hydraulic conductivity in Well PA-17S, there was no noticeable change in the permeability of the aquifer, following the SI/E treatment.

### 5.3 Fate of the TCE-DNAPL Mass in the Demonstration Plot

This part of the assessment was the most difficult because the DNAPL could have taken one or more of the following pathways when subjected to the SI/E treatment:

- TCE recovery in the vapor and groundwater recovery system
- TCE-DNAPL degradation through biological or abiotic mechanisms
- TCE-DNAPL migration to or from surrounding regions
- Potential TCE losses during post-demonstration sampling of hot soil cores.

#### 5.3.1 TCE Recovery in the Vapor Recovery System

Vapor sampling conducted by the SI/E vendor indicates that 7,400 ± 2,200 kg of total TCE was recovered in the vapor extraction system. The ±30% range is necessitated by the uncertainties in the measurement method used by the vendor (Parkinson, 2002). The initial estimate of total TCE mass in the subsurface soil was between 11,150 to 14,150 kg (from pre-demonstration kriging results). The total TCE recovered in the vapor recovery system is between 37 to 87% of the initial TCE mass estimated in the plot. Other possible pathways that the TCE removed may have taken are discussed in subsections 5.3.2 to 5.3.4.

#### 5.3.2 Biotic or Abiotic Degradation of TCE

It is possible that some TCE was reductively dechlorinated due to microbial interactions. The biological sampling (see Section 5.2.4) indicates that the microbes did survive the heat treatment. Levels of *cis*-1,2-DCE, a degradation byproduct, were elevated in some monitoring wells in and around the SI/E plot (see the *cis*-1,2-DCE analysis summary in Table 5-7). On the other hand,

**Table 5-7.** *cis*-1,2-DCE Levels in the Steam Injection Plot and Perimeter Wells

Well ID	Pre-Demonstration (mg/L)	Post-Demonstration (mg/L)
<i>Steam Injection Plot Wells</i>		
PA-16S	<0.002	18.7
PA-16I	0.01	7.6
PA-16D	38.0	52.0
PA-17S	21.0	1.1
PA-17I	260	1.8
PA-17D	36.0	0.2
<i>Steam Injection Perimeter Wells</i>		
PA-14S <sup>(a)</sup>	73.8	21.4
PA-14I	80.0	17.8
PA-14D	2.7	4.2
PA-18S <sup>(b)</sup>	6.4	27.9
PA-18I	<50	10.2
PA-18D	<50	8.8
PA-19S <sup>(b)</sup>	127	2.1
PA-19I	131	34.4
PA-19D	31.3	39.6
BAT-5S	<17	34.0
BAT-5I	<0.01	2.3
BAT-5D	<1.7	9.6

- (a) Well cluster PA-14 S/I/D became clogged after installation; wells were cleared and sampled for pre-demonstration data in June 2001.
- (b) Well clusters PA-18 S/I/D and PA-19 S/I/D were installed and sampled in January 2001 for pre-demonstration data.

*cis*-1,2-DCE levels dropped sharply in some wells (PA-17S/I/D) following the demonstration. TOC levels in the soil and BOD levels in the water declined during the demonstration (see Table 5-8), indicating consumption of carbon sources and heightened microbial activity.

Some abiotic destruction of TCE also is possible. HPO of TCE at higher temperatures, especially in the presence of air, is claimed as one of the features of the SI/E technology. Mineralization of TCE generally is accompanied by elevation of chloride and alkalinity levels in the aquifer. However, because of the large influx (approximately 11 pore volumes) of water from outside the plot, chloride and alkalinity trends attributable to the SI/E technology were difficult to discern (see Tables 5-8 and 5-9). As shown in Figures 5-12 to 5-14, the changes in chloride levels due to the TCE mineralization is very minimal.

### 5.3.3 Potential for DNAPL Migration from the SI/E Plot

The five measurements conducted to evaluate the potential for DNAPL migration to the surrounding aquifer include:

**Table 5-8.** Pre- and Post-Demonstration Inorganic and TOC/BOD Measurements in SI/E Plot Wells

Well ID	Pre-Demo	Post-Demo	Pre-Demo	Post-Demo	Pre-Demo	Post-Demo	Pre-Demo	Post-Demo
	Calcium (mg/L)		Magnesium (mg/L)		Sodium (mg/L)		Potassium (mg/L)	
PA-16S	27.7	88	<2	17	45.3	33.1	1,560	134
PA-16I	30.5	63.4	3.7	20.1	42.4	31.3	511	242
PA-16D	111	86.8	179	37.9	72.4	184	1,600	92.4
PA-17S	108	5.3	73.6	1.51	189	159	330	335
PA-17I	92.6	93.5	101	15.7	213	67.8	32.6	217
PA-17D	89.1	46.9	100	19.1	147	72.8	103	1,860
	Chloride (mg/L)		NO <sub>3</sub> -NO <sub>2</sub> (mg/L)		Sulfate (mg/L)		Alkalinity as CaCO <sub>3</sub> (mg/L)	
PA-16S	<1,000	89	NA	<0.5	<1,000	95.6	661	361
PA-16I	42.8	86	<0.1	<0.5	104	90.9	380	468
PA-16D	415	313	<0.1	<0.5	681	121	2,500	329
PA-17S	297	160	<0.1	<1.0	293	360	1,430	248
PA-17I	448	93	<0.1	<1.0	120	466	422	193
PA-17D	3.5	144	<0.1	<1.0	202	1,960	459	445
	TDS (mg/L)		BOD (mg/L)		TOC (mg/L)			
PA-16S	2,470	728	<3	<6	1,680	61.5		
PA-16I	814	886	13.8	<6	30.5	56		
PA-16D	4,510	1,070	84	<6	134	73.5		
PA-17S	1,740	1,250	70	6.8	74.2	26.8		
PA-17I	1,360	1,200	7.4	4.2	2.1	29.2		
PA-17D	1,200	4,650	22.8	16.6	19.5	79.5		

Shaded cells denote that the post-demonstration concentration level has increased by more than 25% of the pre-demonstration concentration after steam injection.

**Table 5-9.** Chloride and TDS Measurements in Monitoring Wells Surrounding the SI/E Plot

Well ID	Chloride (mg/L)		Total Dissolved Solids (mg/L)	
	Pre-Demo	Post-Demo	Pre-Demo	Post-Demo
<i>Steam Injection Perimeter Wells</i>				
PA-14S	101	175	772	870
PA-14I	156	120	870	669
PA-14D	4,790	2,020	10,700	3,620
PA-18S <sup>(a)</sup>	NA	221	NA	1,290
PA-18I <sup>(a)</sup>	NA	181	NA	933
PA-18D <sup>(a)</sup>	NA	165	NA	817
PA-19S <sup>(a)</sup>	NA	175	NA	354
PA-19I <sup>(a)</sup>	NA	NA	NA	NA
PA-19D <sup>(a)</sup>	NA	237	NA	665
BAT-5S	436	125	6,840	925
BAT-5I	566	23.6	5,380	355
BAT-5D	752	340	6,140	5,000

(a) Well clusters PA-18 and PA-19 were installed in January 2001 after the initial pre-demonstration sampling event. Data are not available.

NA = Not available.

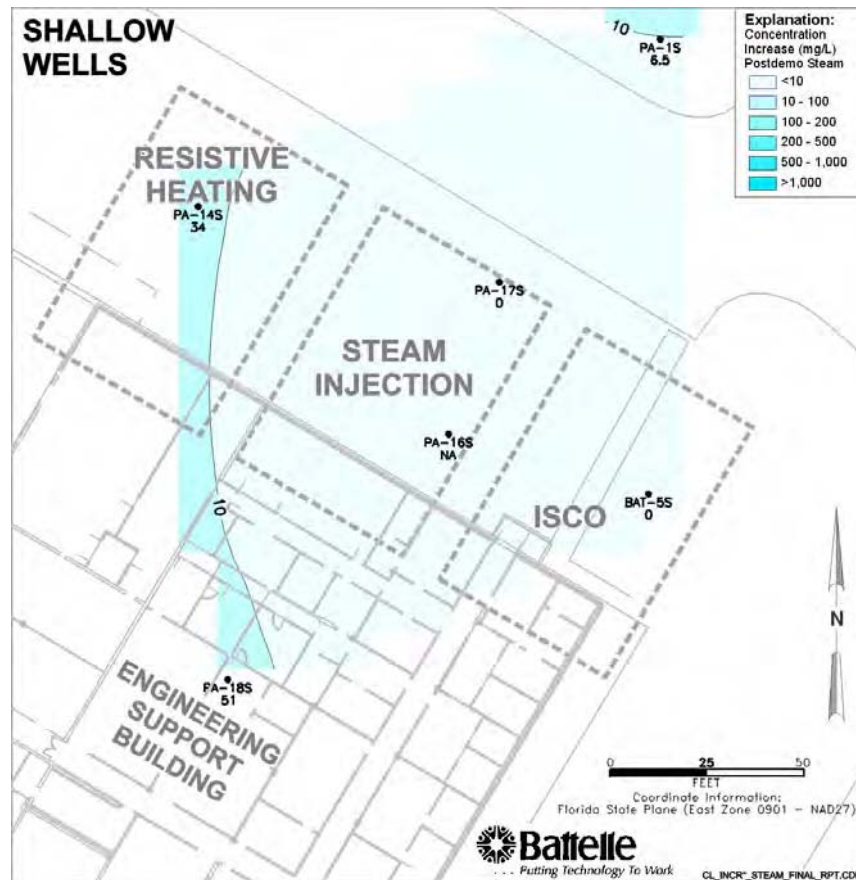
- Hydraulic gradient in the aquifer
- Temperature measurements in the SI/E plot and vicinity
- TCE measurements in perimeter wells

- TCE concentrations in surface emissions to the atmosphere
- TCE concentrations in the semi-confined aquifer wells.

### 5.3.3.1 Hydraulic Gradients

Hydraulic gradients (water-level measurements) can be used to determine the potential for movement of dissolved and solvent phase constituents into and out of the demonstration plots. As mentioned in Section 5.2, pre-demonstration hydraulic gradients in the Launch Complex 34 aquifer are relatively flat in all three stratigraphic units. After the demonstration, hydraulic gradients (see Figures 5-15 to 5-17) were measured in February 2002 shortly after the injection and vacuum extraction systems were shut off.

During the demonstration, the monitoring wells inside the plot were not available for monitoring. However, during one monitoring event (November 2001) while steam was being injected, some data indicated the presence of radially inward gradients toward the SI/E plot (see Figures 5-18, 5-19, and 5-20). This evaluation was hampered by the fact that water-level measurements could



**Figure 5-12.** Increase in Chloride Levels in Shallow Wells (Sampled December 2000 to February 2002)



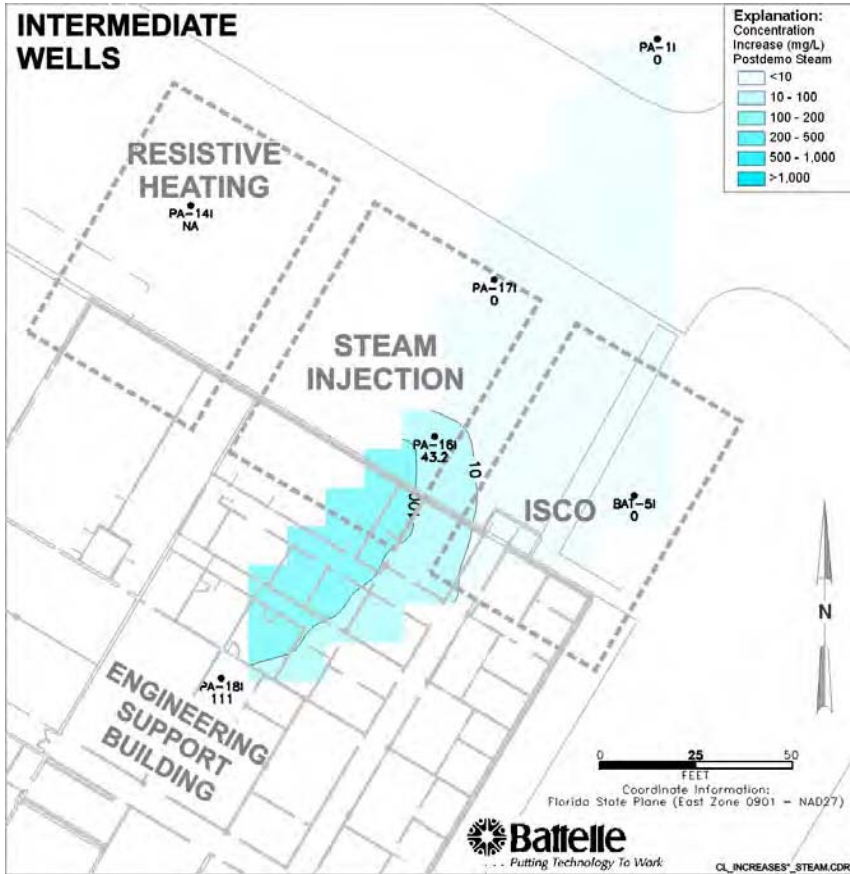


Figure 5-13. Increase in Chloride Levels in Intermediate Wells (Sampled December 2000 to February 2002)

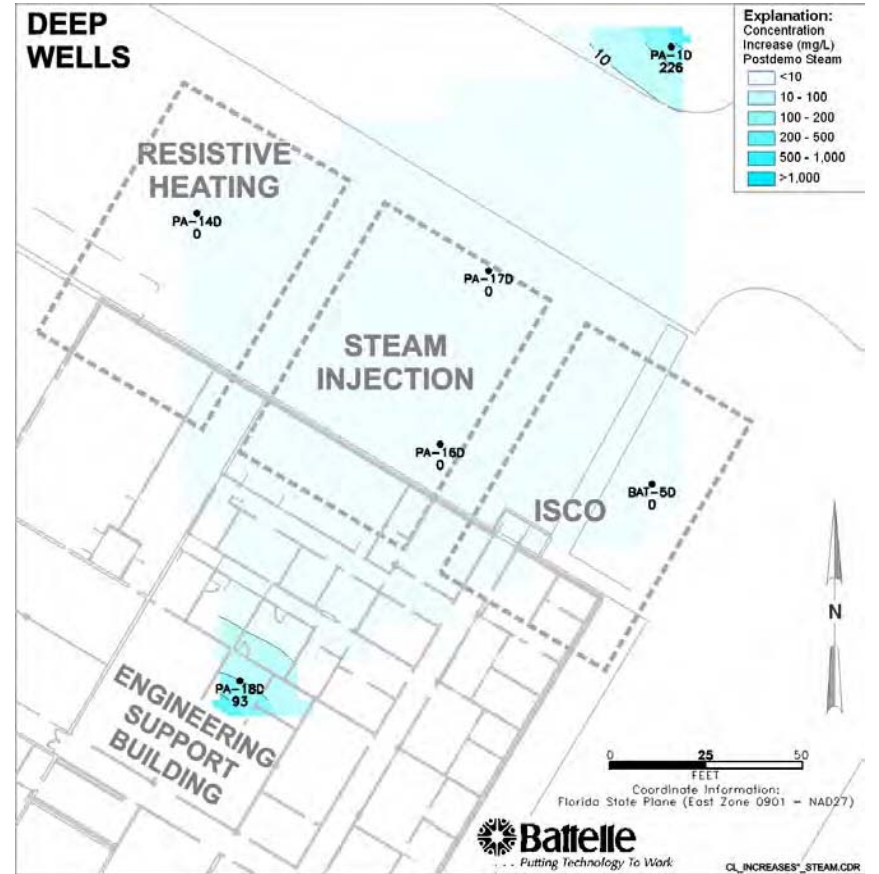


Figure 5-14. Increase in Chloride Levels in Deep Wells (Sampled December 2000 to February 2002)

