ESTCP
Cost and Performance Report

(ER-200314)

Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment

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ACRONYMS AND ABBREVIATIONS

AFP4	Air Force Plant 4
ASU	Arizona State University
bgs	below ground surface
DNAPL	dense non-aqueous phase liquid
DO	dissolved oxygen
DOE	Department of Energy
EGDY	East Gate Disposal Yard (Fort Lewis Site)
ERH	electrical resistance heating
ESTCP	Environmental Security Technology Certification Program
GW	groundwater
HAAF	Hunter Army Airfield
ISTD	in situ thermal desorption
LNAPL	light non-aqueous phase liquid
NAPL	non-aqueous phase liquid
NAS	Naval Air Station
NAVFAC	Naval Facilities Engineering Command
ND	non-detect
QA	quality assurance
SDC	supplemental data collection
SEE	steam-enhanced extraction
SERDP	Strategic Environmental Research and Development Program
TCE	trichloroethylene
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
VOA	volatile organic analysis
VOC	volatile organic compound

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1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES

In situ thermal soil and aquifer remediation technologies (e.g., electrical resistance heating [ERH], conductive heating, steam-based heating) have undergone rapid development and application in recent years. These technologies offer the promise of more rapid and thorough treatment of non-aqueous phase liquid (NAPL) source zones; however, their field-scale application has not been well-documented in the technical literature. The goal of this project was to provide a performance assessment of thermal remediation technologies for dense non-aqueous phase liquid (DNAPL) source zone remediation.

1.2 TECHNOLOGY DESCRIPTION

This Environmental Security Technology Certification Program (ESTCP) project did not involve the development or demonstration of a technology. Rather, the performance of thermal technologies designed and applied by others for DNAPL source zone remediation was assessed, with emphasis on post-treatment groundwater quality and mass discharge (sometimes referred to as “mass flux”). This independent evaluation involved an empirical analysis of available design and operating information and performance results from pilot- and full-scale applications to see what experiences to date have been. This was supplemented with post-treatment field sampling at selected sites to fill data gaps. This project was complementary to and made use of knowledge gained from other ESTCP and Strategic Environmental Research and Development Program (SERDP) projects that were looking at relationships between DNAPL architecture, treatment effectiveness, and groundwater mass discharge (flux).

Documents from 182 applications were collected and reviewed. These applications included 87 ERH, 46 steam-based heating, 26 conductive heating, and 23 other heating technology applications conducted between 1988 and 2007, approximately 90% of which were implemented after 1995 and about half since 2000. Document reviews identified the geologic settings in which these technologies were applied, chemicals treated, design parameters, operating conditions, and performance metrics. Particular emphasis was placed on gaining a better understanding of settings in which thermal technologies have been applied, the design and operating conditions that were used, and the performance of the systems.

Additional data were collected by performing post-treatment groundwater sampling at sites where full-scale thermal applications were applied consistent with recent practice. This involved high spatial density groundwater sampling and hydraulic conductivity characterization along transects oriented perpendicular to groundwater flow at the downgradient edge of the treatment zones at five thermal treatment sites. The data were then used to calculate post-treatment contaminant mass discharge for each site.

1.3 RESULTS

The data collected in this study are captured in tables that relate site characteristics, thermal technology choice, design specifics, operating conditions, and performance. These tables are integrated with technology descriptions in the document *State-of-the-Practice Overview of the Use of In Situ Thermal Technologies For NAPL Source Zone Cleanup*, intended to be a useful tool and primer for program managers considering the use of thermal technologies at their sites. Some key conclusions from this study are:

- Documents from 182 applications were collected and reviewed, which included 87 ERH, 46 steam-based heating, 26 conductive heating, and 23 other heating technology applications conducted between 1988 and 2007. This information indicates that a significant number of applications have occurred and this reflects the acceptance of in situ thermal technologies as viable source zone treatment options.
- It is apparent that the spatial extents of many source zones are likely ill-defined prior to treatment. This results in undersized target treatment zones, untreated source zone areas, and minimal beneficial impact to groundwater quality and mass discharge.
- Approximately half of the 182 applications have been implemented since 2000, and over half of those were ERH systems. ERH applications outnumber all other applications since 2000 by about a factor of three. There also seems to be a recent trend in the increasing use of conductive heating and decreasing use of steam-based heating.
- There seems to be a convergence towards relatively closely spaced energy delivery points in the design of ERH and conductive heating systems. Spacing for most ERH and conductive energy delivery points was less than 20 ft (6 m), while steam application well spacing was usually greater than 20 ft (6 m).
- To date, most applications have been applied to relatively small treatment zones; 117 of 121 treated areas were $<4x10^4$ ft^2 (<4000 m^2 or an acre) and two-thirds of those were $<10^4$ ft^2 (<1000 m^2 or one-quarter acre treatment areas).
- The effect of geologic setting on performance is difficult to discern in this data set because most treatment systems were installed in layered settings, characterized as either primarily fine-grained materials with higher permeability lenses or primarily permeable materials with finer-grained lenses. Thus, our understanding of system design parameters and operating conditions is limited to those scenarios.
- Most applications (independent of specific technology) lasted less than 6 months; there was little documentation as to the criteria or rationale used to determine the duration of operation. There was little indication that the duration of operation was linked to mass removal-, groundwater quality-, or soil concentration-based criteria.

1.4 IMPLEMENTATION ISSUES

The purpose of the study was to summarize knowledge on the performance of in situ heating technologies. The approach, as it pertains to this project, was to identify sites where thermal technologies have been applied and collect and synthesize as much of the available data/documentation for those sites, thus allowing for knowledge on how often each individual technology was being applied. The most challenging implementation issue was a lack of sufficient documentation for most of the 182 applications identified.

2.0 INTRODUCTION

2.1 BACKGROUND

DNAPL source zone treatment is one of the most significant remediation challenges facing the Department of Defense and the private sector. As a result, the number of in situ cleanup technologies developed and tested at DNAPL sites has increased in recent years. Approaches that employ increased temperature, chemical oxidation, surfactant flushing, and biological degradation processes have been developed and applied with varying degrees of success.

More recent critical review of the data from many of these sites has revealed that even with the most recent advancements in application of these treatment technologies, complete DNAPL source removal is unlikely. Hence, residual DNAPL after aggressive technologies have achieved their effective endpoints are expected to continue to have an impact on groundwater quality.

This project focused on thermal-based technologies (e.g., resistive heating, conductive heating, steam-based heating) for DNAPL source treatment and a critical assessment of the potential performance of these technologies as measured by conventional and mass flux metrics. Thermal technologies are of interest because of their rapid development in recent years and because of vendor claims that they offer unique advantages over competing technologies. In particular, it is claimed that thermal technology performance is less hindered by geologic stratification and other sources of mass-transfer resistances than other flow-based technologies applied to DNAPL source zones (such as surfactant flushing, chemical oxidation, and in situ sparging).

2.2 OBJECTIVES OF THE DEMONSTRATION

One objective of this project was to independently assess the performance of thermal technologies for DNAPL source zone remediation through compilation and critical review of data available from pilot- and full-scale applications. This was to lead to a better understanding of settings in which thermal technologies have been applied, the design and operating conditions that were used, and the performance of the systems. With respect to the latter, particular emphasis was placed on post-treatment groundwater quality and source zone residual mass discharge to the aquifer (commonly referred to as “mass flux”). The data gathered from historical site reports was supplemented with post-treatment field sampling at selected sites to fill data gaps.

Another objective was to integrate the results with technology descriptions in the document *State-of-the-Practice Overview of the Use of In Situ Thermal Technologies For NAPL Source Zone Cleanup,* intended to be a useful tool and primer for program managers considering the use of thermal technologies at their sites. Applications and performance experiences were to be linked to a small number of generalized geologic scenario site descriptors, so that the users could choose the generalized scenario that most closely resembled their sites and quickly assess:

- How the technology has been applied to date in that type of setting
- The designs employed
- The operating conditions
- The performance monitoring that results are based on
- The performance observed.