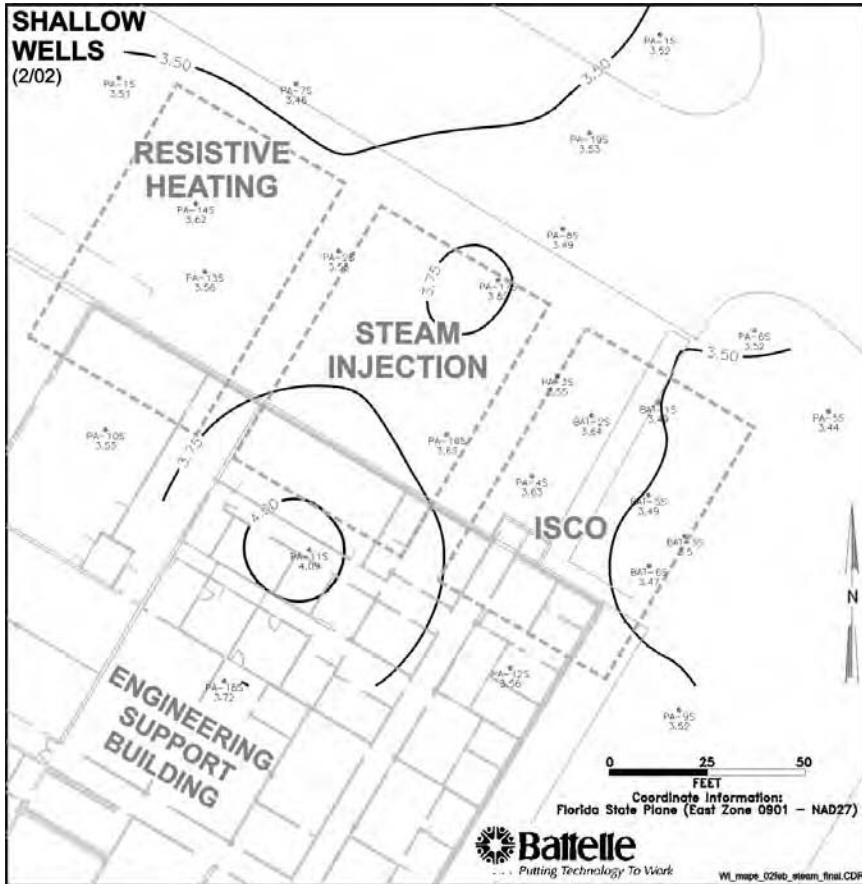


Figure 5-15. Water Levels Measured in Shallow Wells (February 2002)

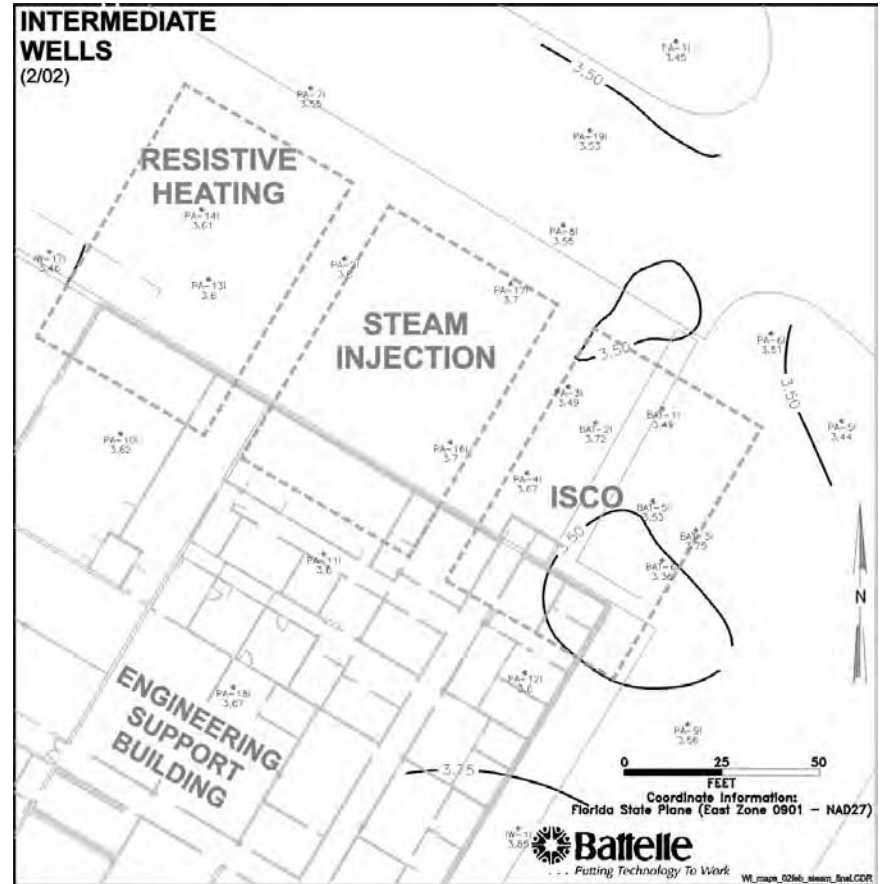


Figure 5-16. Water Levels Measured in Intermediate Wells (February 2002)

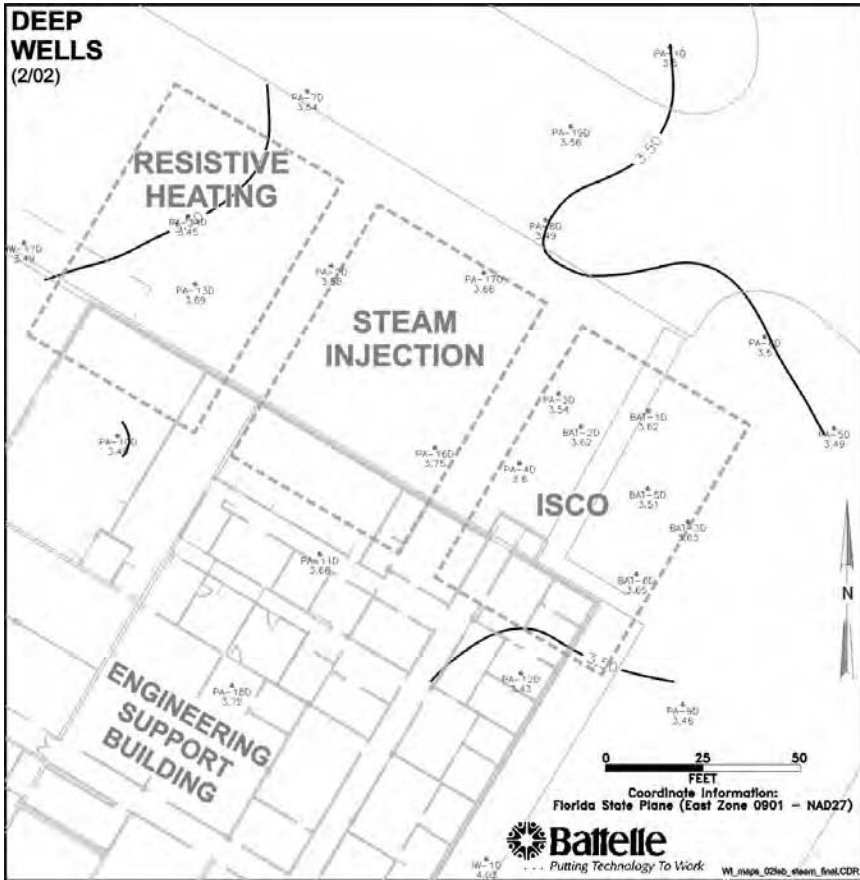


Figure 5-17. Water Levels Measured in Deep Wells (February 2002)

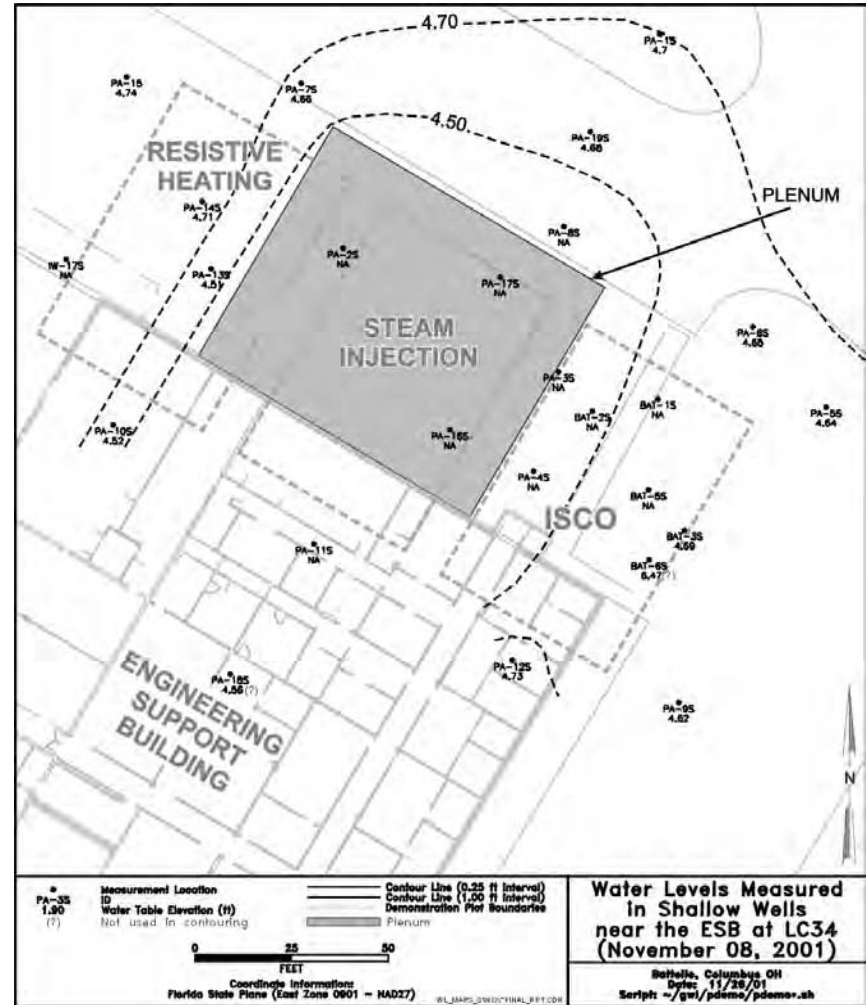


Figure 5-18. Water Levels Measured in Shallow Wells (November 8, 2001)

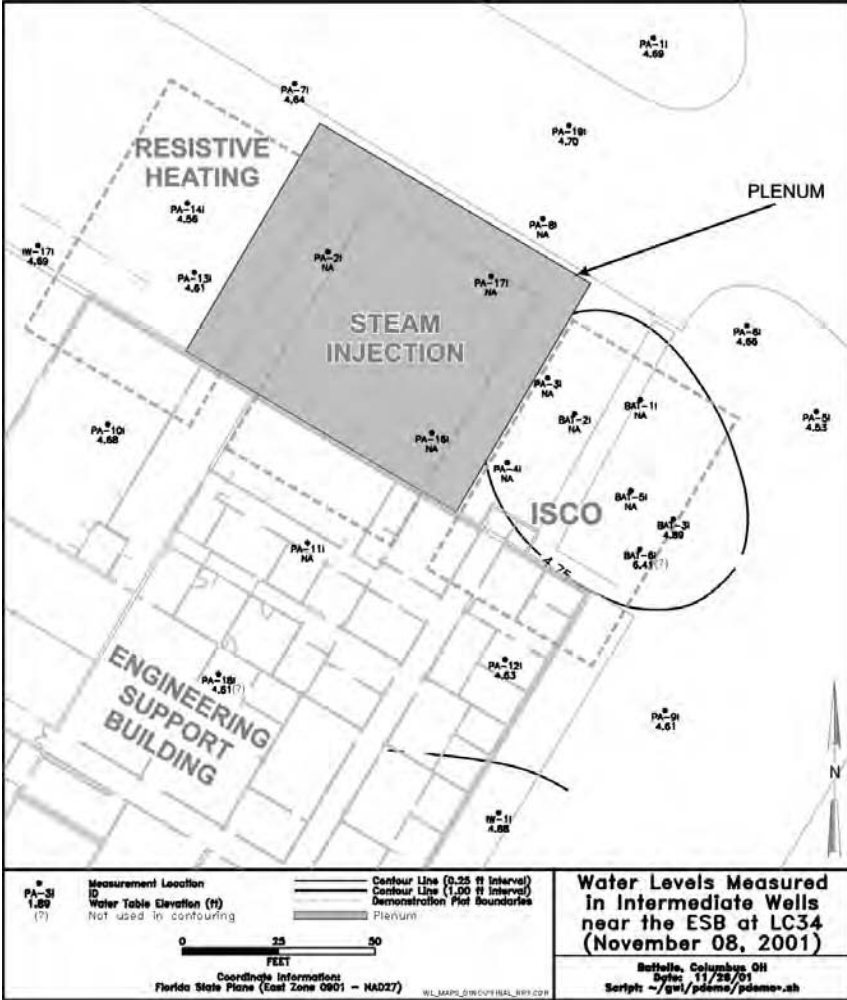


Figure 5-19. Water Levels Measured in Intermediate Wells (November 8, 2001)

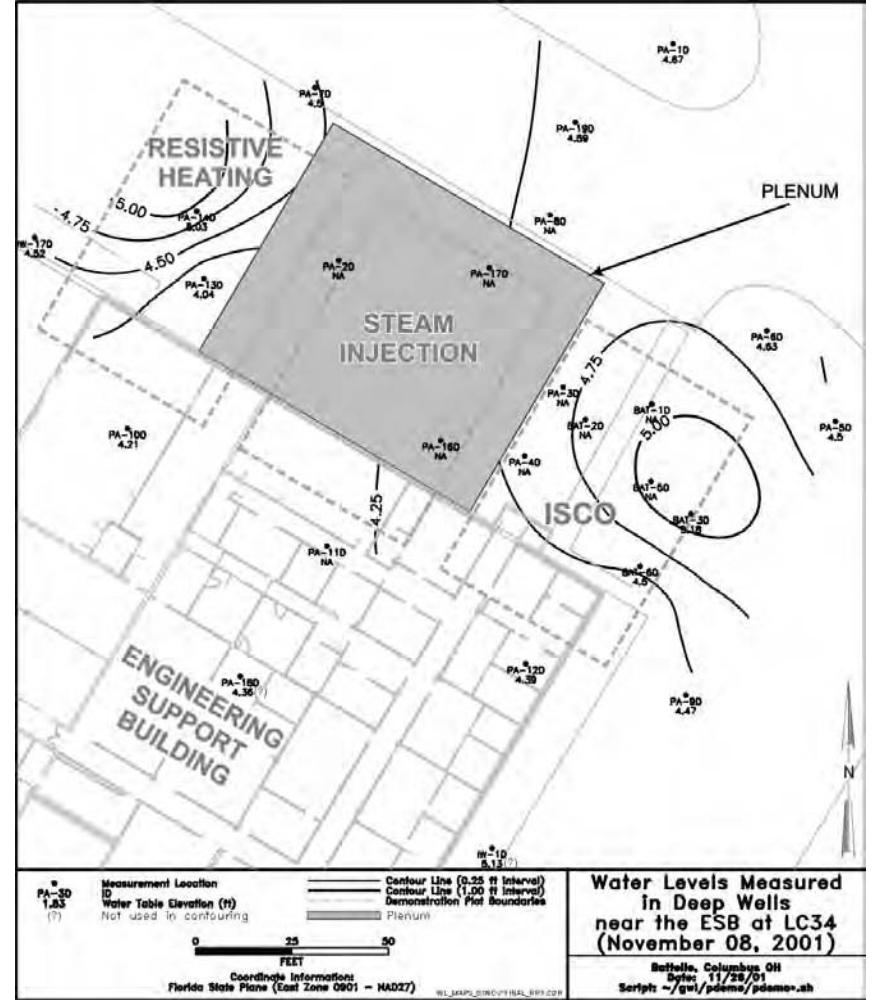


Figure 5-20. Water Levels Measured in Deep Wells (November 8, 2001)

not be conducted inside the plot. However, inward gradients likely occurred because water was being extracted at an average rate of 22 gpm inside the plot to maintain hydraulic control. Therefore, it is unlikely that any outward gradients from the SI/E plot caused any DNAPL to migrate outside.

### 5.3.3.2 Temperature

Temperature measurements conducted with a downhole thermocouple and the preconstructed thermocouples in the surficial aquifer in November 2001, are shown in Figures 5-6, 5-7, and 5-8 for the shallow, intermediate, and deep wells, respectively, in the steam injection plot and vicinity. As expected, the largest increase in temperature was in the middle of the steam injection plot. Temperature increased noticeably in all thermocouples (TMP-6 through TMP-13 installed by Battelle, TetraTech, and FSU) but remained at pre-demonstration levels in the perimeter and distant wells. The temperature plots measured by the vendor are shown in Appendix F.

Post-demonstration soil cores collected in the SI/E plot and on the south side of the plot (inside the Engineering Service Building) also were warm, indicating that heat generated by the steam injection had spread to the surrounding regions through conduction and/or convection. The temperature data indicate that DNAPL in the SI/E plot and vicinity had the potential to be mobilized by convection and hydraulic pressure. Generally, residual DNAPL cannot be mobilized at ambient temperatures; heating reduces surface tension of the DNAPL, making it more amenable to movement in the aquifer. However, DNAPL migration depends on the amount and distribution of DNAPL present.

### 5.3.3.3 TCE Measurements in Perimeter Wells

TCE measurements also were conducted in perimeter and distant wells for the groundwater monitoring (see Appendix C). Figures 5-21 and 5-22 show the TCE trends observed in the **perimeter wells**. During the SI/E application, TCE levels in the perimeter wells showed very little change except in PA-19S, where TCE levels declined considerably. This could be because continuous extraction of groundwater may have caused the plume on the north side of the plot to retract toward the source, thus drawing cleaner water from more distant parts of the aquifer. No free-phase DNAPL was observed in any of the perimeter wells. Figure 5-23 shows the **TCE** trends observed in **distant well** cluster PA-1, which is in a northeast direction from the plot. TCE levels in PA-1S and PA-1I remained relatively constant, but TCE levels in PA-1D rose. The reason for this increase is not clear.

### 5.3.3.4 Surface Emission Tests

Surface emission tests were conducted (as described in Appendix F) to evaluate the possibility of solvent losses to the atmosphere. During the demonstration, surface emission tests were done just beyond the boundary of the plenum. Before and after the demonstration, surface emission tests were conducted inside the SI/E plot. Background samples were collected in areas distant from the DNAPL source areas, where the aquifer was expected to be relatively clean. Ambient air samples were collected at the same locations as the regular samples, except that the sample collection canister was held at shoulder level above the ground surface. Figure F-1 in Appendix F shows the sample locations where the surface emissions samples were collected.

As shown in Table 5-10, there was a noticeable increase in TCE levels in the surface emissions, compared to the background levels, during the demonstration and after the demonstration. This indicated that some loss of TCE to the ambient air occurred around the plot during the treatment and that the vapor extraction system was not 100% efficient. Some surface emission samples collected near the infiltration gallery indicated elevated levels of TCE during the demonstration. It is possible that the warm temperature of the discharged water in the infiltration gallery led to volatilization, which could explain the elevated levels of TCE found in surface emission samples collected near the gallery. After the demonstration and after the vapor recovery system had been shut down, surface emissions tests continued to show elevated levels of TCE. This indicated that the aquifer, which was still heated, was continuing to vaporize TCE. It should be noted that at no time were TCE levels in ambient air present at levels harmful to on-site personnel.

### 5.3.3.5 Potential for DNAPL Migration to the Lower Clay Unit and Semi-Confined Aquifer

The geologic logs of the three semi-confined aquifer wells are provided in Appendix A. Their locations are shown in Figure 4-8 in Section 4.3.1. Table 5-11 shows the depths and thicknesses of the Lower Clay Unit (aquitar) and the screened intervals of the wells installed. Figure 5-24 is a geologic cross section across the three demonstration plots showing the varying thickness of the aquitar. The aquitar is thinnest in the resistive heating plot, where it is only about 1.5 ft thick. The thickness of the aquitar increases in the eastward and northward directions.

Split-spoon samples of the Lower Clay Unit show it to be a medium gray-colored clay with moderate to high plasticity. The clay is overlain by a silt zone which in turn is overlain by sand. The entire sand-silt-clay sequence

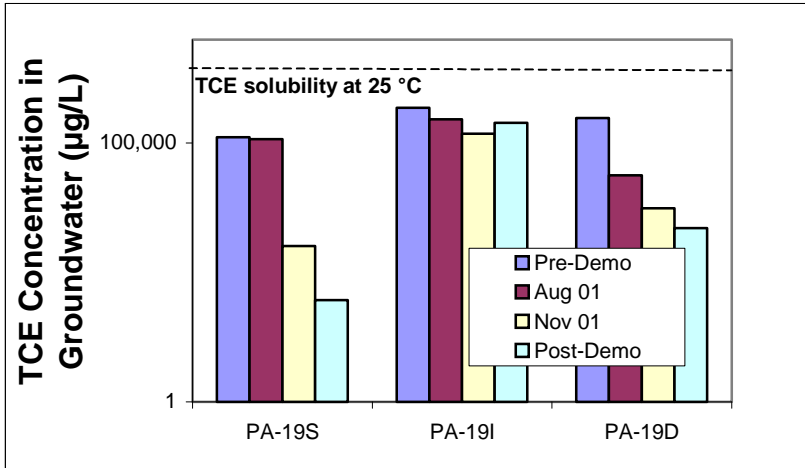
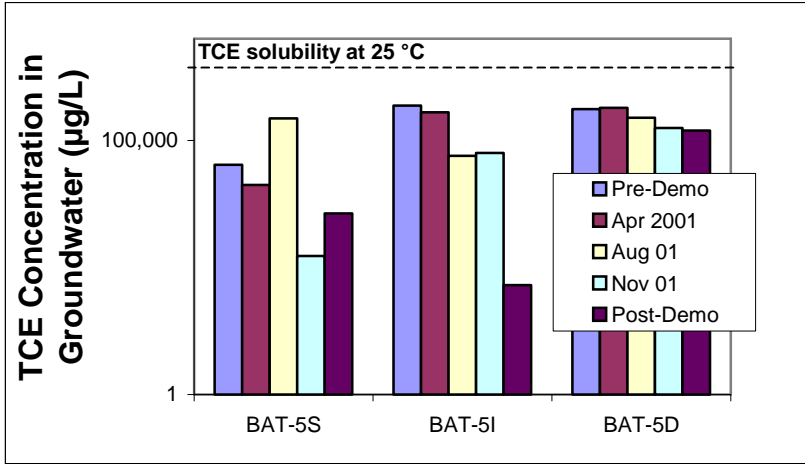


Figure 5-21. Dissolved TCE Levels (µg/L) in Perimeter Wells on the Eastern (BAT-5) and Northern (PA-19) Side of the SI/E Plot

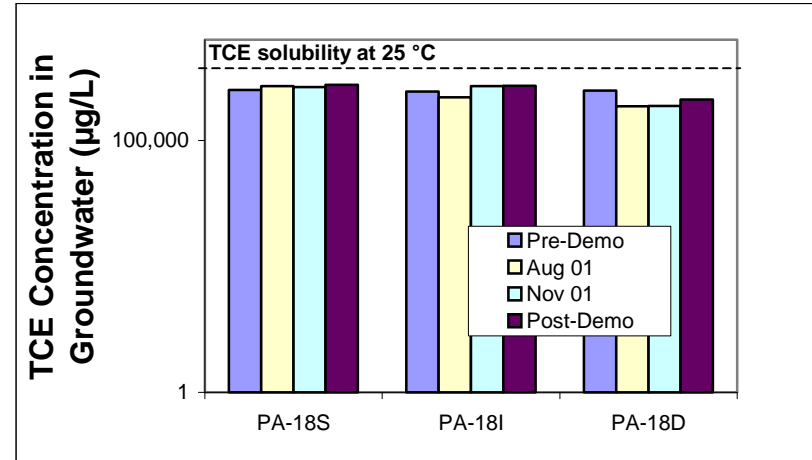
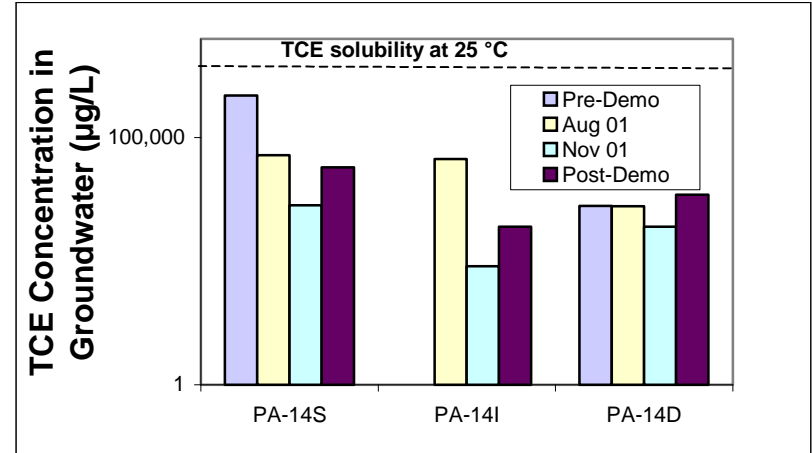
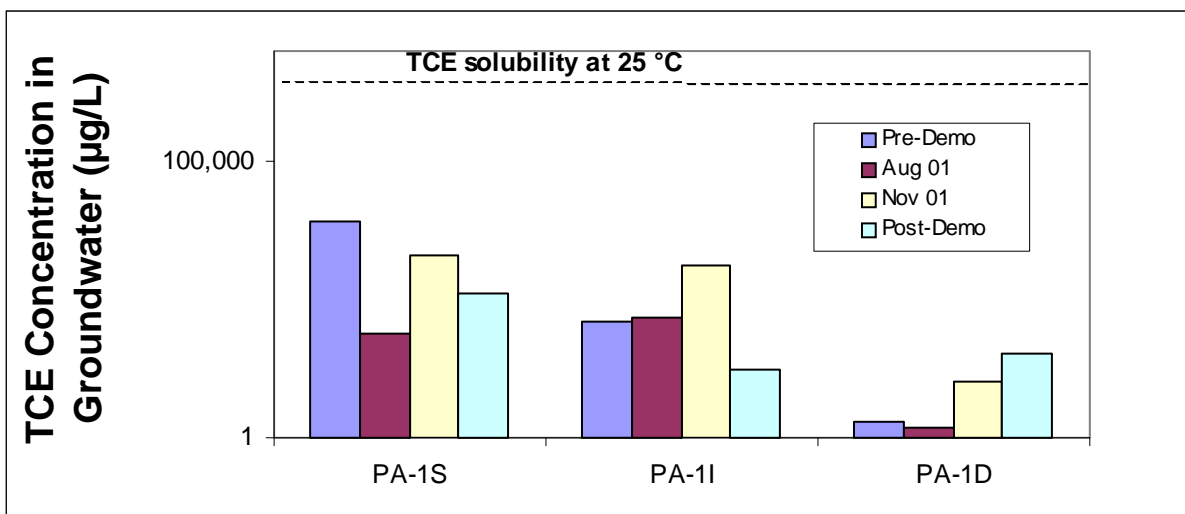


Figure 5-22. Dissolved TCE Levels (µg/L) in Perimeter Wells on the Southern (PA-18) and Western (PA-14) Sides of the SI/E Plot



**Figure 5-23.** Dissolved TCE Levels ( $\mu\text{g/L}$ ) in Distant Well (PA-1) on the Northeast Portion of the SI/E Plot

**Table 5-10.** Surface Emissions Results from the SI/E Demonstration

Sample ID	Sample Date	TCE ppb (v/v)	Sample ID	Sample Date	TCE ppb (v/v)
<i>Pre-Demonstration</i>					
SI-SE-33	12/04/2000	1.2	SI-SE-35	12/05/2000	<0.40
SI-SE-34	12/05/2000	1.1			
<i>During Demonstration</i>					
SI-SE-1	08/27/2001	<37	SI-SE-9	11/06/2001	<0.060
SI-SE-2	08/27/2001	0.45	SI-SE-10	11/07/2001	<0.060
SI-SE-3	08/27/2001	<0.34	SI-SE-11	11/07/2001	<0.060
SI-SE-4	08/27/2001	<0.34	SI-SE-12	11/07/2001	<0.060
SI-SE-5	08/28/2001	51	SI-SE-13	11/08/2001	40
SI-SE-6	08/28/2001	<49	SI-SE-14	11/08/2001	45
SI-SE-7	11/06/2001	<0.060	SI-SE-15	11/08/2001	21
SI-SE-8	11/06/2001	<0.060			
<i>Post-Demonstration</i>					
SI-SE-16	02/18/2002	33	SI-SE-18	02/18/2002	280
SI-SE-17	02/20/2002	15	SI-SE-19	02/20/2002	180
<i>Background</i>					
DW-SE-36	12/06/2000	<0.40	DW-SE-43	11/06/2001	0.26
DW-SE-37	12/06/2000	0.49	DW-SE-44	11/06/2001	0.26
DW-SE-38	12/07/2000	<0.40	DW-SE-45	11/06/2001	0.17
DW-SE-40	11/05/2001	<0.060	DW-SE-47	02/18/2002	<0.03
DW-SE-41	11/05/2001	<0.060	DW-SE-48	02/20/2002	<0.03
DW-SE-42	11/05/2001	<0.060			
<i>Ambient Air at Shoulder Level<sup>(a)</sup></i>			<i>Near the Infiltration Gallery</i>		
DW-SE-39	11/06/2001	<0.060	SI-SE-7	8/28/2001	110
DW-SE-46	02/18/2002	<0.03	SI-SE-8	8/28/2001	74

(a) A Summa canister was held at shoulder level to collect an ambient air sample representative of the local air quality.

ppb (v/v): parts per billion by volume.