2.3 REGULATORY DRIVERS

Regulatory agencies at the federal, state, and local levels generally have groundwater quality, concentration-based metrics that necessitate treatment or containment of DNAPL source zones. Thermal treatment technologies, which have undergone significant development in the past decade, present innovative options for source zone treatment.

3.0 TECHNOLOGY

This project does not involve the demonstration of a developing technology, as is common for most ESTCP projects. Rather, it seeks to supplement our understanding of existing thermal treatment technologies through the development of a practicable tool in which performance experience is linked to a small number of generalized scenario site descriptors.

3.1 TECHNOLOGY DESCRIPTION

The history of in situ thermal technology development and use is summarized in the U.S. Environmental Protection Agency (USEPA), March 2004 report, *In Situ Thermal Treatment of Chlorinated Solvents: Fundamentals and Field Applications*. In brief, most in situ thermal cleanup technologies originate from thermal heating technologies developed for enhanced oil recovery applications. In the past two decades, the understanding of in situ heating and fluid recovery gained from enhanced oil recovery applications has been applied to hazardous waste site cleanups.

The in situ thermal technologies that are most commonly used and for which data are available include steam-based heating (sometimes referred to as steam-enhanced extraction [SEE]), conductive heating (sometimes referred to as in situ thermal desorption [ISTD]), ERH (sometimes referred to as six- or three-phase heating), radio-frequency heating, and in situ soil mixing with large diameter augers combined with steam and hot air injection. These technologies rely on heat to enhance the removal and treatment of contaminant vapors and liquids from the subsurface. Depending on operating temperatures, heating may decrease contaminant liquid viscosity, decrease interfacial tension, increase biodegradation rates, increase solubility, and increase volatility. What differentiates one technology from the next is the method of heating or energy delivery—for example, steam injection, resistive heating by passing a current through the soil between electrodes, conductive heating accomplished by heat conduction away from in situ heating elements, and radio frequency heating from radio waves. Detailed descriptions of these technologies along with vendor supplied state-of-the-practice reports (with the exception of radio-frequency heating, which has had limited application) are provided in Appendix B of the ER-200314 Final Report, *Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment* (Triplett Kingston et al., 2010).

The approach used in this study to summarize data on the application and performance of in situ heating technologies (i.e., performance experience and theoretical bounds on performance expectations linked to a small number of generalized scenario site descriptors) was similar to that employed in the NRC 2004 report *Contaminants in the Subsurface: Source Zone Assessment and Remediation*. The approach, as it pertained to this project, was to identify sites where thermal technologies had been applied and to collect and compile site characterization and in situ thermal design, operation, and treatment data from each. Although about 180 in situ thermal applications were identified, acquisition of detailed application and performance data was difficult and of varying quantity and quality.

For each in situ thermal application studied, data collection focused on:

- Setting (geology, depth to groundwater, source zone boundaries, chemicals present, etc.)
- System design parameters (number of energy delivery points, area and depth of the treatment zone, etc.)
- Operating conditions (temperature achieved, duration of treatment, duration of monitoring, etc.)
- Performance data (emphasizing improvement in groundwater quality and reduction in mass discharge of contaminant to the aquifer).

Data reduction involved interpretation and the use of professional judgment, especially when comparing pre- and post-treatment groundwater impacts. To simplify data reduction and remain consistent with the typical quality and quantity of available data, performance data were quantified only in terms of order-of-magnitude reductions in groundwater concentrations and source zone mass discharges.

Results were compiled in tables in a manner thought to be useful to practitioners who might be interested in evaluating thermal treatment options for their sites and who would benefit from this empirical compilation of historical data.

3.2 TECHNOLOGY DEVELOPMENT

This ESTCP project does not involve the development or demonstration of a technology.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

In situ thermal technologies are thought to have advantages relative to other remedial options, including (1) shorter operation times, (2) treatment of many chemicals at once, and (3) some thermal technologies, ERH and conductive heating in particular, are less sensitive to subsurface heterogeneities across a site. Only energy, and in some cases water and air, are added to the subsurface, rather than chemicals or bio-amendments.

The potential drawbacks of in situ thermal technologies include the following: (1) they can be difficult to apply near occupied/active sites; (2) they require more sophisticated design and operation; (3) they may enhance the potential for contaminant to migrate to previously non-impacted areas; and (4) post-treatment soil temperatures may remain elevated for prolonged periods of time (months to years).

In addition, poor documentation and a lack of quantitative post-treatment performance data has made it difficult to confidently define practicable performance expectations for thermal technologies.

4.0 PERFORMANCE OBJECTIVES

The performance objectives for this project are captured in Table 1.

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Qualitative Performance Objectives			
Collect data on in situ thermal applications	Data on hydrogeologic setting, type and method of application, temperature data, and estimate of contaminant reduction	• Ability to obtain documentation • Data exists in documentation	Summary tables of relevant data
Quantitative Performance Objectives			
Assess groundwater quality and mass discharge	Groundwater concentration, hydraulic conductivity, and hydraulic gradient data	• Ability to estimate mass discharge at downgradient edge of treatment zone	Summary tables of groundwater concentration data and mass discharge estimates

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5.0 SITE DESCRIPTION

As indicated previously, this ESTCP project did not involve the demonstration of a developing technology. Rather, it supplemented our understanding of existing thermal treatment technologies. This was accomplished in two tasks: Task 1) Data Compilation, Interpretation, and Capture in Tables; and Task 2) Supplemental Field Investigations at Thermal Treatment Sites. The former involved an empirical analysis of existing data and is therefore not relevant to this section; the latter involved field data collection at several in situ thermal treatment sites and is therefore the focus of this section.

5.1 SITE SELECTION

The following were desirable characteristics of candidate sites for supplemental field investigations:

- Sufficient post-treatment time had elapsed for subsurface temperatures to return to pre-treatment conditions
- Potential to fill data gaps identified from the empirical database analysis
- Representative relative to the conceptual model types and the frequency of occurrence of each type of site in the broader database population of sites.

In addition, it was preferable that sites had the following characteristics:

- Reasonably well-characterized site hydrogeology (flow direction, depth to groundwater, hydraulic properties and changes with depth are known semi-quantitatively, etc.)
- Reasonably defined source zone (areal extent and depth)
- Depth to groundwater less than 20 ft
- Depth to deepest impacted groundwater less than 40 ft
- Access immediately downgradient of the treatment zone for drilling and additional site investigation
- Possible use of direct-push technology for drilling/sampling purposes
- Local site personnel present to facilitate logistics associated with the sampling events.

Brief descriptions of all the sites are provided below. For more detailed information regarding each site, see Appendix D of the ER-0314 Final Report, *Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment* (Triplett Kingston et al., 2010).