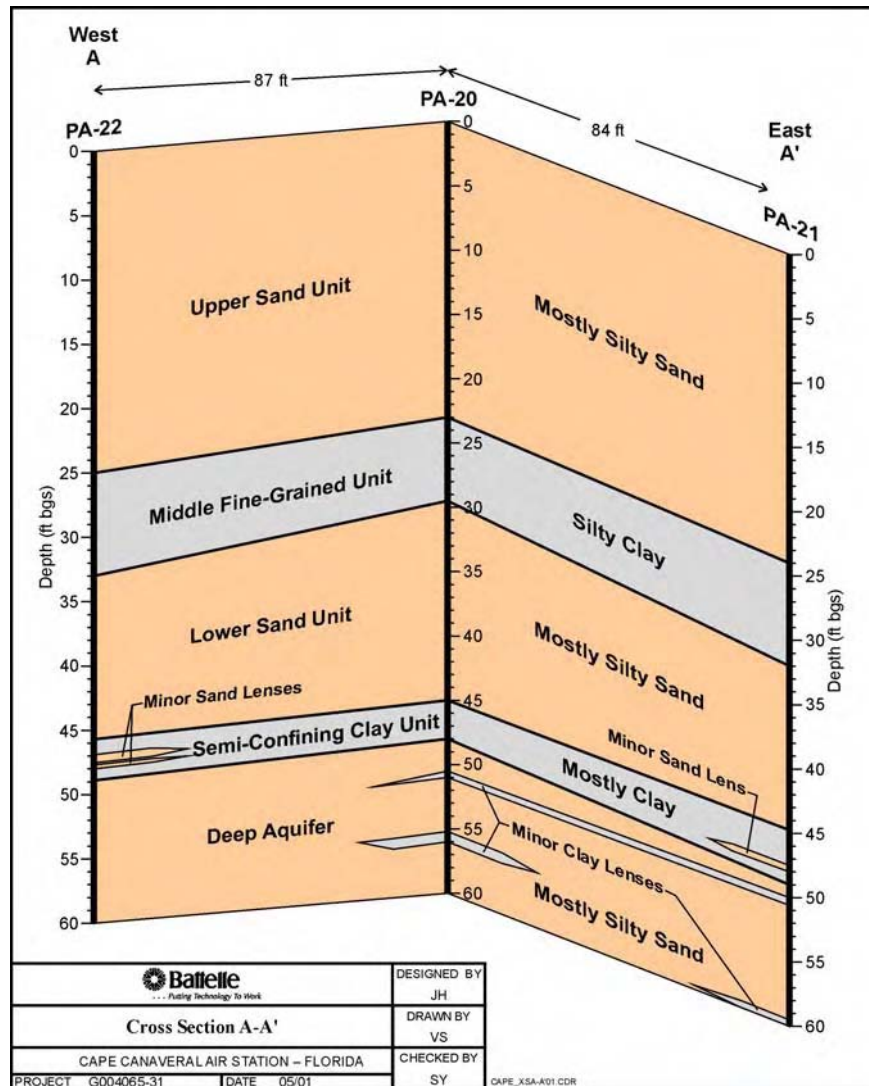
**Table 5-11. Semi-Confined Aquifer Well Screens and Aquitard Depth**

Well ID	Screened Interval (ft bgs)	Depth where Aquitard was Encountered (ft bgs)	Thickness of Aquitard (ft)
PA-20 (north of S/E plot in parking lot)	55-60	45.5	3
PA-21 (in ISCO plot)	55-60	44.8	2.8
PA-22 (in resistive heating plot)	55-60	45.8	3 <sup>(a)</sup>

(a) The confining unit clay contained thin sand lenses. The thickness is overall 3-ft thickness, including the interspersed sand lenses. The effective thickness of the aquitard is approximately 1.5 ft.

appears to be gradational and fining downward with respect to grain size. In PA-21, the overlying sand and silt intervals appeared to be more contaminated (PID reading above 2,000 ppm). The clay itself was generally less contaminated, but lower PID readings in the clay may be due to the fact that volatilization of organic contaminants in clayey soils occurs more slowly. Sandier soils were encountered directly below the confining unit. Only at the PA-20 well did soils underlying the confining unit appear to be clean.

Soil samples were collected for lab analysis from each split spoon. Care was taken to collect soil samples of each 2-ft interval from the retrieved soil core. Multiple samples were collected in cases where both clays and sand were recovered in a spoon. PID readings exceeded 1,000 ppm (or more) at both the PA-21 and PA-22



**Figure 5-24. Geologic Cross Section Showing Lower Clay Unit and Semi-Confined Aquifer**



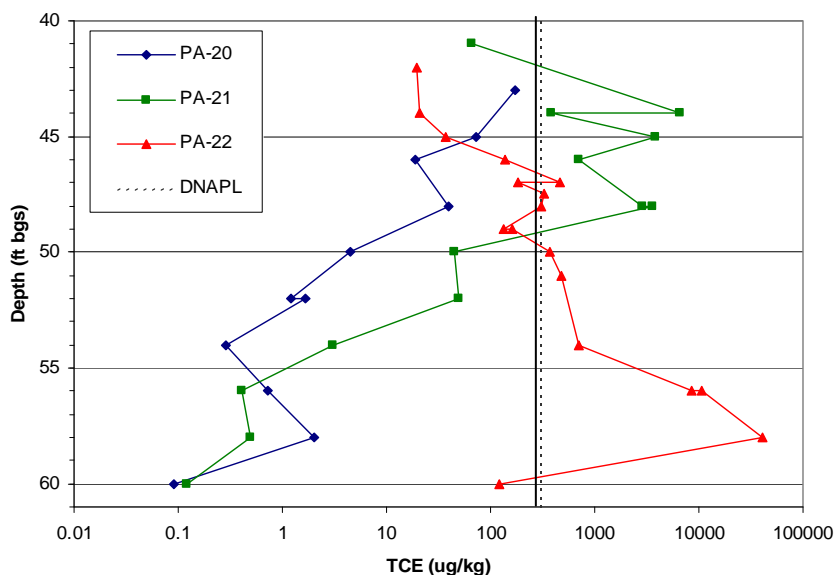
locations both above and below the confining unit. Visual observations of clay samples indicated that the clay has low permeability. Table 5-12 and Figure 5-25 show the vertical distribution of the TCE analysis results of the soil samples collected at the depths of approximately 40 to 60 ft bgs.

**Table 5-12.** TCE Concentrations in Deep Soil Borings at Launch Complex 34

Approximate Depth (ft bgs)	TCE (mg/kg) <sup>(a)</sup>		
	SB-50 (PA-20)	SB-51 (PA-21)	SB-52 (PA-22)
39-40			
40-41		66	
41-42			20
42-43	174	6,578	
43-44			21
44-45	72	3,831	37
45-46	19	699	138
46-47			466
47-47.5	39	2,857	330
47.5-48			310
48-49	5	46	132
49-50			367
50-51	1	49	473
51-52			707
52-53	<1	3	
53-54			
54-55	<1	<1	8,496; 10,700
55-56			
56-57	2	<1	40,498
57-58			
58-59	<1	<1	122
59-60			

(a) Shaded cells represent the Lower Clay Unit between the surficial and confined aquifers.

Soil borings SB-50, SB-51, and SB-52 are the borings done for wells PA-20, PA-21, and PA-22 (see Figure 4-8 in Section 4.3.1). Soil boring SB-50, in the parking lot, did not show any concentrations approaching the DNAPL threshold of 300 mg/kg at any depth. Soil boring SB-51, in the ISCO plot, indicated the presence of DNAPL in the Lower Sand Unit and Lower Clay Unit, but relatively low levels of TCE in the confined aquifer. Soil boring SB-52, in the resistive heating plot, showed the presence of DNAPL in the Lower Clay Unit, the semi-confining unit from the aquifer below; TCE levels were as high as 40,498 mg/kg in the semi-confined aquifer (56-58 ft bgs) at this location. Previously, no monitoring was done in the semi-confining layer or in the semi-confined aquifer before the demonstration because of NASA's concern about breaching the relatively thin aquitard. Subsequently, these three wells were drilled because nonintrusive (seismic) monitoring indicated the possibility of DNAPL being present in the semi-confined aquifer (Resolution Resources, 2000). Because there is no information regarding the state of the confined aquifer before the demonstration, it is unclear whether the DNAPL had migrated to the semi-confined aquifer before or during the demonstration. Heating could have lowered the surface tension of DNAPL, making it easier to penetrate the Lower Clay Unit. However, given the strong electrical heating achieved in the Lower Sand Unit (of the surficial aquifer) that would tend to volatilize TCE and move it upward, the greater probability is that the DNAPL penetrated the Lower Clay Unit and entered the semi-confined aquifer before the demonstration. Although the Lower Clay Unit is approximately 3 ft thick in other parts of Launch Complex 34, it appears to contain sand lenses that reduce the effective thickness of the aquitard to



**Figure 5-25.** TCE Concentrations in Soil with Depth from Semi-Confined Aquifer Soil Borings

approximately 1.5 ft near PA-22, under the resistive heating plot. Therefore, the barrier to gradual downward migration over time is geologically weaker in this region.

Table 5-13 summarizes the results of the CVOC analysis of the groundwater from the semi-confined aquifer. CVOC measurements were taken on seven occasions over a one-year period to evaluate natural fluctuation.

Groundwater samples from the semi-confined aquifer wells reinforce the soil sampling results. High levels of TCE approaching solubility (free-phase DNAPL) were observed in PA-22 where high soil concentrations were also observed (Yoon et al., 2002). In wells PA-20 and PA-21, relatively lower CVOC concentrations were measured, suggesting that the semi-confining clay layer is more competent in these areas and free-phase contamination has not migrated into the semi-confined aquifer in this area. Elevated levels of *cis*-1,2-DCE (all three wells) and vinyl chloride (PA-21) also were found in the semi-confined aquifer wells. Overall, CVOC concentrations appear to be relatively stable over time in all three wells, namely, PA-20, PA-21, and PA-22 (see Figure 5-26).

Since the S/E demonstration started in July 2001, there has been no noticeable increase in TCE, *cis*-1,2-DCE, or vinyl chloride levels in the semi-confined aquifer wells.

Therefore, there is no indication from the semi-confined aquifer wells that any downward DNAPL migration occurred through the Lower Clay Unit during the demonstration, although the time frame for these measurements is relatively short. The constant extraction of groundwater at 22 gpm in the surficial aquifer makes it likely that an upward gradient existed across the Lower Clay Unit during the steam injection. In addition, the co-injection of air along with the steam may have mitigated any tendency of the DNAPL to migrate downward.

Table 5-14 shows the field parameter measurements in the confined aquifer wells. Based on the relatively low DO and ORP levels, the semi-confined aquifer appears to be anaerobic. The groundwater has a neutral-to-slightly-alkaline pH. The temperature was in the range of 26 to 28°C in PA-20 and PA-21, but in PA-22, which is below the resistive heating plot, the temperature during both events was elevated (44 to 49°C). The higher temperature in this well may be due to heat conduction from the resistive heating application in the surficial aquifer, although migration of heated water from the surficial aquifer through the thin Lower Clay Unit cannot be ruled out.

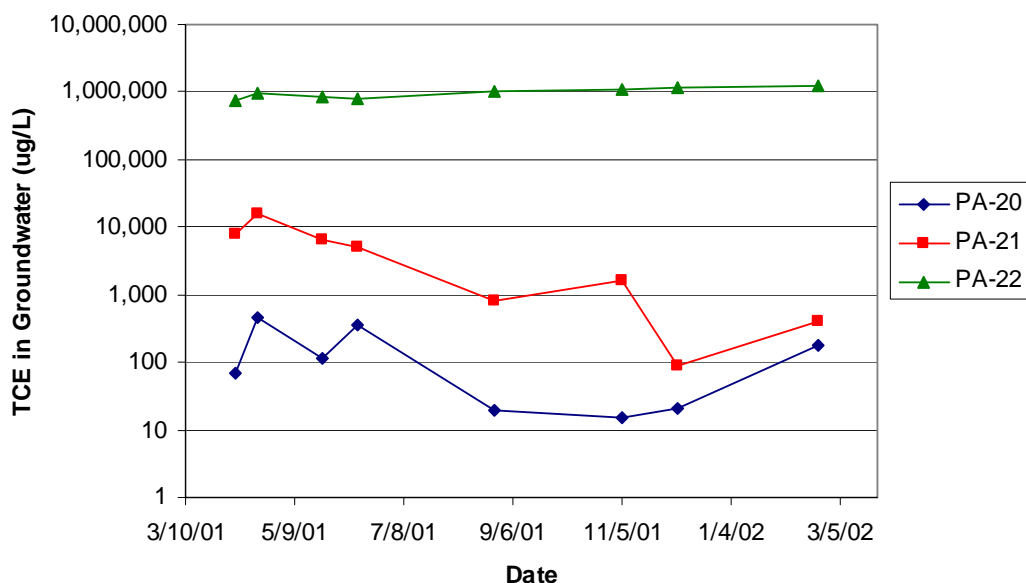
Table 5-15 shows the inorganic measurements in the semi-confined aquifer wells. The geochemical composition of the groundwater appears to be relatively constant

**Table 5-13.** Results of CVOC Analysis in Groundwater from the Semi-Confined Aquifer

TCE							
Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	67.1	447	111	350	19	15	181
PA-20-DUP	58.4	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	7,840	15,700	6,400	5,030	790	1,640	416
PA-22	736,000	980,000	877,000	801,000	1,000,000	1,110,000	1,240,000
PA-22-DUP	N/A	N/A	939,000	N/A	1,000,000	N/A	N/A
<i>cis</i> -1,2-DCE							
Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	21.7	199	37.4	145	10	52	66
PA-20-DUP	18.5	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	1,190	5,790	1,490	1,080	330	5,140	315
PA-22	8,130	8,860	11,000	11,900	12,000 J	14,900	13,300
PA-22-DUP	N/A	N/A	10,700	N/A	12,000 J	N/A	N/A
<i>trans</i> -1,2-DCE							
Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	<0.1	1.45	0.24J	0.38	<1.0	0.48J	0.3J
PA-20-DUP	<0.1	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	<1	51.7	6 J	5	<33	<10	2
PA-22	<100	<1,000	<1,120	<100	<17,000	<100	<1,000
PA-22-DUP	N/A	N/A	<1,090	N/A	<17,000	N/A	N/A
Vinyl Chloride							
Well ID	Feb 2001	Apr 2001	May 2002	Jun 2001	Aug 2001	Nov 2001	Feb 2002
PA-20	<0.1	0.36J	<1.08	<0.1	<2.0	<0.10	<1.0
PA-20-DUP	<0.1	N/A	N/A	N/A	N/A	N/A	N/A
PA-21	<1	4.22	<22.2	<1	<67	1,050	<1.0
PA-22	<100	<1,000	<1,120	<100	<33,000	<100	260J
PA-22-DUP	N/A	N/A	<1,090	N/A	<33,000	N/A	N/A

N/A: Not analyzed.

J: Estimated value, below reporting limit.



**Figure 5-26.** TCE Concentration Trend in Groundwater from Semi-Confined Aquifer

**Table 5-14.** Key Field Parameter Measurements in Semi-Confined Aquifer Wells

Well ID	Date	Temperature (°C)	DO (mg/L)	pH	ORP (mV)
PA-20	04/06/2001	27.2	0.65	7.8	67.4
PA-21	04/06/2001	28.4	0.05	8.84	30.2
PA-22	04/06/2001	48.9	0.36	6.77	39.1
PA-20	06/12/2001	26.2	0.42	7.21	-42.5
PA-21	06/12/2001	26.1	0.47	7.17	-36.5
PA-22	06/12/2001	44.4	0.78	7.25	-33.6

throughout the semi-confined aquifer, and is similar to that of the surficial aquifer.

Table 5-16 shows slug test results in the semi-confined aquifer wells. Slug tests were performed in July 2001 on the wells PA-20, PA-21, and PA-22. The recovery rates of the water levels were analyzed with the Bouwer (1989), Bouwer and Rice (1976), and Hvorslev (1951) methods for slug tests. The Bouwer and Rice methods may be used in confined aquifers where the top of the screen is well below the bottom of the confining layer,

but are more suitable for unconfined aquifers. The Hvorslev method is more applicable in confined aquifers, but may fail to account for the effects of a sand pack. Overall, the hydraulic conductivity (K) estimates range from 0.4 to 29.9 ft/day. The Hvorslev method results are about two to four times higher than estimates using the Bouwer and Rice method. The replicate tests are similar, except for PA-20, where the Hvorslev method differed. It appears that the aquifer conductivity near well PA-20 is greater than near PA-21 and PA-22. The conductivity of wells PA-21 and PA-22 is lower and reflects the silty-clayey sands that were observed during drilling. The conductivities in the semi-confined aquifer are similar to the conductivities measured in the surficial aquifer wells.

Figure 5-27 shows the potentiometric map for water levels measured in April 2001 in the new semi-confined aquifer wells near the demonstration plots at Launch Complex 34. Although very few wells were available to make a positive determination, the water levels measured in four semi-confined aquifer wells (PA-20, PA-21, PA-22, and previously existing well IW-2D1, southeast from the demonstration plots) indicate that there is an

**Table 5-15.** Geochemistry of the Confined Aquifer

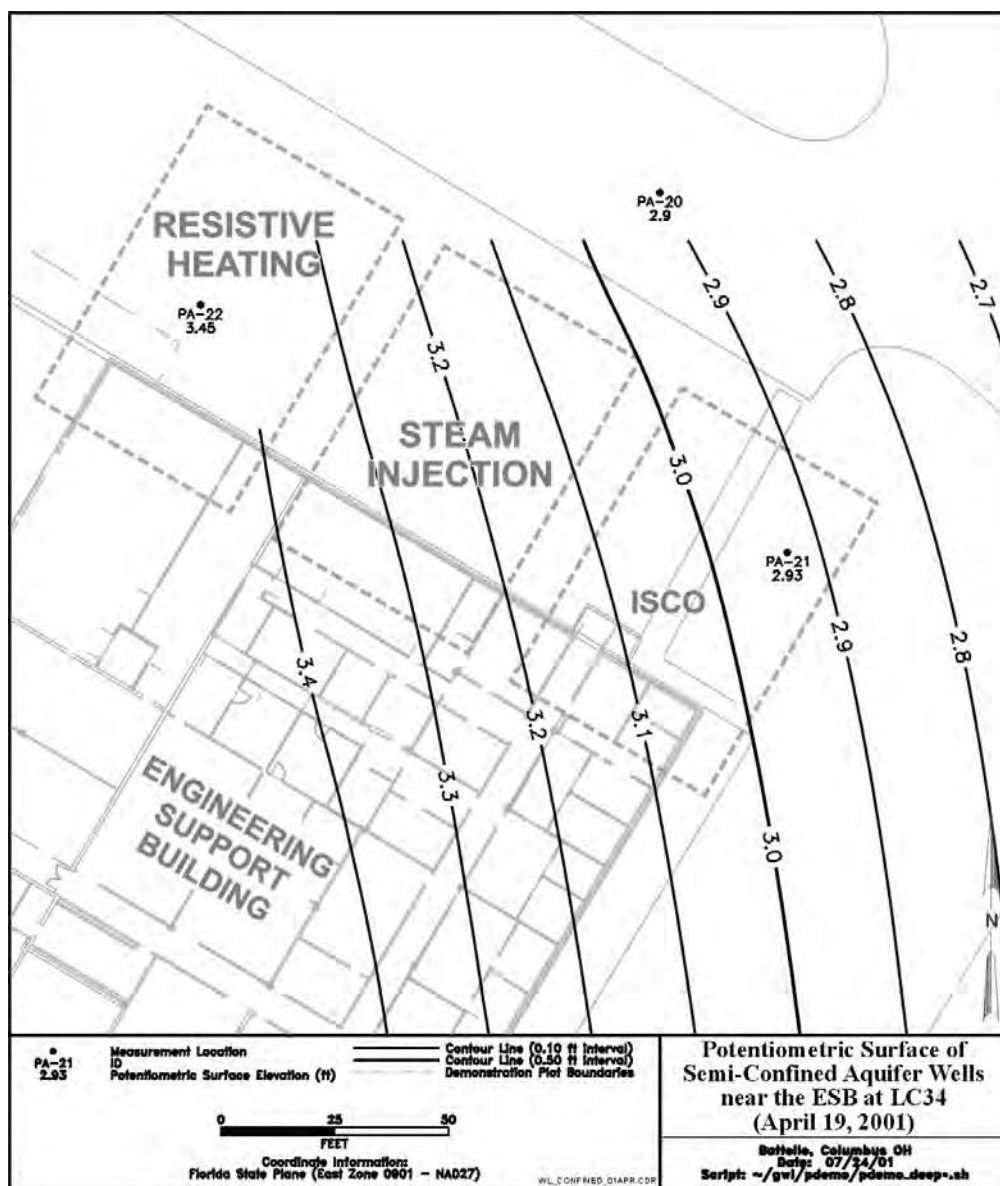
Well ID	Ca (mg/L)	Fe (mg/L)	Mg (mg/L)	Mn (mg/L)	Alkalinity (mg/L as CaCO <sub>3</sub> )	Cl (mg/L)	SO <sub>4</sub> (mg/L)	TDS (mg/L)
PA-20	71.8	<0.1	64	0.0145	180	664	114	1,400
PA-20-DUP	69.4	<0.1	62.8	0.0128	168	680	114	1,410
PA-21	74	<0.1	48	<0.01	196	553	134	1,310
PA-22	120	0.109	79.7	0.0534	276	802	122	1,840

**Table 5-16.** Results for Slug Tests in Semi-Confined Aquifer Wells at Launch Complex 34

Well	Test	Method	K (ft/d)	Response
PA-20	a	Bouwer and Rice	4.1	Good
PA-20	b	Bouwer and Rice	6.9	Good
PA-20	a	Hvorslev	8.6	Good
PA-20	b	Hvorslev	29.9	Good
PA-21	a	Bouwer and Rice	0.7	Excellent
PA-21	b	Bouwer and Rice	0.8	Excellent
PA-21	a	Hvorslev	1.1	Excellent
PA-21	b	Hvorslev	1.1	Excellent
PA-22	a	Bouwer and Rice	0.4	Excellent
PA-22	b	Bouwer and Rice	0.5	Excellent
PA-22	a	Hvorslev	1.5	Excellent
PA-22	b	Hvorslev	1.1	Excellent










eastward or northeastward gradient, similar to the regional gradient observed in the surficial aquifer. The gradient and magnitude are summarized in Table 5-17.

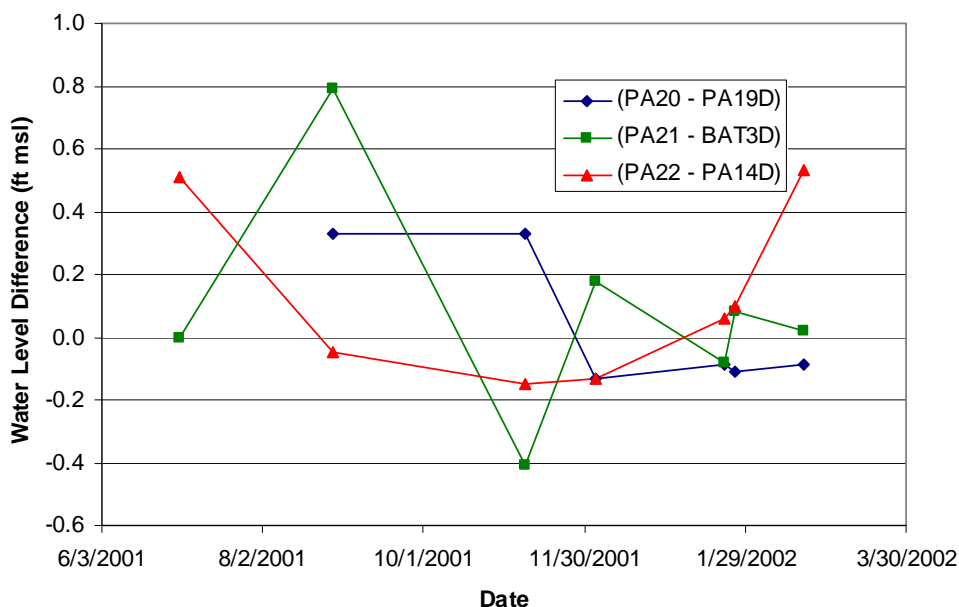
Figure 5-28 displays vertical gradients from paired wells between nearby surficial aquifer wells and the newly installed wells (PA-20 to PA-22). A positive vertical gradient suggests upward flow from the deep aquifer to the surficial aquifer, which would inhibit downward migration of contamination. A negative gradient would promote downward migration. As shown in Figure 5-28, it appears that the vertical gradient fluctuates, beginning as an upward gradient when the wells were installed, changing to a downward gradient in Fall 2001, and finally recovering to an upward gradient.



**Figure 5-27.** Hydraulic Gradient in the Semi-Confined Aquifer (April 19, 2001)

**Table 5-17.** Summary of Gradient Direction and Magnitude in the Semi-Confined Aquifer

Date	4/19/01	5/24/01	7/2/01	8/28/01	11/8/01	12/4/01	1/21/02	1/25/02	2/20/02
Direction	ENE 	E 	ENE 	SW 	NE 	NW 	ESE 	ESE 	ENE 
Magnitude (ft/ft)	0.0046	0.0056	0.0052	0.0033	0.0028	0.0013	0.0014	0.0013	0.0026



**Figure 5-28.** Vertical Gradients from the Spatially Neighboring Paired Wells between the Surficial Aquifer and the Semi-Confined Aquifer

In summary, the following were the key results and conclusions from the installation of three semi-confined aquifer wells at Launch Complex 34:

- Use of the two-stage (dual-casing) drilling and completion process led to the installation of three semi-confined aquifer wells that appeared to be sealed from the surficial aquifer above.
- At all three locations, the Lower Clay Unit occurs at approximately 45 ft bgs and is approximately 3 ft thick; at PA-22, located in the resistive heating plot, the Lower Clay Unit was found to contain sand lenses that appeared to reduce the effective thickness of the aquitard.
- Groundwater sampling in the three semi-confined aquifer wells confirmed that dissolved-phase CVOCs were present in the semi-confined aquifer at all three locations.
- At PA-20, in the parking lot north of the demonstration plots, no DNAPL was present in any of the soil samples.
- At PA-21, in the ISCO plot, soil analysis indicated that DNAPL was present both in the Lower Clay Unit and in the Lower Sand Unit, immediately above the aquitard. No DNAPL was found in the semi-confined aquifer at this location.
- At PA-22 in the resistive heating plot, PID screening and field extraction/laboratory analysis of the soil samples indicated that DNAPL was present in the Lower Clay Unit and in the semi-confined aquifer, although not in the Lower Sand Unit, immediately above the aquitard. No monitoring was done in the

semi-confining layer (Lower Clay Unit) or in the semi-confined aquifer before the demonstration because of NASA's concern about breaching the relatively thin aquitard. Subsequently, these three wells were drilled because nonintrusive (seismic) monitoring indicated the possibility of DNAPL being present in the semi-confined aquifer. There is no information regarding the state of the semi-confined aquifer before the demonstration, so it is unclear whether the DNAPL had migrated to the confined aquifer before or during the demonstration. However, given the strong electrical heating achieved in the Lower Sand Unit (in the surficial aquifer) which would tend to volatilize TCE upward, the greater probability is that the DNAPL penetrated the Lower Clay Unit before the demonstration. Whereas the Lower Clay Unit is 3 ft thick in other parts of Launch Complex 34, near PA-22 it appears to contain sand lenses that reduce the effective thickness of the aquitard to approximately 1.5 ft. Therefore, the barrier to downward migration is geologically weaker in this region.

- Hydraulic measurements in the semi-confined aquifer indicate an eastward gradient similar to the overlying surficial aquifer. Vertical gradients fluctuate between the semi-confined aquifer and the surficial aquifer.

As the semi-confined aquifer extends down to approximately 120 ft bgs, additional investigation of the deeper geologic strata would be required to obtain an understanding of the CVOC distribution in the semi-confined aquifer.

### **5.3.4 Potential TCE Losses during Hot Soil Core Sampling**

Even after waiting for two months following the end of the SI/E application to the subsurface, the demonstration plot had cooled down to 90°C or less (from a maximum of 120°C during heating). Therefore, post-demonstration soil coring had to be conducted while the plot was still hot. To minimize VOC losses due to volatilization, the following primary steps were taken (See Appendix A.1.1):

- Soil coring was started only after steam generation had subsided and the plot had cooled to 90°C or less in all parts.
- As the core barrel was retrieved from the ground, each 2-inch-diameter, 4-ft-long acetate sleeve in the core barrel was capped on both ends and dipped in an ice bath until the core soil was cooled to ambient temperature. The soil core was kept in

the ice bath long enough for cooling to occur without breaking the seals at the capped ends.

In order to determine volatilization losses due to the hot soil core, surrogate of 1,1,1-TCA was spiked for a few soil samples as described in Appendix G. Overall, the results show that between 84 and 113% of the surrogate spike was recovered from the soil cores, as confirmed by the high percent recovery of an injected surrogate compound (Gaberell et al., 2002). The results also indicate that the timing of the surrogate spike (i.e., pre- or post-cooling) appeared to have only a slight effect on the amount of surrogate recovered (see Table G-1 in Appendix G). Slightly less surrogate was recovered from the soil cores spiked prior to cooling, which implies that any losses of 1,1,1-TCA in the soil samples spiked prior to cooling are minimal and acceptable, within the limitations of the field sampling protocol.

### **5.3.5 Summary of Fate of TCE/DNAPL Removed**

The TCE/DNAPL removed from the plot could have taken one or more of the following pathways:

- **TCE recovery in the vapor recovery system.** The vendor reported that between 5,200 and 9,700 kg (7,400 ± 2,200 kg) of TCE was measured in the recovered vapor and groundwater. The estimated pre-demonstration TCE mass in the SI/E plot before the demonstration was between 11,150 and 14,150 kg of TCE. However, the source of the TCE recovered aboveground by the vendor is unclear. It is possible that some dissolved TCE was drawn into the extracted water from the surrounding aquifer, parts of which are in untreated DNAPL source areas. The maximum amount of TCE that is possibly extracted from outside the cell is approximately 1,000 lb. This is all the TCE in the wastewater stream and therefore includes condensate from the vapor stream as well as the groundwater and condensed steam from within the plot. The TCE should reasonably be reduced by approximately 50%, resulting in a figure of about 500 lb as the likely amount of TCE extracted in groundwater from outside the plot.
- **TCE degradation by biotic or abiotic means.** It is possible that some of the TCE was degraded to other products due to the SI/E process. There is some evidence of heightened microbial activity in the SI/E plot at the elevated temperatures. Also, HPO of the TCE at elevated temperatures is one of the claims of the SI/E technology vendor. There was no noticeable buildup of expected degradation products (such as chloride, alkalinity, or

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*cis*-1,2-DCE), possibly due to the masking effect of the 11 pore volumes of water drawn into the plot from the surrounding aquifer.

- **DNAPL migration to surrounding regions.** The possibility of DNAPL migration from the SI/E plot to surrounding regions is minimal. The hydraulic containment maintained by the vendor was relatively strong (an average of 22 gpm of water was extracted by the vendor along the boundaries of the plot). Therefore, it is unlikely that any DNAPL migrated to the surrounding aquifer, despite the expected reduction in surface tension of the DNAPL due to heating. No elevated TCE concentrations were found in the vadose zone soil samples collected during post-demonstration soil coring. No elevated TCE levels or elevated temperatures were apparent in the confined aquifer wells below the SI/E plot, once the demonstration began. Also, the continuous pumping (22 gpm) in the surficial aquifer might have exerted an upward gradient across the Lower Clay Unit. TCE levels were slightly elevated (above background levels) in the surface emission tests conducted on the ground around the plenum, but were not particularly high. Most of the vaporized TCE appears to have been recovered in the vapor recovery system.