5.2 SITE LOCATION AND HISTORY

Five sites were selected for supplemental data collection (SDC) and investigation of post-treatment groundwater quality. These sites and a brief history for each are shown below while Figure 1 shows the location for each on a map of the continental United States:

1. Site 89, Camp LeJeune, Jacksonville, NC:
   <u>History</u>: Site 89 at the Camp Geiger portion of Marine Corps Base Camp LeJeune was used primarily as a storage yard for the Defense Re-Utilization Marketing Office until June 2000.
   <u>Treatment History</u>: ERH was selected as the technology to remove DNAPL. The system consisted of 43 deep heating electrodes installed to a depth of 26 ft below ground surface (bgs) and 48 shallow heating electrodes installed to a depth of 19 ft bgs. The system was operated from September 2003 until the beginning of May 2004. The remedial system performance was continuously monitored during operation, and an estimated 48,000 lb of volatile organic compound (VOC) contamination was removed in recovered volatile vapors and 428 lb of chlorinated compounds were recovered from the groundwater during the application. After the shutdown of the system, the monitoring well network was monitored for one year.
2. Building 5, Site 5-1, Naval Air Station (NAS) Alameda, Alameda, CA:
   <u>History</u>: Building 5 housed specialty shops for aircraft component repair and maintenance from 1942 until the base was closed in April 1997. Chemical contaminants from the various industrial processes inside Building 5 are believed to have been released directly to the subsurface beneath certain operational areas.
   <u>Treatment History</u>: A pilot scale ERH application was performed in June of 2002. Based on the results of the pilot, a full-scale system was installed and operated. The system consisted of seven electrodes installed to a depth of 19 ft bgs, 28 electrodes installed to a depth of 14 ft bgs, and one electrode installed to 15 ft bgs. The full-scale system was operated from July 2004 until November 2004. The remedial system performance was continuously monitored during operation, and an estimated 3000 lb of VOC contamination were removed in recovered volatile vapors and groundwater. After the shutdown of the system, the monitoring well network was monitored for 4 months.
3. Building 181, Air Force Plant 4 (AFP4), Fort Worth, TX:
   <u>History</u>: Building 181 is part of a mile long structure designed for aircraft production. The primary contaminant at Building 181 is trichloroethylene (TCE). The TCE source is believed to be degreaser tanks in Building 181, which have since been removed. Several subsequent investigations found that releases of TCE had migrated through cracks in the concrete building floor resulting in contamination in the saturated and unsaturated zone.
   <u>Treatment History</u>: A pilot-scale six-phase ERH application was completed in the winter of 2001. Based on the results of the pilot, a full-scale three-phase electrical resistance application was performed in Building 181 in 2002. The full-scale system consisted of 73 electrodes installed to a depth of 32 ft bgs, including 7 electrodes from the pilot-scale test and 2 electrodes installed during operation to

enhance heat generation in target areas. The full-scale system was operated from May 2002 until December 2002. The remedial system performance was continuously monitored during operation, and an estimated 1417 lb of TCE was removed via steam and vapor extraction systems. The treatment area has been monitored semi-annually since the system was shut down in 2002.

4. Former Pumphouse No. 2, Hunter Army Airfield (HAAF), Savannah, GA:
   History: Former Pumphouse No. 2 at HAAF was an aviation-gas fuel island that was used from 1953 until the early 1970s. During previous investigations, petroleum contaminates were identified in the soil and groundwater, including benzene, toluene, ethylbenzene, and xylenes, as well as polynuclear aromatic hydrocarbon constituents in the form of free product light non-aqueous phase liquid (LNAPL). The LNAPL source area was determined to be approximately 11,500 ft^2 by the time the ERH application was performed.
   Treatment History: During the previous investigations, free product was identified. It was recommended that ERH be implemented to remove the free product. The system consisted of 111 electrodes installed to a depth of 16 ft bgs with the conductive interval set from 8 to 16 ft bgs. A full-scale ERH system was operated from March 2002 until July 2002. After shutdown, the piezometers installed for the ERH application were left in place and are still being sampled semi-annually.

5. Fort Lewis East Gate Disposal Yard (EGDY) Area 3, Fort Lewis, Washington
   History: Fort Lewis was initially developed as a Logistics Center in April 1942, but was transferred to ordnance jurisdiction in August 1942. It operated as an ordnance depot until 1963 when the area was turned back over to the Logistics Center to serve as the primary non-aircraft maintenance facility for Fort Lewis. The main degreasing agent used at this facility until the mid-1970s was TCE when it was replaced with 1,1,1-trichloroethane. The waste TCE was disposed of with waste oils at several locations including the EGDY. The EGDY was used between 1946 and the mid-1970s as a waste disposal site storing barrels and vats in trenches around the yard.
   Treatment History: The remedial investigations identified free product interspersed throughout the soil matrix mainly in the form of ganglia and globules. It was recommended that ERH be implemented to remove the free-phase product and optimize the existing groundwater pump-and-treat system. The system consisted of 93 electrodes installed to a depth of 30 ft bgs with the conductive interval set from 0 to 30 ft bgs. The third full-scale ERH system at the EGDY was operated from October 2006 until January 2007. After shutdown, the monitoring wells installed for the ERH application were left in place and were sampled throughout the cool-down process.

Data collection at the Fort Lewis EGDY was different in that it involved data collection before, during, and after thermal treatment.

Figure 1. Site locations for supplemental investigations.

5.3 SITE GEOLOGY/HYDROGEOLOGY

Table 2 below provides pertinent information regarding the site geology/hydrogeology for each SDC site. In addition, the table includes information regarding the thermal treatment applied at each.

Table 2. Site geology, hydrogeology, and treatment area information.

Site ID	Technology	Geology at This Site Is Most Like This Conceptual Scenario[1]	Number of Permanent Monitoring Wells	Type of Chemicals Treated (C-chlorinated solvents, P-petroleum hydrocarbons, W-Wood-treating, O-other)	Size of Target Treatment Area [ft^2]	Thickness of Target Treatment Interval [ft]	Depth-to-Water [ft]
Hunter Army Airfield Former Pumphouse #2	ERH	A	12	P, O	30,000	8	13
Air Force Plant 4 Bldg. 181	ERH	B	21	C	21,780	37	30
NAS Alameda Building 5, Site 5-1	ERH	C	15	C	14,520	20	6
Fort Lewis EDGY Area 3	ERH	C	17	C, P	18,200	30	N/A
Camp LeJeune Site 89	ERH	C	26	C	15,873	21	5

[1] Scenario Descriptors (for the target treatment zone)
A – relatively homogeneous and permeable unconsolidated sediments (sands, etc.)
B – largely impermeable sediments with interbedded layers of higher permeable material
C – largely permeable sediments with interbedded lenses of low permeable material
D – Competent, but fractured bedrock
E – Weathered Bedrock
ERH – Electrical resistance heating
N/A – Not available

5.4 CONTAMINANT DISTRIBUTION

Field investigations associated with this project focused on post-treatment groundwater sampling across a transect perpendicular to groundwater flow and immediately downgradient of the treatment zone at each site. The lateral and vertical distributions of contaminants in groundwater were determined at each site by on-site chemical analyses conducted as samples were collected. The width of each transect is given in Table 3.

Table 3. Sampling transect widths at the supplemental field sites.

Site ID	Treatment Zone Width Perpendicular to GW* Flow (ft)	Comments
Hunter Army Airfield Former Pumphouse #2	400	Documentation indicated quasi radial groundwater flow from the source zone, likely the result of drainage to a dog-legged drainage ditch adjacent to the site.
Air Force Plant 4 Bldg 181	170	Flow direction based on groundwater contour maps and contaminant distribution from site documentation; transect geometry based in part on physical constraints (drilling inside building).
NAS Alameda Building 5, Site 5-1	115	Flow direction based on groundwater contour maps and site documentation.
Fort Lewis EGDY Area 3*	110	Flow direction based on groundwater contour maps and site documentation.
Camp LeJeune Site 89	255	Flow direction based on groundwater contour maps. However, site constraints dictated a v-shaped transect with an approximate 30° angle, the apex of which was directly downgradient of source zone.

*GW - groundwater

6.0 TEST DESIGN

As in Section 5.0, this section focuses on the supplemental field investigation component of this project.

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

The goal of the supplemental field investigations was to collect sufficient groundwater and aquifer characterization data to assess post-treatment groundwater quality and estimate mass discharge immediately downgradient of source zones where an in situ thermal remediation had been applied. To accomplish these goals, the following field activities were undertaken:

- Groundwater sampling and aquifer characterization at a minimum of 10 sampling locations, each with at least five depth-discrete sampling points, along a transect downgradient of the treatment zone, perpendicular to the direction of groundwater flow, and equal in width to the original source zone and downgradient dissolved plume
- Groundwater sampling and aquifer characterization at select monitoring wells in or adjacent to the treatment zone
- Analysis of water samples for general chemistry and hydrocarbon concentrations.

Aquifer characterization involved the following activities:

- Aquifer specific-capacity tests or slug tests of both depth-discrete sampling points along transects and permanent monitoring wells
- Depth-to-water measurements for flow direction and gradient
- Soil core collection.

These activities were conducted at HAAF, AFP4, NAS Alameda Building 5, and Camp LeJeune Site 89. The Fort Lewis EGDY site SDC involved analysis of groundwater samples collected from permanent monitoring wells (shipped to Arizona State University [ASU] by Army Corps of Engineers personnel). Samples were collected during 16 sampling events over a 1.5 year time frame, and included pre-, concurrent-, and post-treatment sampling events.

6.2 BASELINE CHARACTERIZATION

Baseline characterization data for each supplemental characterization site were obtained from existing reports. The field studies associated with this project focused on post-treatment groundwater quality and mass flux assessment from completed thermal remediation sites, and therefore, baseline pre-treatment data had to be obtained from site reports.

6.3 TREATABILITY OR LABORATORY STUDY RESULTS

No treatability or laboratory studies were conducted as part of this project as the focus was on critical assessment of thermal technologies already being applied at the pilot- and full-scale.

6.4 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

No system design was conducted in this project as the focus was on critical assessment of thermal technologies being applied at the pilot- and full-scale. The designs of the thermal remediation systems implemented at sites selected for the supplemental post-treatment assessment can be found in Appendix D of the ER-200314 Final Report, *Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment* (Triplett Kingston et al., 2010).

6.5 FIELD TESTING

Field testing for this project differed from other ESTCP projects since no demonstration was performed. Field investigations focused on the assessment of post-treatment groundwater quality and mass flux of contaminant from the treatment zone, and included groundwater sampling for analyses of general water quality parameters and contaminant concentrations, aquifer characterization, soil core collection for verification of geology, and depth-to-water measurements for groundwater flow direction and gradient.

6.6 SAMPLING AND ANALYTICAL METHODS

Sampling and analytical methods are summarized in Table 4.

Depth-discrete testing and groundwater sampling were conducted using direct-push groundwater samplers (e.g., Geoprobe screen point sampler or groundwater profiler) and peristaltic pumps with dedicated polyethylene tubing. Groundwater sample collection from permanent monitoring wells and/or piezometers was facilitated by peristaltic pump, disposable bailers, or submersible electric pump.

Slug tests were conducted in selected monitoring wells within and directly adjacent to the treatment zone. At one site where depths-to-water were too great for aquifer specific-capacity tests (AFP4), pneumatic slug testing was used at all depth-discrete groundwater sampling locations.

Sample collection procedures are shown in Table 5. Samples collected at four field sites were analyzed within 24 hours of collection (and typically within 4 hours), and those samples were only preserved on ice. For the Fort Lewis EGDY site, samples were shipped on ice and with hydrochloric acid (HCl) preservative.

Table 4. Sampling methods.

Measurement	Description of Analyses
Field water quality measurements	Analysis of pH, electrical conductivity, temperature, dissolved oxygen (DO), and oxidation reduction potential using an Horiba U-22 with flow-through cell. In certain circumstances, only DO was measured using a YSI 550A DO meter with flow-through cell. Meters were calibrated as per manufacturer instructions at least once per day.
Chemicals of interest in groundwater	Sample collection: Samples were collected with zero-headspace in 40 mL volatile organic analysis (VOA) vials and placed on ice until analyzed. Sample analysis: Heated headspace method with on-column injection. 30 mL sample warmed in 40 mL VOA vial to 35°C followed by 0.5 mL on-column injection of headspace on the gas chromatograph. Separation by capillary column and analysis by photo-ionization detector, flame ionization detector, and/or dry electrolytic conductivity detector. Samples were analyzed on site at all locations except Fort Lewis EGDY where samples were collected at specific intervals by on-site contractors and sent to ASU.
Specific capacity	Specific capacity tests were conducted using an electronic water level indicator, a volumetric cylinder, a peristaltic pump, and a stop watch. After driving a direct-push rod to the desired depth, the water level was measured in the rod until stable. Then the polyethylene tubing inlet was lowered 1 ft below the stable water level and the peristaltic pump was run at a high speed that draws the water down to that level (this is apparent by slugs of air coming up in the tubing). At this point, the flow was measured by recording the time to collect 1 L of water, or under low flow conditions, how much water was collected in a 10-minute interval. Successive analyses were conducted to ensure that the yield had reached a stable value.
Slug tests	Slug tests were conducted in conventional wells using a data-logging pressure transducer and a slug capable of displacing about 2 ft of water. The slug was either lowered into or pulled out of the well, and the water level response was monitored until it stabilized at the pre-test level. The data was then analyzed by standard slug-test analysis methods. At AFP4 where depths-to-water were too great for aquifer specific-capacity tests, pneumatic slug testing was used at all depth-discrete groundwater sampling locations.
Geologic confirmation	At each site except Fort Lewis EGDY, soil cores were collected along the downgradient edge of the treatment zone and would extend from about 2 ft above the groundwater elevation and extend to the deepest known depth of groundwater impact. Soil cores were used to confirm the site geologic conceptual model and, as needed, were subdivided in the lab into sections with visually distinct geologies for permeameter testing.
Depth-to-water	Depth-to-water was measured in all monitoring wells in and adjacent to the treatment zone, converted to water level elevations, and used to determine flow direction at the time of sampling.

Table 5. Groundwater sample collection procedures.

Matrix	Analyte	Container	Preservative	Holding Time
Groundwater	Chlorinated and petroleum hydrocarbons	40 mL VOA	Ice	<24 hours (on site)
		40 mL VOA	HCl, Ice (Fort Lewis EGDY site only)	<7 days (shipped to ASU)

Quality assurance (QA) samples were collected at a frequency of not less than one in 10 samples. QA samples included both duplicate (split) sample collection and analysis and replicate sample analysis.

6.7 SAMPLING RESULTS

Tables 6 and 7 provide the number of locations where groundwater samples were collected and aquifer characterization tests were performed, and the numbers and types of samples and tests conducted. Tables 8 and 9 provide an overview of pre- and post-treatment groundwater concentrations and calculated mass discharge for each site, respectively. Table 9 also provides the calculated mass discharge normalized to the width of the treatment zone perpendicular to the flow direction (mass discharge per linear distance). The mass discharge calculations were performed using the ESTCP-sponsored Mass Flux Toolkit software provided by GSI, Inc. Details including mass flux calculations for individual field sites can be found in Appendix D of the ER-200314 Final Report, *Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment* (Triplett Kingston et al., 2010).

Table 6. Mass discharge sampling transect details for supplemental site investigations.

Site ID	Number of Transect Sampling Locations	Transect Length (ft)	Vertical Sampling Interval (ft bgs)	Number of Depth-Specific GW Samples	Number of Aquifer Specific-Capacity Tests
Hunter Army Airfield Former Pumphouse #2	10	400	12 - 22	48	47
Air Force Plant 4 Bldg 181	10	170	29 - 35	13	9
NAS Alameda Site 5-1, Bldg. 5	7	115	6.5 - 21	39	39
Camp LeJeune Site 89	7	255	3 - 40	78	62
Fort Lewis EGDY Area 3*	N/A	N/A	N/A	N/A	N/A

ft – feet
bgs – below ground surface
N/A – Not Applicable to this site
Note: All analyses were performed via groundwater samples from permanent monitoring wells collected by the Corps of Engineers and were sent directly to ASU for analysis. Analyses were performed pre-, during, and post-treatment to gauge how contaminant flux changed while treatment was occurring.
*Aquifer characterization data for the wells used were obtained from site reports for the Fort Lewis EGDY site.