- **Potential TCE losses during post-demonstration sampling of hot soil cores.** The potential for TCE loss through this pathway is minimal. The hot soil cores were cooled to ambient temperature in the sleeves they were brought to the ground surface in. Recoveries of 84 to 113% of a surrogate compound spiked into the hot and cold soil cores were achieved during tests conducted to verify the field sampling and extraction procedures.

Therefore, despite some uncertainties due to the large influx of groundwater into the SI/E plot, it is likely that much of the TCE removed from the plot was recovered aboveground in the vapor recovery system. It is unclear how much of the TCE in the plot was degraded in situ, due to the SI/E application. The TCE recovered above ground was ultimately recovered on the GAC or destroyed in the thermal oxidizer.

#### 5.4 Operating Requirements and Cost

Section 3 contains a description of the SI/E field operations at Launch Complex 34. Section 7 contains the costs and economic analysis of the technology.

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## 6. Quality Assurance

A QAPP (Battelle, 2001c) was prepared before the demonstration that outlined the performance assessment methodology and the QA measures to be taken during the demonstration. The results of the field and laboratory QA activities for the critical soil and groundwater CVOC (primary) measurements and groundwater field parameter (secondary) measurements are described in this section. The results of the QA associated with other groundwater quality (secondary) measurements are described in Appendix G. The QA efforts were focused on the critical TCE measurement in soil and groundwater, for which, in some cases, special sampling and analytical methods were used. For other measurements (chloride, calcium, etc.), standard sampling and analytical methods were used to ensure data quality.

### 6.1 QA Measures

This section describes the data quality in terms of representativeness and completeness of the sampling and analysis conducted for technology performance assessment. Chain-of-custody procedures also are described.

#### 6.1.1 Representativeness

Representativeness is a measure that evaluates how closely the sampling and analysis represents the true value of the measured parameters in the target matrices. The critical parameter in this demonstration is TCE concentration in soil. The following steps were taken to achieve representativeness of the soil samples:

- The statistical design for determining the number and distribution of soil samples in the 75-ft × 50-ft SI/E plot was based on the horizontal and vertical variability observed during a preliminary characterization event (see Section 4.1). Twelve locations (one in each cell of a 4 × 3 grid in the plot) were cored before and after the demonstration. Continuous cores were collected from these 12 locations and sampled in 2-ft sections from the ground surface to the lower clay unit at each coring location. At the 80% confidence level, the pre- and post-

demonstration TCE mass estimates in the plot (see Section 5.1) did not overlap, and were sufficiently separated to enable a good judgment of the mass removal achieved by the steam injection technology.

- Sampling and analysis of duplicate post-demonstration soil cores were conducted to determine TCE concentration variability within each grid cell. Two complete cores (SB-239 and SB-339) were collected within about 2 ft of each other in the post-demonstration SI/E plot, with soil sampling at every 2-ft interval (see Figure 5-1 for the TCE analysis of these cores). The resulting TCE concentrations showed a relatively good match between the duplicate cores. These results indicated that dividing the plot into 12 grid cells enabled a sampling design that was able to address the horizontal variability in TCE distribution.
- Continuous sampling of the soil column at each coring location enabled the sampling design to address the vertical variability in the TCE distribution. By sampling soil along the entire 2-ft section of core for extraction and analysis, essentially every vertical depth was sampled.
- Appropriate modifications were made to the standard methods for sampling and analysis of soil. To increase the representativeness of the soil sampling, the sampling and extraction procedures in U.S. EPA Method 5035 were modified so that a representative vertical section of each 2-ft core could be sampled and extracted, instead of the 5-g aliquots specified in the standard method (see Section 4.1). This was done to maximize the capture of TCE-DNAPL in the entire soil column at each coring location.

The following steps taken to achieve representativeness of the groundwater samples:



- Two well clusters were installed in the 75-ft × 50-ft SI/E plot and sampled. Each cluster consisted of three wells screened in the three stratigraphic units—Upper Sand Unit, Middle Fine-Grained Unit, and Lower Sand Unit.
- Standard methods were used for sampling and analysis. Disposable tubing was used to collect samples from all monitoring wells to avoid cross-contaminating the sample tubing after use in wells with high TCE-DNAPL levels.

### 6.1.2 Completeness

All regular samples specified in the QAPP were collected and analyzed. Additional samples were collected when new requirements were identified as the demonstration progressed. Additional groundwater samples were collected from all SI/E plot and surrounding wells to better evaluate chloride generation and migration, as well as the presence of potassium ion and potassium permanganate from the nearby chemical oxidation plot. One additional soil core was collected during post-demonstration sampling to evaluate the variability within the same grid cell.

All the quality control (QC) samples planned in the QAPP were collected and analyzed, including equipment rinsate blanks during soil coring. Based on the preliminary speed of the soil coring, one rinsate blank per day was thought to be sufficient to obtain a ratio of 1 blank per 20 samples (5%). Rinsate blanks were collected more frequently near the end of the pre-demonstration sampling event, at a rate of 2 per day, as the number of soil samples collected increased. During post-demonstration sampling, one rinsate blank was collected per boring location. None of the blanks contained any elevated levels of CVOCs. Detailed data on the rinsate blanks may be found in Appendix G.

### 6.1.3 Chain of Custody

Chain-of-custody forms were used to track each batch of samples collected in the field and delivered to the off-site analytical laboratory. Copies of the chain-of-custody

records can be found in Appendix G. Chain-of-custody seals were affixed to each shipment of samples to ensure that only laboratory personnel accessed the samples while in transit. Upon arrival at the laboratory, the laboratory verified that the samples were received in good condition, and the temperature blank sample sent with each shipment was measured to ensure that the required temperature was maintained during transit. Each sample received was then checked against the chain-of-custody form, and any discrepancies were brought to the attention of field personnel.

## 6.2 Field QC Measures

The field QC checks included calibration of field instruments, field blanks (5% of regular samples), field duplicates (5% of regular samples), and trip blanks; the results of these checks are discussed in this section.

Table 6-1 summarizes the instruments used for field groundwater measurements (pH, ORP, DO, temperature, water levels, and conductivity) and the associated calibration criteria. Instruments were calibrated at the beginning and end of the sampling period on each day. The field instruments were always within the acceptance criteria during the demonstration. The DO membrane was the most sensitive, especially to extremely high (near saturation) levels of chlorinated solvent or permanganate in the groundwater, and this membrane had to be changed more frequently as a result. Because of interference with DO and other measurements, field parameter measurements in deeply purple (high permanganate level) samples were avoided, as noted in Appendix D.

### 6.2.1 Field QC for Soil Sampling

During post-demonstration sampling, one primary change and one addition were made to the sampling protocol outlined in the QAPP (Battelle, 2001c). The primary change to the QAPP involved the point at which methanol was added to the soil sample. The QAPP specified that the soil sample would be collected first into an empty, preweighed bottle, and then approximately 250 mL of methanol would be added to the soil in the

**Table 6-1.** Instruments and Calibration Acceptance Criteria Used for Field Measurements

Instrument	Measurement	Acceptance Criteria
YSI Meter Model 6820	pH	3 point, ±20% difference
YSI Meter Model 6820	ORP	1 point, ±20% difference
YSI Meter Model 6820	Conductivity	1 point, ±20% difference
YSI Meter Model 6820	Dissolved Oxygen	1 point, ±20% difference
YSI Meter Model 6820	Temperature	1 point, ±20% difference
Ohaus Weight Balance	Soil – Dry/Wet Weight	3 point, ±20% difference
Hermit Water-Level Indicator	Water Levels	±0.01 ft

bottle. Due to concerns about the amount of CVOC volatilization that might be occurring during the time between collecting the sample and adding the methanol, the decision was made to add the appropriate amount (250 mL) of methanol to the bottle first, and then place the soil sample directly into the methanol-filled bottle. Soil extractions then were conducted in the field using modified U.S. EPA Method 5035 as described in the QAPP, and the extract was sent to the off-site analytical laboratory for CVOC analysis.

The addition to the QAPP sampling and analysis protocol involved the use of a surrogate compound to test the recovery efficiency of the methanol extraction procedure used on-site. The surrogate compound, 1,1,1-TCA, was chosen by the analytical lab as having properties and characteristics very similar to TCE, but would not interfere with the analytical analysis of TCE. The surrogate was spiked directly into one soil sample from every boring location collected during post-demonstration sampling. The injection volume of 1,1,1-TCA was approximately 10  $\mu$ L. The spiked soil samples were handled in the same manner as the remaining soil samples during the extraction procedure. Of the 13 soil samples spiked with 1,1,1-TCA, 12 were within the acceptable range of precision for the post-demonstration soil sampling, calculated as the relative percent difference (RPD), where RPD is less than 30%. The results indicate that the methanol extraction procedure used in the field was suitable for recovering CVOCs. The detailed results of the 1,1,1-TCA spike recoveries are presented in Appendix G (Table G-1).

Duplicate soil samples were collected in the field and analyzed for TCE to evaluate sampling precision. Duplicate soil samples were collected by splitting each 2-ft soil core vertically in half and subsequently collecting approximately 250 g of soil into two separate containers, marked as SB#-Depth# and SB#-Depth#-DUP. Appendix G (Tables G-3 and G-4) shows the result of the field soil duplicate analysis and the precision, calculated as the RPD for the duplicate soil cores, which were collected before and after the demonstration. The precision of the field duplicate samples was generally within the acceptable range ( $\pm 30\%$ ) for the demonstration, indicating that the sampling procedure was representative of the soil column at the coring location.

The RPD for two of the thirteen duplicate soil samples collected during the pre-demonstration sampling was greater than 30%, but less than 60% (see Table G-3). These exceedances of the RPD target are attributed to the low TCE concentrations found in those samples, which significantly affected the RPD calculations. One sample-duplicate pair significantly exceeded the target level of 30% (RPD=115%) due to the presence of free-phase TCE found in part of the sample. This result indi-

cated the heterogeneous nature of the contaminant distribution in the soil. However, this large a deviation occurred only for 2 of the 13 sets of duplicate soil samples collected, and may be an extreme example of the nugget effect associate with sampling free-phase or particulate contaminants.

The RPD for 4 of the 15 duplicate soil samples collected during the post-demonstration sampling was greater than 30% but less than 40% (see Table G-4). These four samples had RPD values slightly above the targeted range because of the low TCE concentrations found in the samples, which significantly affected the RPD calculation. In general though, the variability in the two vertical halves that each soil core section was split into before the extraction was in a reasonable range, given the typically heterogeneous nature of the DNAPL distribution.

Field blanks for the soil sampling consisted of rinsate blank samples and methanol blank samples. The rinsate blank samples were collected once per drilling day (approximately 20 soil samples) to evaluate the decontamination procedure for soil sampling equipment. Decontamination between samples consisted of a three-step process where the sampling equipment was emptied, washed with soapy water, rinsed in distilled water to remove soap and debris, and then rinsed a second time with distilled water. The rinsate blank samples were collected by pouring distilled water over the sampling equipment after the equipment had been processed through the routine decontamination procedure. As seen in Appendix G (Table G-5), TCE levels in the rinsate blanks were always below detection ( $<1.0 \mu\text{g/L}$ ), indicating that the decontamination procedure was preventing CVOC cross-contamination between samples.

Methanol method blank samples (5%) were collected in the field to evaluate the soil extraction process. The results are listed in Appendix G (Table G-6). All of the methanol blank samples were below the targeted detection limit of 0.250 mg/kg of TCE in dry soil.

## **6.2.2 Field QC Checks for Groundwater Sampling**

QC checks for groundwater sampling included field duplicates (5%), field blanks (5%), and trip blanks. Field duplicate samples were collected once for every 20 wells sampled. Appendix G (Tables G-7 and G-8) contains the analysis of the field duplicate groundwater samples that were collected before, during, and after the demonstration. The RPD (precision) calculated for these samples always met the QA/QC target criteria of  $\pm 30\%$ .

New disposable Teflon<sup>®</sup> tubing was used to collect groundwater from each well during each groundwater

sampling event. The tubing was disposed of after sampling each well. Therefore decontamination procedures were not used on the groundwater sampling tubing. Rinse blanks for the sample tubing consisted of passing fresh deionized water through the sample tubing into 40-mL VOA vials. All rinse sample results for pre- and post-demonstration sampling events were below the non-detect level (<1.0 µg/L). The field rinse analytical results are contained in Appendix G (Tables G-9 and G-10).

TCE levels in trip blank samples were always less than 1 µg/L (Appendix G, Table G-11), indicating that the integrity of the samples was maintained during shipment.

### 6.3 Laboratory QC Checks

The off-site analytical laboratory performed QA/QC checks consisting of 5% matrix spikes (MS) or laboratory control spikes (LCS), as well as the same number of matrix spike duplicates (MSD) or laboratory control spike duplicates (LCSD). The analytical laboratories generally conducted MS and MSD whenever the groundwater samples were clear, in order to determine accuracy. MS and MSD or LCS and LCSD were used to calculate analytical accuracy (percent recovery) and precision (RPD between MS and MSD or LCS and LCSD).

#### 6.3.1 Analytical QC Checks for Soil

Analytical accuracy for the soil samples (methanol extracts) analyzed was within the acceptance limits (70-130%) for the pre- and post-demonstration period (Appendix G, Tables G-12, G-13, G-14, and G-15). Matrix spike recoveries (MS/MSD) were all less than the QA/QC target RPD of 30% for both pre- and post-demonstration sampling events. However, 7 of the 42 MS/MSD spike recoveries were outside the target recovery range of 70-130% for the pre- and post-demonstration sampling events (Appendix G, Tables G-12 and G-13). Laboratory control spike recoveries (LCS/LCSD) were all less than the QA/QC target RPD of 25% for both pre- and post-demonstration sampling events. There were no exceedances of the target recovery range of 70-130% for LCS/LCSD samples (Appendix G, Tables G-14 and G-15).

The off-site analytical laboratory (DHL Analytical) conducted surrogate spikes in 5% of the total number of methanol extracts prepared from the soil samples for CVOC analysis. Table 6-2 lists the surrogate and laboratory control sample compounds used by the off-site laboratory to perform the QA/QC checks. Surrogate and laboratory control sample recoveries were always within the specified acceptance limits. Method blank samples were run at a frequency of at least one for every 20 samples analyzed in the pre- and post-demonstration

**Table 6-2.** List of Surrogate and Laboratory Control Sample Compounds and Their Target Recoveries for Soil and Groundwater Analysis by the Off-Site Laboratory (DHL)

Surrogate	Laboratory Control Sample
4-Bromofluorobenzene (75-125%)	1,1,1-TCA (75-125%)
Toluene-d8 (75-125%)	<i>cis</i> -1,2-DCE (75-125%)
Dibromofluoromethane (75-125%)	<i>trans</i> -1,2-DCE (75-125%)
1,2-Dichloroethane-d4 (62-139%)	TCE (75-125%)
	Vinyl chloride (75-125%)

periods (Appendix G, Tables G-16 and G-17). CVOC levels in the method blanks were always below detection (<0.250 mg/kg TCE).