Table 7. Total number and types of samples collected.[1]

Site	Sampling Location	Number of GW Sample Locations	Number of Aquifer Characterization Test Locations	Analytes
Hunter Army Airfield, Former Pumphouse 2	Permanent monitoring wells	12	11	Petroleum hydrocarbons
	Transect/discrete-depth locations	10	48	
Air Force Plant 4 Bldg. 181	Permanent monitoring wells	18	15	Chlorinated solvents
	Transect/discrete-depth locations	11	13	
NAS Alameda Site 5-1, Bldg. 5	Permanent monitoring wells	11	11	Chlorinated solvents
	Transect/discrete-depth locations	7	39	
Camp LeJeune Site 89	Permanent monitoring wells	26	23	Chlorinated solvents
	Transect/discrete-depth locations	7	78	
Fort Lewis EGDY Area 3	Permanent monitoring wells	17 (16 sampling events)	0* (16 sampling events)	Chlorinated solvents

[1] Exact information on total number of samples collected can be found in Appendix D which contains the Field Reports for each site.

* Aquifer characterization data for the wells used were obtained from site reports for the Fort Lewis EGDY site.

Table 8. Range of permanent monitoring well pre- and post-treatment concentration data (µg/L).

Site	Contaminant	Pre-Treatment Concentration Ranges from Site Documentation (µg/L)		Post-Treatment Concentration Ranges from Supplemental Field Investigations Performed under this Study (µg/L)	
		High	Low	High	Low
Hunter Army Airfield, Former Pumphouse 2	Benzene	1670	102	342	ND*<1
	Toluene	3630	7.6	18	ND<1
	Ethylbenzene	9470	426	377	ND<1
	Xylenes	40,500	594	169	ND<1
	Naphthalene	N/A	N/A	43	ND<1
Air Force Plant 4, Bldg 181	Vinyl Chloride	N/A	N/A	1	ND<1
	1,1-dichloroethene	N/A	N/A	120	ND<1
	Trans-1,2-dichloroethene	N/A	N/A	26	ND<1
	1,1-dichloroethane	N/A	N/A	390	ND<1
	Cis-1,2-dichloroethene	N/A	N/A	14,000	ND<1
	1,2-dichloroethane	N/A	N/A	670	ND<1
	1,1,1-trichloroethane	N/A	N/A	1	ND<1
	Trichloroethylene	285,000	5960	59,000	130
	1,1,2-trichloroethane	N/A	N/A	ND<1	ND<1
	Tetrachloroethene	N/A	N/A	5	ND<1
NAS Alameda, Site 5-1, Bldg. 5	Vinyl chloride	8140	ND<0.5	29	ND<1
	1,1-dichloroethene	15,100	ND<0.5	2	ND<1
	Trans-1,2-dichloroethene	300	ND<0.5	2	ND<1
	1,1-dichloroethane	48,800	15	2	ND<1
	Cis-1,2-dichloroethene	13,700	ND<1.3	71	ND<1
	1,2-dichloroethane	ND<250	ND<0.5	ND<1	ND<1
	1,1,1-trichloroethane	42,000	ND<0.5	ND<1	ND<1
	Trichloroethylene	1600	ND<0.5	76	1
	1,1,2-trichloroethane	ND<250	ND<0.5	ND<1	ND<1
	Tetrachloroethene	54	ND<0.5	47	ND<1

Table 8. Range of permanent monitoring well pre- and post-treatment concentration data (µg/L). (continued)

Site	Contaminant	Pre-Treatment Concentration Ranges from Site Documentation (µg/L)		Post-Treatment Concentration Ranges from Supplemental Field Investigations Performed under this Study (µg/L)	
		High	Low	High	Low
Camp LeJeune, Site 89	Vinyl chloride	1400	ND<1	24,000	ND<1
	1,1-dichloroethene	N/A	N/A	1700	ND<1
	Trans-1,2-dichloroethene	49,800	ND<2	33,000	ND<1
	Cis-1,2-dichloroethene	224,000	ND<2	110,000	1
	Trichloroethylene	541,000	ND<2	140,000	ND<1
	1,1,2-trichloroethane	18,600	ND<2	3600	ND<1
	Tetrachloroethene	3720	ND<2	1800	ND<1
	1,1,2,2-tertrachloroethane	2,240,000	ND<2	240,000	ND<1
Fort Lewis EGDY Area 3	Vinyl chloride	5800	ND<1	170	ND<1
	1,1-dichloroethene	N/A	N/A	24	ND<1
	Trans-1,2-dichloroethene	480	ND<1	38	ND<1
	Cis-1,2-dichloroethene	30,000	ND<1	2200	ND<1
	Trichloroethylene	17,000	2	2200	ND<1
	Tetrachloroethene	9	ND<1	1	ND<1
	1,3,5-trimethylbenzene	88	ND<1	19	ND<1
	1,2,4-trimethylbenzene	22	ND<1	ND<1	ND<1

Note: NAPL was found in a well; ND<X denotes non-detection at X **µ**g/L detection level
*ND – Non-detect

Table 9. Summary of mass discharge (mass flux) calculations at field investigation sites.

Site	Contaminant	Pre-Treatment Discharge (kg/yr)[1]	Post-Treatment Mass Discharge (kg/yr)[2]	Post-Treatment Mass Discharge per Linear Foot (kg/yr/ft)
Hunter Army Airfield Former Pumphouse 2*	Total contaminant flux	5.2×10^{1}	1.9×10^{-1}	1.1×10^{-3}
Air Force Plant 4 Bldg 181**		6.0×10^{1}	2.1×10^{1}	1.4×10^{-1}
			4.9	3.4×10^{-2}
NAS Alameda Site 5-1, Bldg. 5*		4.9×10^{1}	1.3×10^{-1}	9.6×10^{-4}
Camp LeJeune Site 89*		6.8×10^{2}	8.2×10^{1}	5.5×10^{-1}
Fort Lewis EGDY Area 3***		3.2×10^{1}	2.1	1.9×10^{-2}

Notes:
[1] Mass discharge calculations were based on monitoring well data from the documentation.
[2] Mass discharge calculations were based on discrete-depth sampling data, or a combination of discrete-depth sampling data and monitoring well data.
* Mass discharge calculations were base on discrete-depth sampling data only.
** Mass discharge calculations were performed for discrete-depth sampling data only and discrete-depth sampling data with monitoring well data.
*** Mass discharge calculations were based on monitoring well data analyzed by ASU personnel.

7.0 PERFORMANCE ASSESSMENT

The performance objectives of this demonstration included:

- Collecting application data (design, setting, operating conditions, performance) from in situ thermal applications and compiling and synthesizing that information in a way that would assist others to anticipate the applicability and performance of in situ thermal technologies at their sites.
- Assess changes in groundwater quality and contaminant mass discharge from source zones treated with in situ thermal technologies.

The results from each are discussed below. Section 7.1 focuses on the former, while Section 7.2 focuses on the latter.

7.1 EMPIRICAL DATA COLLECTION AND SYNTHESIS WITH EMPHASIS ON SETTING, DESIGN, AND OPERATING CONDITIONS

The in situ thermal treatment application data collected in this study were obtained from a variety of sources including (1) site reports; (2) published literature; (3) USEPA cost and performance reports; (4) discussions with project managers, vendors, and consultants; and (5) unpublished data.

For each technology application reviewed, emphasis was placed on identifying the following:

- The setting (geology, depth to groundwater, source zone boundaries, chemicals present, etc.)
- System design parameters (number of energy delivery points, area and depth of the treatment zone, etc.)
- Operating conditions (temperature achieved, duration of treatment, duration of monitoring, etc.)
- Performance data (emphasizing improvement in groundwater quality and reduction in mass discharge of contaminant to the aquifer).

To simplify geologic interpretation and to provide a consistent base for the site categorization, each technology application reviewed was assigned to one of five idealized geologic scenarios:

- *Scenario A:* relatively homogeneous and permeable unconsolidated sediments (mixtures of sands, gravels, silts, etc.)
- *Scenario B:* largely impermeable sediments with interbedded layers of higher permeability sediments
- *Scenario C:* largely permeable sediments with interbedded lenses of low permeability sediments

- *Scenario D:* competent, but fractured bedrock (i.e., crystalline rock)
- *Scenario E:* weathered bedrock (limestone, sandstone, etc.).