#### 6.3.2 Laboratory QC for Groundwater

MS and MSD results for groundwater sampling events during and after the demonstration are listed in Appendix G (Table G-18). The MS and MSD recoveries (70 to 130%) and their precision (RPD<25%) were generally within acceptance criteria. The recoveries for two MS/MSD pairs of samples exceeded 130% recovery. Recoveries and RPDs for LCS and LCSD samples (Appendix G, Tables G-19 and G-20) were always within the acceptance range.

Method blanks (Appendix G, Tables G-21 and G-22) for the groundwater samples were always below the targeted 3 µg/L detection limit.

#### 6.3.3 Analytical Detection Limits

Detection limits for TCE in soil (1 mg/kg) and groundwater (3 µg/L) generally were met. The only exceptions were samples that had to be diluted for analysis, either because one of the CVOC compounds (e.g., TCE) was at a relatively high concentration compared to another VOC compound (e.g., *cis*-1,2-DCE), or because excessively high levels of organics in the sample necessitated dilution to protect the analytical instruments. The proportionately higher detection limits are reported in the CVOC tables in Appendix C. The detection limits most affected were those for *cis*-1,2-DCE and vinyl chloride, due to the masking effect of high levels of TCE. Additionally, the laboratories verified and reported that analytical instrumentation calibrations were within acceptable ranges on the days of the analyses.

### 6.4 QA/QC Summary

Given the challenges posed by the typically heterogeneous TCE distribution in a DNAPL source zone, the collected data were a relatively good representation of the TCE distribution in the Launch Complex 34 aquifer

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before, during, and after the demonstration, for the following reasons:

- A sufficient number of locations (12) were sampled within the plot to adequately capture the horizontal variability in the TCE distribution. The continuous sampling of the soil at each coring location ensured that the vertical variability of the TCE distribution was captured. Sampling and analytical procedures were appropriately modified to address the expected variability. At the 80% confidence level, the soil sampling results provided pre- and post-demonstration confidence intervals (range of TCE mass estimates) that did not overlap, and were sufficiently separated to enable a good judgment of the TCE and DNAPL mass removal achieved by the steam injection technology.
- Standard sampling and analysis methods were used for all other measurements to ensure that data were comparable between sampling events.
- Accuracy and precision of the soil and groundwater measurements were generally in the acceptable range for the field sampling and laboratory analysis. In some cases, extremely low (near detection) or extremely high levels of TCE in the sample caused greater deviation in the precision (repeatability) of the data.
- In some cases, the masking effect of high TCE levels on other CVOCs and the need for sample dilution caused detection limits for TCE, to rise to 5 µg/L (instead of 3 µg/L). However, post-demonstration levels of dissolved TCE in many of the monitoring wells in the SI/E plot were considerably higher than the 3-µg/L detection and regulatory target.
- Field blanks associated with the soil samples and groundwater samples had undetected levels of TCE.



## 7. Economic Analysis

An economic analysis for an innovative technology generally is based on a comparison of the cost of the innovative technology with a conventional alternative. In this section, the economic analysis involves a comparison of the steam injection technology cost with the cost of a conventional pump-and-treat system.

The cost estimation for the steam injection technology application involves the following three major components:

- Application cost of steam injection at the demonstration site. Costs of the technology application at Launch Complex 34 were tracked by the steam injection vendor and by MSE, the DOE contractor who subcontracted the vendor.
- Site preparation and waste disposal costs incurred by the owner. NASA and MSE tracked the costs incurred by the site owner.
- Site characterization and performance assessment costs. Battelle and TetraTech EM, Inc., estimated these costs based on the site characterization and performance assessment that was generally based on U.S. EPA's SITE Program guidelines.

### 7.1 Steam Injection Application Costs

The costs of the steam injection technology were tracked and reported by both the vendor and MSE, the DOE contractor who subcontracted the vendor. Table 7-1 summarizes the major cost components for the application. The total cost of the steam injection demonstration was approximately \$1,201,000. This total includes the design, permitting support, implementation, process monitoring, waste disposal, and reporting costs incurred by the vendor. The total does not include the costs for site characterization, which was conducted by other organizations (Remedial Investigation/Feasibility Study [RI/FS] by NASA, preliminary characterization by WSRC,

**Table 7-1.** Steam Injection Application Cost Summary Provided by Vendor

Cost Item	Actual Cost (\$)	Percentage (%)
Design and plans	120,000	10
Surface plant set-up	168,000	14
Well installation	132,000	11
Air, water, and limited soil analyses	72,070	6
Operations	420,411	35
Waste disposal	55,100	5
Electricity used	13,902	1
Water	941	.1
Fuel (propane and diesel)	82,210	7
Project management and reporting	132,129	11
<b>Total Cost</b>	<b>1,201,175</b>	<b>100</b>

Source: MSE, 2002.

detailed characterization by Battelle/TetraTech EM, Inc./U.S. EPA); and the cost of the operating fuel (propane and diesel), waste disposal, electricity, and water, incurred by NASA. Based on the average total TCE reduction efficiency at 85% by kriging analysis results, the treated TCE was estimated to be 19,556 lb including 16,383 lb from the liquid/vapor extraction system and 3,173 lb by in situ TCE reduction. Thus, the unit cost is estimated to be at \$61 per lb treated TCE. The total cost for treatment is approximately \$192 per yd<sup>3</sup> treated TCE (MSE, 2002).

### 7.2 Site Preparation and Waste Disposal Costs

Soil cuttings from the hollow-stem auger used for installing the steam injection and vapor extraction wells were disposed of offsite by the vendor. Soil (i.e., waste) disposal costs are shown in Table 7-1. The wastes generated during the steam injection operation were disposed of off site by NASA at a cost of \$55,100. Wastes shipped off site included the spent GAC, and steam boiler blowdown.

### 7.3 Site Characterization and Performance Assessment Costs

This section describes two categories of costs:

- Site characterization costs (see Table 7-2). These are the costs that a site would incur in an effort to bridge the gap between the general site information in an RI/FS or RFI report and the more detailed information required for DNAPL source delineation and remediation technology design. This cost component is perhaps the most reflective of the type of costs incurred when a site of the size and geology of Launch Complex 34 undergoes site characterization in preparation for remediation. Assuming that groundwater monitoring and plume delineation at a site indicates the presence of DNAPL, these site characterization costs are incurred in an effort to define the boundaries of the DNAPL source zone, obtain an order-of-magnitude estimate of the DNAPL mass present, and define the local hydrogeology and geochemistry of the DNAPL source zone.
- Performance assessment costs (see Table 7-3). These are primarily demonstration-related costs. Most of these costs were incurred in an effort to further delineate the portion of the DNAPL source contained in the steam injection plot and determine the TCE/DNAPL mass removal achieved by the steam technology. Only a fraction of these costs would be incurred during full-scale deployment of this technology; depending on the site-specific regulatory requirements, only the costs related to determining compliance with cleanup criteria would be incurred in a full-scale deployment.

Table 7-2 summarizes the costs incurred by Battelle for the February 1999 site characterization. This event was a suitable combination of soil coring and groundwater sampling, organic and inorganic analysis, and hydraulic testing (water levels and slug tests) that may be expected to bridge the gap between the RI/FS or RFI data usually available at a site and the typical data needs for DNAPL source delineation and remediation design.

Table 7-3 lists the performance assessment costs incurred jointly by Battelle and TetraTech EM, Inc. in evaluating the effectiveness of the steam injection technology.

### 7.4 Present Value Analysis of Steam Injection and Pump-and-Treat System Costs

DNAPL, especially of the magnitude present at Launch Complex 34, is likely to persist in an aquifer for several

**Table 7-2. Estimated Site Characterization Costs**

Activity	Cost
Site Characterization Work Plan	\$ 25,000
<ul style="list-style-type: none"> <li>• Additional characterization to delineate DNAPL source</li> <li>• Collect hydrogeologic and geochemical data for technology design</li> </ul>	
Site Characterization	\$ 165,000
<ul style="list-style-type: none"> <li>• Drilling – soil coring and well installation (12 continuous soil cores to 45 ft bgs; installation of 36 monitoring wells)</li> <li>• Soil and groundwater sampling (36 monitoring wells; 300 soil samples collection and field extraction)</li> <li>• Laboratory analysis (organic and inorganic analysis)</li> <li>• Field measurements (water quality; hydraulic testing)</li> </ul>	
Data Analysis and Site Characterization Report	\$ 65,000
<b>Total</b>	<b>\$ 255,000</b>

**Table 7-3. Estimated Performance Assessment Costs**

Activity	Cost
Pre-Demonstration Assessment	\$208,000
<ul style="list-style-type: none"> <li>• Drilling – 12 continuous soil cores, installation of 18 monitoring wells</li> <li>• Soil and groundwater sampling for TCE/DNAPL boundary and mass estimation (36 monitoring wells; 300 soil samples collection and field extraction)</li> <li>• Laboratory analysis (organic and inorganic analysis)</li> <li>• Field measurements (water quality; hydraulic testing)</li> </ul>	
Demonstration Assessment	\$100,000
<ul style="list-style-type: none"> <li>• Groundwater sampling (steam injection plot and perimeter wells)</li> <li>• Laboratory analysis (organic and inorganic analysis)</li> <li>• Field measurements (water quality; hydraulic testing; ISCO plot and perimeter wells)</li> </ul>	
Post-Demonstration Assessment	\$215,000
<ul style="list-style-type: none"> <li>• Drilling – 12 continuous soil cores</li> <li>• Soil and groundwater sampling (36 monitoring wells; collection and field extraction of 300 soil samples)</li> <li>• Laboratory analysis (organic and inorganic analysis)</li> <li>• Field measurements (water quality; hydraulic testing)</li> </ul>	
<b>Total</b>	<b>\$ 523,000</b>

decades or centuries. The resulting groundwater contamination and plume also will persist for several decades. The conventional approach to this type of contamination has been the use of pump-and-treat systems that extract

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and treat the groundwater above ground. This conventional technology is basically a plume control technology and would have to be implemented as long as groundwater contamination exists. Steam injection is an innovative in situ technology that seeks to replace the conventional pump-and-treat approach. Therefore, the costs of these two alternatives are compared in this section.

Because a pump-and-treat system would need to be operated for the next several decades, the life-cycle cost of this long-term treatment must be calculated and compared with the cost of steam injection, a short-term treatment. The present value (PV) of a long-term pump-and-treat application is calculated as described in Appendix H. The PV analysis is conducted over a 30-year period, as is typical for long-term remediation programs at Superfund sites. Site characterization and performance (compliance) assessment costs are assumed to be the same for both alternatives and are not included in this analysis.

For the purpose of comparison, it is assumed that a pump-and-treat system would have to treat the plume emanating from a DNAPL source the size of the steam injection plot. Recent research (Pankow and Cherry, 1996) indicates that the most efficient pump-and-treat system for source containment would capture all the groundwater flowing through the DNAPL source region. For a 75-ft-long x 50-ft-wide x 40-ft-deep DNAPL source region at Launch Complex 34, a single extraction well pumping at 2 gpm is assumed to be sufficient to contain the source in an aquifer where the hydraulic gradient (and therefore, the groundwater flow velocity) is extremely low. This type of minimal containment pumping ensures that the source is contained without having to extract and treat groundwater from cleaner surrounding regions, as would be the case in more aggressive conventional pump-and-treat systems. The extracted groundwater is treated with an air stripper, polishing carbon (liquid phase), and a catalytic oxidation unit (for air effluent).

As shown in Appendix H, the total capital investment for an equivalent pump-and-treat system would be approximately \$167,000, and would be followed by an annual operation and maintenance (O&M) cost of \$57,000 (including quarterly monitoring). Periodic maintenance requirements (replacements of pumps, etc.) would raise the O&M cost every five years to \$70,000 and every 10 years to \$99,000. A discount rate (real rate of return)

of 2.9%, based on the current recommendation for government projects, was used to calculate the PV. The PV of the pump-and-treat costs over 30 years is estimated to be **\$1,406,000**.

An equivalent treatment cost for full-scale deployment of the steam injection technology would be approximately **\$1,201,000**. This estimate is based on a total steam injection treatment including waste disposal cost (\$55,100) during the demonstration (from Table 7-1 and Section 7-2).

Therefore, the steam injection technology is comparable in cost to an equivalent pump-and-treat system. As seen in Table H-3 in Appendix H, an investment in steam injection has a slightly lower PV than the long-term investment in a pump-and-treat system, although not by much. The capital invested in steam injection would be recovered in the 24th year, when the PV of the pump-and-treat system exceeds the cost of steam injection. More importantly, there may be other tangible and intangible economic benefits to using a source remediation technology that are not factored into the analysis. For example, the economic analysis in Appendix H assumes that the pump-and-treat system is operational all the time over the next 30 or more years, with most of the annual expense associated with operation and routine (scheduled) maintenance. Experience with pump-and-treat systems at several sites has shown that downtime associated with pump-and-treat systems is fairly high (as much as 50% downtime reported from some sites). This may negatively impact both maintenance requirements (tangible cost) and the integrity of plume containment (intangible cost) with the pump-and-treat alternative. In addition, with steam injection or other source removal technology, there are no permanent aboveground structures, as there are with a long-term pump-and-treat system application, so the site can be put to many more uses.

Another factor to consider is that although the economic analysis for long-term remediation programs typically is conducted for a 30-year period, the DNAPL source and therefore the pump-and-treat requirement may persist for many more years or decades. This would lead to concomitantly higher remediation costs for the pump-and-treat or plume containment option (without source removal). As seen in Appendix H, the PV of a pump-and-treat system operated for 100 years would be **\$2,188,000**.





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## 8. Technology Applications Analysis

This section evaluates the general applicability of the SI/E technology to sites with contaminated groundwater and soil. The analysis is based on the results and lessons learned from the IDC demonstration, as well as general information available about the technology and its application at other sites.

### 8.1 Objectives

This section evaluates the SI/E technology against the nine evaluation criteria used for detailed analysis of remedial alternatives in feasibility studies under the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA). Much of the discussion in this section applies to DNAPL source removal in general, and SI/E in particular.

#### 8.1.1 Overall Protection of Human Health and the Environment

The SI/E technology is protective of human health and environment in both the short and long term. At Launch Complex 34, for example, the SI/E technique removed more than 8,000 kg of DNAPL contamination from the plot, with the possibility of some TCE mass destruction. Because DNAPL acts as a secondary source that can contaminate an aquifer for decades or centuries, DNAPL source removal or mitigation considerably reduces the duration over which the source is active. Even if DNAPL mass removal is not 100%, the resulting long-term weakening of the plume and the reduced duration over which the DNAPL source contributes to the plume reduces the threat to potential receptors.

#### 8.1.2 Compliance with ARARs

This section describes the technology performance versus applicable or relevant and appropriate requirements (ARARs). Compliance with chemical-, location-, and action-specific ARARs should be determined on a site-specific basis.

Compliance with chemical-specific ARARs depends on the efficiency of the SI/E process at the site and the cleanup goals agreed on by various stakeholders. In general, reasonable **short-term** (DNAPL mass removal) goals are more achievable and should lead to eventual and earlier compliance with long-term groundwater cleanup goals. Achieving **intermediate-term** groundwater cleanup goals (e.g., federal or state maximum contaminant levels [MCLs]), especially in the DNAPL source zone, is more difficult because various studies (Pankow and Cherry, 1996) have shown that almost 100% DNAPL mass removal may be required before a significant change in groundwater concentrations is observed. However, removal of DNAPL, even if most of the removal takes place from the more accessible pores, probably would result in a weakened plume that may lead to significant risk reduction in the downgradient aquifer. In the **long term**, source treatment should lead to earlier compliance with groundwater cleanup goals at the compliance boundary and earlier dismantling of any interim remedies (e.g., pump-and-treat).

The specific federal environmental regulations that are potentially impacted by remediation of a DNAPL source with SI/E are described below.

#### 8.1.2.1 Comprehensive Environmental Response, Compensation, and Liability Act

CERCLA, as amended by the Superfund Amendments and Reauthorization Act (SARA), provides for federal authority to respond to releases or potential releases of any hazardous substance into the environment, as well as to releases of pollutants or contaminants that may present an imminent or significant danger to public health and welfare or the environment. Remedial alternatives that significantly reduce the volume, toxicity, or mobility of hazardous materials and that provide long-term protection are preferred. Selected remedies also must be cost-effective and protective of human health and the environment. The SI/E technology meets several of these criteria relating to a preferred alternative. SI/E

reduces the volume of contaminants by removing DNAPL from the aquifer; it is possible that the toxicity of contaminants is reduced depending on how much the degradation pathways contribute to contaminant mass removal (see Sections 5.3.1 and 5.3.2). Although aquifer heterogeneities and technology limitations often result in less than 100% removal of the contaminant and elevated levels of dissolved solvent may persist in the groundwater over the short term, in the long term, there is faster eventual elimination of groundwater contamination. Section 7.4 shows that S/E is cost-effective compared with the conventional alternative of long-term pump and treat.

#### **8.1.2.2 Resource Conservation and Recovery Act**

RCRA, as amended by the Hazardous and Solid Waste Amendments (HSWA) of 1984, regulates management and disposal of municipal and industrial solid wastes. Both the U.S. EPA and RCRA-authorized states (listed in 40 CFR Part 272) implement and enforce RCRA and state regulations. Generally, RCRA does not apply to in situ groundwater treatment because the contaminated groundwater may not be considered hazardous waste while it is still in the aquifer. The contaminated groundwater becomes regulated if it is extracted from the ground, as would happen with the conventional alternative of pump and treat. Some aboveground wastes are generated that may require off-site landfill disposal. During the Launch Complex 34 demonstration, soil cuttings (from drilling and installation of S/E wells) were kept in drums and disposed of by NASA. The spent GAC was shipped back to the supplier for regeneration.

#### **8.1.2.3 Clean Water Act**

The Clean Water Act (CWA) is designed to restore and maintain the chemical, physical, and biological quality of navigable surface waters by establishing federal, state, and local discharge standards. When steam or groundwater extraction is conducted, and the resulting water stream needs to be treated and discharged to a surface water body or a publicly owned treatment works (POTW), the CWA may apply. On-site discharges to a surface water body must meet National Pollutant Discharge Elimination System (NPDES) requirements, but may not require an NPDES permit. Off-site discharges to a surface water body must meet NPDES limits and require an NPDES permit. Discharge to a POTW, even if it is through an on-site sewer, is considered an off-site activity. At Launch Complex 34, surface water was discharged through an infiltration trench. Approximately 4,013,588 gal of extracted groundwater and steam condensate was generated during the demonstration. This water was run through an air stripper, liquid-phase GAC, and permanganate-impregnated silica, before being discharged to the on-site infiltration trench.

Sometimes, soil or groundwater monitoring may lead to small amounts of purge and decontamination water wastes that may be subject to CWA requirements. Micropurging was one measure implemented at Launch Complex 34 to minimize such wastes during site characterization and technology performance assessment.

#### **8.1.2.4 Safe Drinking Water Act**

The Safe Drinking Water Act (SDWA), as amended in 1986, requires U.S. EPA to establish regulations to protect human health from contaminants in drinking water. The legislation authorizes national drinking water standards and a joint federal-state system for ensuring compliance with these standards. The SDWA also regulates underground injection of fluids and includes sole-source aquifer and wellhead protection programs.

The National Primary Drinking Water Standards are found at 40 CFR Parts 141 through 149. The most critical standards to meet are the health-based SDWA primary standards (e.g., for TCE); SDWA secondary standards (e.g., for dissolved manganese) are based on other factors, such as aesthetics (discoloration) or odor. The MCLs based on these standards generally apply as cleanup standards for water that is, or potentially could be, used for drinking water supply. In some cases, such as when multiple contaminants are present, alternative concentration limits (ACLs) may be used. CERCLA and RCRA standards and guidance are used in establishing ACLs. In addition, some states may set more stringent standards for specific contaminants. For example, the federally mandated MCL for vinyl chloride is 2 µg/L, whereas the State of Florida drinking water standard is 1 µg/L. In such instances, the more stringent standard is usually the cleanup goal.

Although the long-term goal of DNAPL source zone treatment is meeting applicable drinking water standards or other risk-based groundwater cleanup goals agreed on between site owners and regulatory authorities, the short-term objective of the S/E technology is DNAPL mass removal. Because technology, site, and economic limitations may limit DNAPL mass removal to less than 100%, it may not always be possible to meet groundwater cleanup targets in the source region in the short term. Depending on other factors, such as the distance of the compliance point (e.g., property boundary, at which groundwater cleanup targets have to be met) from the source (as negotiated between the site owner and regulators), the degree of weakening of the plume due to DNAPL source treatment, and the degree of natural attenuation in the aquifer, it may be possible to meet groundwater cleanup targets at the compliance point in the short term. DNAPL mass removal will always lead to faster attainment of groundwater cleanup goals in the

long term, as compared to the condition in which no source removal action is taken.

#### **8.1.2.5 Clean Air Act**

The Clean Air Act (CAA) and the 1990 amendments establish primary and secondary ambient air quality standards for protection of public health, as well as emission limitations for certain hazardous pollutants. Permitting requirements under CAA are administered by each state as part of State Implementation Plans (SIPs) developed to bring each state in compliance with National Ambient Air Quality Standards (NAAQS).

Pump-and-treat systems often generate air emissions (when an air stripper is used). Source removal technologies that use thermal energy (e.g., SI/E or resistive heating) also may have the potential to generate air emissions, unless adequate controls are implemented. Surface emission tests conducted in the SI/E plot (on the ground around the oversized plenum covering the steam injection plot and perimeter areas) during and after the demonstration showed TCE emissions that were noticeably above background levels. This indicates that, although the strong vapor recovery system was over designed and succeeded in significantly capturing and mitigating vapor emissions, a small fraction of TCE may have been discharged to the atmosphere. As the canister samples collected at shoulder height above the ground showed, these emissions were minor and were not a safety hazard. One precaution that could be taken in the future, if relatively high concentrations of TCE remain in the aquifer after treatment, is to leave the plenum and vapor recovery system on for a longer time after steam injection has ended. Surface emission tests showed that the TCE emissions remained above background levels while the aquifer was still hot (about 60°C when the last measurement was taken).

The air effluent from the air stripper was treated with a thermal oxidizer unit before being discharged to the atmosphere.

#### **8.1.2.6 Occupational Safety and Health Administration**

CERCLA remedial actions and RCRA corrective actions must be carried out in accordance with Occupational Safety and Health Administration (OSHA) requirements detailed in 20 CFR Parts 1900 through 1926, especially Part 1910.120, which provides for the health and safety of workers at hazardous waste sites. On-site construction activities at Superfund or RCRA corrective action sites must be performed in accordance with Part 1926 of RCRA, which provides safety and health regulations for construction sites. State OSHA requirements, which may be significantly stricter than federal standards, also must be met.

The health and safety aspects of SI/E are described in Section 3.2.3, which describes the operation of this technology at Launch Complex 34. Level D personal protective equipment generally is sufficient during implementation. Operation of heavy equipment, handling of hot fluids, and high voltage are the main working hazards and are dealt with by using appropriate PPE and trained workers. Monitoring wells should be fitted with pressure gauges and pressure release valves to facilitate sampling during and/or after the steam application. All operating and sampling personnel are required to have completed the 40-hour Hazardous Waste Operations and Emergency Response (HAZWOPER) training course and 8-hour refresher courses. There were no injuries during the SI/E demonstration at Launch Complex 34.

#### **8.1.3 Long-Term Effectiveness and Permanence**

SI/E leads to removal of DNAPL mass and therefore permanent removal of contamination from the aquifer. Dissolved solvent concentrations may rebound in the short-term when groundwater flow redistributes through the treated source zone containing DNAPL remnants; however, in the long-term, depletion of the weakened source through dissolution will continue and lead to eventual and earlier compliance with groundwater clean-up goals.

#### **8.1.4 Reduction of Toxicity, Mobility, or Volume through Treatment**

SI/E affects treatment by reducing the volume of the contamination and possibly, reducing its toxicity as well (depending on how much the degradation pathway contributes to contaminant mass removal).

#### **8.1.5 Short-Term Effectiveness**

The short-term effectiveness of the SI/E technology depends on a number of factors. If the short-term goal is to remove as much DNAPL mass as possible, this goal is likely to be met. If the short-term goal is to reduce dissolved contaminant levels in the source zone, achievement of this goal will depend on the hydrogeology and DNAPL distribution in the treated region. TCE levels declined in some monitoring wells in the SI/E plot, but were well above federal MCLs or State of Florida groundwater cleanup standards (5 ppb and 3 ppb, respectively). Geologic heterogeneities, preferential flowpaths taken by the steam, and localized permeability changes that determine flow in the treated region may lead to such variability in post-treatment groundwater levels of contamination. As discussed in Section 8.1.2.4, the chances of DNAPL mass removal resulting in reduced contaminant levels at a compliance point

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downgradient from the source is less likely in the short or intermediate term. In the long term, DNAPL mass removal will always shorten the time period required to bring the entire affected aquifer into compliance with applicable standards.

### **8.1.6 Implementability**

As mentioned in Section 7.2, site preparation and access requirements for implementing the steam injection technology are minimal. Firm ground for equipment setup is required. The equipment involved is commercially available. Setup and shakedown times are relatively high compared to other technologies, such as chemical oxidation. Overhead space available at open sites generally is sufficient for housing the SI/E equipment.

### **8.1.7 Cost**

As described in Section 7.4, the cost of SI/E, as it was implemented at Launch Complex 34, is competitive with the life-cycle cost of pump and treat (over a 30-year period of comparison). The cost comparison becomes even more favorable for source remediation in general when other tangible and intangible factors are taken into account. For example, a DNAPL source, such as the one at Launch Complex 34, is likely to persist much longer than 30 years (the normal evaluation time for long-term remedies), thus necessitating continued costs for pump and treat into the distant future (perhaps 100 years or more). Annual O&M costs also do not take into account the nonroutine maintenance costs associated with the large amount of downtime typically experienced by site owners with pump-and-treat systems.

A rise in fuel prices (for operating the steam generation boiler) may increase the cost of the SI/E application.

### **8.1.8 State Acceptance**

The ITRC, a consortium of several states in the United States, is participating in the IDC demonstration through review of reports and attendance at key meetings. The ITRC plays a key role in innovative technology transfer by helping disseminate performance information and regulatory guidance to the states.

The IDC set up a partnering team consisting of representatives from NASA and Patrick Air Force Base (site owners), U.S. EPA, State of Florida Department of Environmental Protection (FDEP), and other stakeholders early on when the demonstration was being planned. The partnering team was and is being used as the mechanism to proactively obtain regulatory input in the design and implementation of the remediation/demonstration

activities at Launch Complex 34. Because of the technical limitations and costs of conventional approaches to DNAPL remediation, state environmental agencies have shown growing acceptance of innovative technologies.

### **8.1.9 Community Acceptance**

The SI/E technology's low noise levels and ability to reduce short- and long-term risks posed by DNAPL contamination are expected to promote local community acceptance. Supply of sufficient power and control of air emissions may be issues of concern for communities.

## **8.2 Operability**

Unlike a pump-and-treat system that may involve continuous long-term operation by trained operators for the next 30 or 100 years, a source remediation technology is a short-term application. The field application of SI/E in the 75-ft x 50-ft plot at Launch Complex 34 took about 6 months to complete. The remediation generally is done as a turnkey project by multiple vendors, who design, build, and operate the steam injection system. Site characterization, site preparation (utilities, etc.), monitoring, and any waste disposal often are done by the site owner. The SI/E process used at Launch Complex 34 is patented, but is commercially available from multiple licensed vendors.

The SI/E process is relatively complex and requires proficient operators trained in this particular technology. Handling of hot fluids may require additional precautions.

## **8.3 Applicable Wastes**

SI/E has been applied to remediation of aquifers contaminated with chlorinated solvents, PAHs, and petroleum (nonchlorinated) hydrocarbons both in the vadose and saturated zones. Source zones consisting of perchloroethylene (PCE) and TCE in DNAPL or dissolved form, as well as dissolved *cis*-1,2-DCE and vinyl chloride, can be addressed by SI/E.

## **8.4 Key Features**

The following are some of the key features of SI/E that make it attractive for DNAPL source zone treatment:

- Applied in situ
- Uses relatively complex, but commercially available, equipment
- Relatively fast field application time possible, when applied properly

- The heat generated distributes reasonably well in the aquifer, thus achieving good contact with contaminants
- At many sites, a one-time application has the potential to reduce a DNAPL source to the point where either natural attenuation is sufficient to address a weakened plume or pump and treat needs to be applied for a shorter duration in the future.

## 8.5 Availability/Transportability

SI/E is commercially available from multiple vendors as a service on a contract basis. All reusable system components can be trailer-mounted for transportation from site to site. Steam injection and extraction wells and other subsurface components usually are left in the ground after the application.

## 8.6 Materials Handling Requirements

SI/E requires hot fluids handling capabilities. Heavy equipment needs to be moved around with forklifts. Drilling equipment is required to install subsurface electrodes. Design and operation of the steam injection and extraction equipment requires specially trained operators.

## 8.7 Ranges of Suitable Site Characteristics

The following factors should be considered when determining the suitability of a site for steam application:

- **Type of contaminants.** Contaminants should be amenable to mobilization, volatilization, or degradation by heat.
- **Site geology.** SI/E can heat sandy soils, and to some extent silty soils. However, aquifer heterogeneities and preferential flowpaths can make uniform heating more difficult, especially in regions such as the base of the aquifer (near the aquitard). DNAPL source zones in fractured bedrock also may pose a challenge. Longer application times and higher cost may be involved at sites with a high groundwater flow velocity because of increased rate of heat loss from the treated zone.

- **Soil characteristics.** SI/E is more suitable for high-permeability soils. However, many low-permeability aquifers contain preferential flow zones through which steam can travel. Therefore, the application must be carefully evaluated.
- **Regulatory acceptance.** Regulatory acceptance is important for this application. It is essential that the application achieve good hydraulic control (i.e., to mitigate potential for outward or downward migration) and adequate treatment of aboveground residuals, such as extracted water and condensate.
- **Site accessibility.** Sites that have no aboveground structures and fewer utilities are easier to remediate with SI/E. Presence of buildings or a network of utilities can make the application more difficult.

None of the factors mentioned above necessarily eliminates SI/E from consideration at any site. Rather, these are factors that may make the application less or more economical.

## 8.8 Limitations

The SI/E technology has the following limitations:

- Not all types of contaminants are amenable to heat treatment. In addition, some co-contaminants, such as certain heavy metals, if present, could be mobilized by heating.
- Aquifer heterogeneities can make the application more difficult, necessitating more complex application schemes, greater amounts of heat (steam), and/or longer application times.

Some sites may require greater hydraulic control to minimize the spread of contaminants. This may require the use of appropriate extraction wells and associated aboveground treatment to treat the extracted water and condensate. Although the geometrical constraints of this site (treating a small part of a larger DNAPL source) may have pressed the vendor to inject inside the plot and extract along the boundary, the reverse may provide better hydraulic control at many sites. In general, the outside-in mode, where the steam is injected along the perimeter of the DNAPL source and the contamination is "herded" to the center and extracted, may be the preferable mode of operation.



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