A total of 182 in situ thermal treatment technology applications at 163 different sites were identified in this study. Table 10 presents the number of in situ thermal applications by technology. It also indicates how many were full-scale versus pilot-scale applications and how many occurred since 2000.

Table 10. Summary of technology applications by technology type.

Technology	Number of Applications	Pilot-Scale*	Full-Scale*	Number Since Year 2000
Steam-based heating	46	26	19	15
Electrical resistance heating	87	23	56	48
Conductive heating	26	12	14	17
Other (including mixing/heating)	23	14	9	4
Total	182	75	98	84

* Some sites have an unknown application size and thus are not included in the pilot- and full-scale count.

Since the quantity and quality of information available for each application varied, a scale of 0 to 4 was used to characterize data availability for each site. Table 11 defines this scale and also summarizes the number of applications falling into each category.

Table 11. Characterization of the data available from the 182 applications reviewed.

Level of Data Quantity	Description	Number of Sites
-	Application in progress	1
0	No documentation available at the time of this study	26
1	Insufficient data to assess performance of technology, but some design information	78
2	Limited performance data; some soils and/or groundwater concentration data and some operating data (e.g., temperature information)	37
3	Good performance data record, but insufficient for estimating differences between pre- and post-mass discharge from source zone	26
4	Data sufficient for full assessment of performance (groundwater concentrations and mass discharge)	14
	Total	**182**

Table 12 summarizes the aggregate design information for all applications reviewed, and Table 13 summarizes the basic operating conditions for all of the applications reviewed.

Table 12. Basic design information compiled for all sites reviewed.

Technology	Number of Sites with Target Treatment Zones with Sizes in this Range [ft^2]				Number of Sites with Density of Energy Delivery Points (electrodes or wells) in this Range [# per 100 ft^2]			
	$<10^4$	10^4-4x10^4	<4x10^4	Unknown	<0.25	0.25-0.50	>0.5	Unknown
Steam-based heating	16	6	4	20	20	2	4	20
Resistance heating	36	24	0	27	10	23	27	27
Conductive heating	19	6	0	1	1	1	23	1
Other (including mixing/heating)	8	2	0	13	2	0	8	13

* For the three steam auger sites, the density is one energy point per cell. This does not fit into the number calculation so it is classified as <0.5.

Table 13. Basic operating conditions summary for all applications reviewed.

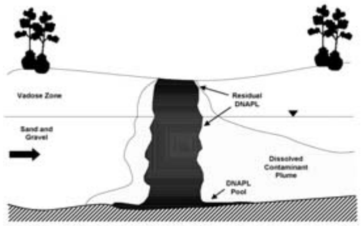
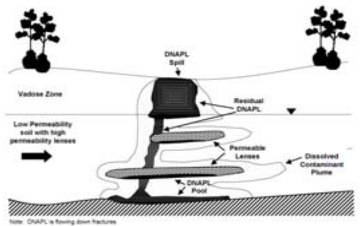
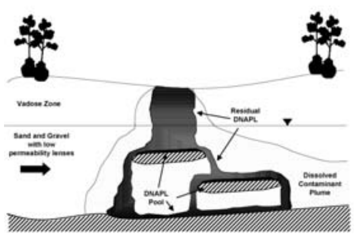
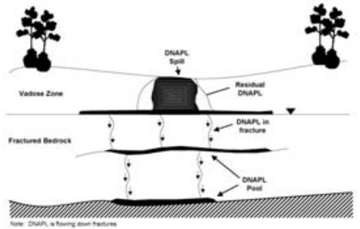
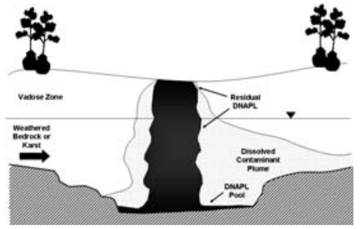
Technology	Number of Sites with Temperatures in Target Treatment Zone in These Ranges [°C]				Number of Sites with Active Heating Durations in These Ranges [y]				Number of Sites with Post-Treatment Monitoring in These Ranges [y]			
	<80	80 - 110	>110	Unknown	<0.5	0.5 - 1.0	>1.0	Unknown	<0.5	0.5 - 2.0	>2.0	Unknown
Steam-based heating	7	13	1	25	14	0	3	29	2	0	0	44
Resistance heating	9	37	0	41	38	2	0	47	1	5	1	80
Conductive heating	0	11*	12*	4	18	3	0	5	1	1	0	24
Other (including mixing/heating)	2	2	1	18	6	0	0	17	3	0	0	20

* One site had two different temperature values. The 80-110 °C temperature was for the saturated zone and the >110 °C temperature for the vadose zone.

Table 14 provides a summary of data collected for each site, including design and operating parameter information. This table was prepared using only data from the 84 applications conducted since 2000, since some might argue that applications conducted in recent years are more representative of the current state-of-the practice. This table was formatted to flow from left to right, beginning with the five "generalized conceptual scenarios."

An additional summary table, the Site-Specific Summary Table, contains detailed site-specific information for all thermal applications identified in this study. This table can be found as Plate 1 of Triplett Kingston et al., (2010).

Table 14. Summary of key information gathered from reviewed applications conducted since 2000.

Generalized Conceptual Scenario	Technology	Total Sites		Chemical(s) Treated				Design Parameters*						Operating Parameters*									Performance Measurements*													Name(s) of Well-Studied Sites
		# of Sites		# of Sites Treating these Chemicals (C-chlorinated solvents, P-petroleum hydrocarbons, W-wood treating, O-other)				# of Sites with Target Treatment Zones with Sizes in this Range [ft^2]			# of Sites with Density of Energy Delivery Points (electrodes or wells) in this Range [# per 100 ft^2]			# of Sites with Temperatures in Target Treatment Zone in these Ranges [C]			# of Sites with Active Heating Durations in these Ranges [y]			# of Sites with Post-Treatment Monitoring in these Ranges [y]			Sites with Final Dissolved Concentrations Generally in this Range [µg/L]			Sites with Concentration Reduction in this Range [%]			Sites with Final Mass Discharges Generally in this Range [kg/y]			Sites with Mass Discharge Reduction in this Range [%]			
		Pilot Tests	Full-Scale	C	P	W	O	$<10^4$	10^4 - $4x10^4$	$<4x10^4$	<0.25	0.25 - 0.50	>0.5	<80	80 - 110	>110	<0.5	0.5 - 1.0	>1.0	<0.5	0.5 - 2.0	>2.0	<10	10 - 100	100 - 1000	10X	100X	1000X	<1	1.0 - 10	>10	10X	100X	1000X	
Generalized Scenario A: relatively homogeneous and permeable unconsolidated sediments (mixtures of sands, gravels and silts, etc.) 	SEE	1	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	Guadalupe
	ERH	1	2	0	3	0	1	1	1	0	0	1	1	0	3	0	1	0	0	0	0	1	0	0	1	1	0	0	1	0	0	0	1	0	Hunter Army Airfield
	ISTD	2	4	4	3	0	2	2	1	0	0	0	3	0	2	2	1	2	0	0	1	0	0	0	1	0	0	1	0	0	0	0	0	0	
	Other	2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Generalized Scenario B: largely impermeable sediments with interbedded layers of higher permeable material 	SEE	2	3	3	2	0	0	1	0	0	1	0	0	0	1	0	1	0	1	1	0	0	0	1	0	1	0	0	0	0	0	0	0	0	
	ERH	10	25	22	15	1	1	14	7	0	3	8	9	3	10	0	11	7	2	1	0	0	1	1	5	2	2	3	0	0	1	1	0	0	Air Force Plant 4
	ISTD	7	9	7	2	2	6	7	3	0	0	1	9	0	7	2	1	5	2	0	0	0	0	0	2	0	2	0	0	0	0	0	0	0	Alhambra Pole Yard
	Other	3	1	2	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Generalized Scenario C: largely permeable sediments with interbedded lenses of low permeable material 	SEE	15	12	8	12	4	3	2	2	1	4	0	0	2	2	0	2	0	3	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	Visalia, Lawrence Livermore National Laboratory
	ERH	4	23	25	5	1	0	4	9	0	1	4	8	1	11	0	8	5	1	0	2	0	0	0	9	7	1	1	2	4	2	6	2	0	NAS Alameda Site 5-1 ERH, Young Rainey Star, Ft. Lewis Areas 1, 2, and 3
	ISTD	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Other	6	2	3	6	0	2	1	2	0	0	0	0	0	0	0	2	0	0	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	Cape Canaveral Air Force Station
Generalized Scenario D: competent, but fractured bedrock 	SEE	1	1	3	1	0	0	2	0	0	1	0	1	1	1	0	3	0	0	1	0	0	0	0	2	2	0	0	1	0	0	1	0	0	Edwards Air Force Base, Loring Air Force Base
	ERH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	ISTD	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Other	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Generalized Scenario E: weathered bedrock 	SEE	2	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	ERH	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	ISTD	1	0	1	1	0	0	1	0	0	0	0	1	0	1	0	1																		
	Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Unknown Scenario	SEE	1	2	2	1	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	ERH	4	4	7	2	0	0	1	3	0	1	2	0	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	ISTD	1	0	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
	Other	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	

* Limited to information from sites with systems installed since 2000 with designs reflecting state-of-the-practice design.

Notes:

84 sites with systems have been installed since 2000, but only 72 of these sites have known geologic settings.

Data may total more than the total number of sites because some sites treated more than one type of contaminant during an application.

SEE – Stream enhanced extraction (steam-based heating)

ERH – Electrical resistance heating

ISTD – In situ thermal desorption (conductive heating)

Other – Other heating methods (i.e., radio-frequency heating or in situ soil mixing combined with heating)

7.2 DATA COLLECTION AND SYNTHESIS WITH EMPHASIS ON PERFORMANCE (GROUNDWATER QUALITY AND MASS DISCHARGE CHANGES)

This section focuses on data collection and synthesis with emphasis on groundwater quality and mass discharge changes as a result of thermal treatment. As a reminder, sufficient data were available for fewer than 10 sites identified in the empirical analysis. That information was combined with the supplemental post-treatment assessment field data collected in this project, resulting in a total of 14 applications. Of those 14, two were described in documents as pilot treatments, but the treatment zone appeared to completely encompass the source zone, so a mass discharge analysis was performed. Table 15 presents estimated order-of-magnitude concentration and mass discharge reductions for those 14 sites, and Table 16 provides estimated mass discharge rates.

Mass discharge calculations were performed using the ESTCP-sponsored Mass Flux Toolkit software by GSI, Inc. In addition to the mass flux calculation, this software allows for an uncertainty analysis of calculations and presents a statistical breakdown of the contribution each sampling location makes to the total mass discharge. An uncertainty analysis was performed for the main contaminant of concern at each field site and can be found in Appendix F of the ER-0314 Final Report, *Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment* (Triplett Kingston et al., 2010).

Table 15. Summary of source zone dissolved groundwater concentration and mass discharge reductions achieved at sites with sufficient data to perform this analysis.

Site No.	Heating Technology	Generalized Scenario/Site	Dissolved Groundwater Concentration Reduction	Mass Discharge Reduction				
				<10x	10x	100x	1000x	>1000x
1	ERH	Generalized Scenario A $^{(SDC)}$	10x			x		
2	ERH	Generalized Scenario B$^{+\ (SDC)}$	<10x	x	x			
3	ERH	Generalized Scenario C	10x		x			
4	ERH	Generalized Scenario C* $^{(SDC)}$	>10x to <100x		x			
5	ERH	Generalized Scenario C$^{\wedge}$	<10x	x				
6	ERH	Generalized Scenario C$^{\wedge}$	<10x	x		x		
7	ERH	Generalized Scenario C	<10x				x	
8	ERH	Generalized Scenario C $^{(SDC)}$	10x		x			
9	ERH	Generalized Scenario C $^{(SDC)}$	100x			x		
10	ERH	Generalized Scenario C	1000x		x			
11	SEE	Generalized Scenario C	100x			x		
12	SEE	Generalized Scenario C	10x	x				
13	SEE	Generalized Scenario C$^{\wedge}$	10000x				x	x
14	SEE	Generalized Scenario D*	<10x	x				

* Pilot application appeared to encompass the entire source zone based on documentation reviewed.

\+ Mass discharge assessment involved two calculations using first only the post-treatment field investigation data and then the post-treatment field investigation data supplemented with data from a set of monitoring wells that were directly in line with the field investigation transect.

^ Site used two different vertical intervals to calculate mass discharge: 1) only shallow geology and 2) shallow and deep geology.

SDC – supplemental data collection site for this project

Table 16. Summary of mass discharge estimates for sites with sufficient data.

Site No.	Heating Technology	Site	Contaminant	Pre-treatment Discharge (kg/y)[1]	Post-treatment Discharge (kg/y)[2]	Post-treatment Discharge per Linear Foot (kg/y/ft)
1	ERH	Generalized Scenario A * (SDC)	Total Contaminant Mass Discharge (sum of all components)	5.2 x 10^{1}	1.9 x 10^{-1}	1.1 x 10^{-3}
2	ERH	Generalized Scenario B** (SDC)		6.0 x 10^{1}	2.1 x 10^{1}	1.4 x 10^{-1}
					4.9	3.4 x 10^{-2}
3	ERH	Generalized Scenario C		4.0 x 10^{-1}	3.1 x 10^{-2}	1.5 x 10^{-3}
4	ERH	Generalized Scenario C * (SDC)		6.8 x 10^{2}	8.2 x 10^{1}	5.5 x 10^{-1}
5	ERH	Generalized Scenario C ^		1.7	6.0 x 10^{-1}	4.0 x 10^{-3}
				2.4	9.7 x 10^{-1}	6.5 x 10^{-3}
6	ERH	Generalized Scenario C^		9.4	2.7 x 10^{-2}	1.4 x 10^{-4}
				4.9	1.6	8.7 x 10^{-3}
7	ERH	Generalized Scenario C^		9.3	1.7 x 10^{-2}	6.3 x 10^{-5}
				7.4	1.6 x 10^{-2}	6.0 x 10^{-5}
8	ERH	Generalized Scenario C*** (SDC)		3.2 x 10^{1}	2.1	1.9 x 10^{-2}
9	ERH	Generalized Scenario C * (SDC)		4.9 x 10^{1}	1.3 x 10^{-1}	9.6 x 10^{-4}
10	ERH	Generalized Scenario C		1.2	5.4 x 10^{-2}	1.6 x 10^{-4}
11	SEE	Generalized Scenario C		4.6	7.3 x 10^{-2}	3.4 x 10^{-4}
12	SEE	Generalized Scenario C		1.3	2.8	1.0 x 10^{-5}
13	SEE	Generalized Scenario C ^		1.9 x 10^{-2}	1.8 x 10^{-7}	1.2 x 10^{-9}
				2.9 x 10^{-4}	1.1 x 10^{-7}	7.1 x 10^{-10}
14	SEE	Generalized Scenario D		9.7 x 10^{-2}	6.1 x 10^{-2}	1.2 x 10^{-4}

[1] Mass discharge calculations were based on monitoring well data from the documentation.

[2] Mass discharge calculations were based on monitoring well data from the documentation, discrete-depth sampling data, or a combination of discrete-depth sampling data and monitoring well data.

* Mass discharge calculations were based on discrete-depth sampling data only.

** Mass discharge calculations were based on monitoring well data analyzed solely by ASU personnel.

^Mass discharge calculations were performed for two different geologic settings: 1) shallow and 2) deep and/or intermediate.

SDC – supplemental data collection site for this project

7.3 SUMMARY OF KEY OBSERVATIONS

In reviewing the information presented in Sections 7.1 and 7.2, the following are of note:

- Documents from 182 applications were collected and reviewed, which included 87 ERH, 46 steam-based heating, 26 conductive heating, and 23 other heating technology applications conducted between 1988 and 2007. This information indicates that a significant number of applications have occurred, and this reflects the acceptance of in situ thermal technologies as viable source zone treatment options.
- Approximately half of the 182 applications have been implemented since 2000, and over half of those were ERH systems. ERH applications outnumber all other applications since 2000 by about a factor of three. There also seems to be a recent

trend in the increasing use of conductive heating and decreasing use of steam-based heating.

- There seems to be a differentiation of the technologies occurring, with it being better understood that steam and ERH are primarily limited to operating temperatures at about the atmospheric boiling point of water (100 °C) or lower and conductive heating is the only option for achieving significantly higher temperatures than that.
- There seems to be a convergence towards relatively closely-spaced energy delivery points in the design of ERH and conductive heating systems. Spacing for most ERH and conductive energy delivery points was less than 20 ft (6 m), while steam application well spacing was usually greater than 20 ft (6 m).
- To date, most applications have been applied to relatively small treatment zones; 117 of 121 treated areas were $<4x10^4$ ft^2 (<4000 m^2 or an acre) and two-thirds of those were <104 ft^2 (<1000 m^2 or one-quarter acre treatment areas). It is also apparent that the spatial extents of many source zones are likely ill-defined prior to treatment. This results in undersized target treatment zones, untreated source zone areas, and minimal beneficial impact to groundwater quality and mass discharge.
- The effect of geologic setting on performance is difficult to discern in this data set because most treatment systems were installed in layered settings, characterized as either primarily fine-grained materials with higher permeability lenses (Generalized Scenario B) or primarily permeable materials with finer-grained lenses (Generalized Scenario C). Thus, our understanding of system design parameters and operating conditions is limited to those scenarios.
- Most applications (independent of specific technology) lasted less than 6 months; there was little documentation as to the criteria or rationale used to determine the duration of operation. There was little indication that the duration of operation was linked to mass removal-, groundwater quality-, or soil concentration-based criteria.

With respect to performance as measured by groundwater quality improvement and mass discharge reduction:

- Data from the five SDC sites indicated that a 100x order of magnitude reduction was achievable if the source zone was adequately delineated and fully encompassed during treatment and if the system was operated for a sufficient period of time. Reductions of less than 100x were seen if the system was not operated for a sufficient period of time, and at sites where the source zone was not fully encompassed a reduction of <10x was typical.
- For sites with a concentration reduction of 100x or more, the final groundwater concentrations could be less than 100 µg/L for individual constituents, which then could correspond to a mass discharge of 1E-01 kg/y or less. This type of treatment is desirable and can be achieved if the treatment is applied to the complete source zone and operated for a sufficiently long period of time.

- Further analysis of the data set focused on mass discharge reduction and its correlation with geology and maximum treatment temperature. Correlations between mass discharge reduction and geology were investigated; however, based on the number of sites with usable data and the fact that many had similar generic geological descriptions, it was not possible to correlate these.

- Temperature was one of the significant operational variables for thermal treatments. For each site, the maximum representative temperature or the highest temperature that was achieved throughout most of the treatment zone and held for at least one day was recorded. Analysis of the data indicated that contaminant concentration reductions ranged from <10x to 100x, and the maximum representative temperatures achieved for each site ranged from 89°C to 100°C. Based on available data, no correlation was found, suggesting achieving a target temperature is insufficient to achieve good cleanup and that application duration, in combination with the treatment zone temperature and treatment zone size, likely control the performance.

8.0 COST ASSESSMENT

8.1 COST MODEL

This ESTCP project did not involve the demonstration and cost-tracking of a technology. Instead, this project was conducted to better understand the post-treatment performance of in situ thermal technologies on DNAPL source zones and the state of the practice for thermal remedial applications.

This project involved:

- Collection, compilation, and critical review of data available from pilot- and full-scale applications
- Definition of settings in which thermal technologies have been applied, the design and operating conditions that were used, and the performance of the systems
- Collection of post-treatment groundwater quality and hydraulic conductivity data to gain additional information on post-treatment groundwater quality and source zone residual mass discharge to aquifers where in situ thermal treatments had been applied.

The cost model discussed below will focus on the supplemental collection of post-treatment groundwater quality and hydraulic conductivity data as the post-treatment sampling conducted for this project could be a model for assessing performance at other sites.

Table 17 summarizes the data collection needs for a post-treatment assessment of groundwater quality and source zone residual mass discharge and the incremental effort required relative to routine data collection at in situ thermal remediation sites.

Table 17. Cost model for post-treatment assessment of in situ thermal treatment.

Cost Element	Data Tracked	Estimated Costs	
Depth to groundwater measurements and conversion to groundwater elevations	Groundwater flow direction and hydraulic gradient determination	No incremental cost or effort – this would be data already ascertained during previous site investigations	
Preparation and depth discrete groundwater concentration and hydraulic conductivity measurements at a variety of locations along a transect downgradient of the treatment zone and perpendicular to flow direction	Depth discrete hydraulic conductivity and groundwater contaminant concentrations at locations along transect	Project Engineer, 80 h	$10,000
		Project Technician, 120 h	$9000
		Drilling costs	$9000
		Sampling supplies	$2000
		Shipping	$1500
		Miscellaneous	$2000
		Laboratory	$9000
Use of Mass Flux Toolkit to determine mass flux and reporting	Mass flux of contaminant	Project Engineer, 40 h	$5000
Waste disposal	NA	3 barrels of GW	$1000
		Total	**$48,500**

8.2 COST DRIVERS

As indicated previously, this ESTCP project did not involve the demonstration and cost-tracking of a technology. The costs provided are for assessment of mass flux from the treatment zone. Cost drivers would include the sampling density, man-hour costs, drilling costs, and analytical costs.

8.3 COST ANALYSIS

The costs described below involve planning, execution, and reporting of a single, post-treatment assessment of mass discharge from the in situ thermal treatment zone, based on the following assumptions:

- Depth-to-water less than 20 ft bgs
- Total depth of contaminated water less than 50 ft bgs
- Sampling density of five depth discrete intervals at 10 locations along a transect
- Formation conducive to the use of direct-push technology
- Depth-discrete samples collected using direct-push technology with a Geoprobe Screen Point Sampler or similar and hydraulic conductivity tests performed using a constant drawdown technique within the sampler
- Waste generation limited to approximately 3 barrels of purge water
- Samples sent to a contract laboratory for USEPA Method 8260B analysis.

Costs associated with the post-treatment evaluation of groundwater concentrations were performed at sites where the formation had cooled to ambient subsurface temperatures. Any costs associated with the time necessary to allow a site to cool down have not been incorporated.

The costs provided above are incremental. Costs will vary based on the thickness of the source zone, the type of drilling and sampling techniques used, the number of samples collected, and the types of analyses requested. It should be noted that for any mass discharge assessment, an increased data density will provide greater confidence in the mass flux estimate.

9.0 IMPLEMENTATION ISSUES

The purpose of the study was to summarize knowledge on the performance of in situ heating technologies. The approach, as it pertains to this project, was to identify sites where thermal technologies have been applied and collect and synthesize available data/documentation for those sites, thus allowing for knowledge on how often each individual technology was being applied. The most challenging implementation issue was a lack of sufficient documentation for most of the 182 applications identified.

Other observations with respect to implementation include the following:

- The sampling conducted in this project is relatively easy to implement although it is at a significantly greater level of detail than is typically collected during post-treatment at in situ thermal remediation applications.
- This technology can be applied under current regulatory guidance and does not require any additional approvals, licenses, etc. beyond those already required for electrical, construction, building, etc. by the state, city, and local governments.

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10.0 REFERENCES

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APPENDIX A

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