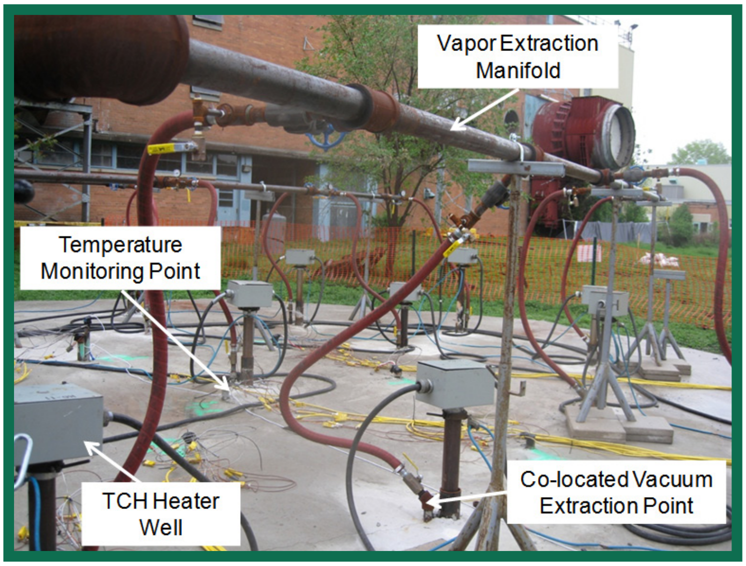
ESTCP
Cost and Performance Report

(ER-200715)



Dense Non Aqueous Phase Liquid (DNAPL) Removal from Fractured Rock Using Thermal Conductive Heating (TCH)

January 2013

ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **JAN 2013**	2. REPORT TYPE	3. DATES COVERED **00-00-2013 to 00-00-2013**

4. TITLE AND SUBTITLE **Dense Non Aqueous Phase Liquid (DNAPL) Removal from Fractured Rock Using Thermal Conductive Heating (TCH)**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Environmental Security Technology Certification Program (ESTCP),4800 Mark Center Drive, Suite 17D08,Alexandria,VA,22350-3605**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**63**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

COST & PERFORMANCE REPORT
Project: ER-200715

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

LIST OF FIGURES

LIST OF TABLES

Page

ACRONYMS AND ABBREVIATIONS

ANOVA	analysis of variance
bgs	below ground surface
BR	borehole
BRAC	Base Realignment and Closure
BTU/hr	British Thermal Units per hour
ºC	degrees Celsius
cis-DCE	*cis*-dichloroethene
cm	centimeter
COC	contaminant of concern
CVOC	chlorinated volatile organic compound
DEM/VAL	demonstration and validation
DNAPL	dense non-aqueous phase liquid
DoD	Department of Defense
ESTCP	Environmental Security Technology Certification Program
F	Fahrenheit
GAC	granular activated carbon
Geosyntec	Geosyntec Consultants
gpm	gallons per minute
HASP	health and safety plan
HO	heater borings
ISTD	in situ thermal desorption
kW	kilowatt
kWh	kilowatt-hour
µg/L	micrograms per liter
MCL	maximum contaminant level
mg/kg	milligrams per kilogram
MNA	monitored natural attenuation
NAPL	non-aqueous phase liquid
NAVFAC ESC	Naval Facilities Engineering Command / Engineering Service Center
NAWC	Naval Air Warfare Center
NJDEP	New Jersey Department of Environmental Protection
NRC	National Research Council

ACRONYMS AND ABBREVIATIONS (continued)

OMB	Office of Management and Budget
OSHA	Occupational Safety and Health Administration
P&T	pump and treat
PCA	principal component analysis
PCB	polychlorinated biphenyl
PCE	perchloroethene
PID	photoionization detector
PLC	programmable logic controller
PMO	Program Management Office
ppb	parts per billion
SCR	silicon controlled rectifier
SERDP	Strategic Environmental Research and Development Program
SVE	soil vapor extraction
SVOC	semi-volatile organic compound
TC	thermocouple
TCE	trichloroethene
TCH	thermal conductive heating
TTZ	target treatment zone
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VC	vinyl chloride
VOC	volatile organic compound
yd^3	cubic yards

ACKNOWLEDGEMENTS

The project team consisted of the following organizations (details regarding these points of contact are provided in Appendix A):

- Naval Facilities Engineering Command / Engineering Service Center (NAVFAC ESC): Carmen A. Lebrón
- TerraTherm, Inc.: Gorm Heron, John LaChance, David Brogan, Steffen Griepke Nielsen, and Devon Phelan;
- Queen's University: Bernie Kueper, David Rodriguez, Ashley Wemp, and Daniel Baston; and
- U.S. Geological Survey (USGS): Pierre Lacombe, Frank Chapelle, Daniel Goode and Claire Tiedeman.

The team greatly appreciates the support of the organizations and individuals that assisted in this endeavor, and through which the successful on-site execution and generation of the Final Report was possible. We would like to thank NAVFAC Base Realignment and Closure (BRAC) Program Management Office (PMO) North East, ECOR Solutions and the USGS who contributed to the implementation of the field demonstration.

Specifically:

- Robert Lewandowski (now retired), Brian Helland and Jeffrey Dale (BRAC PMO North East);
- Patrick Schauble, Matt Lapp, William Torres and Ed King (ECOR Solutions);
- Donna Gaffigan and Bill Hanrahan (New Jersey Department of Environmental Protection [NJDEP]);
- Kathy Davies (U.S. Environmental Protection Agency [USEPA]); and
- Claire Tiedeman, Daniel Goode and Pierre Lacombe without whom executing the on-site demonstration would have been impossible.

We would also like to thank the U.S. Navy and the parcel owners and their representatives for their support.

This page left blank intentionally.

EXECUTIVE SUMMARY

PROJECT OBJECTIVES

The goal of the ER-200715 project was to demonstrate and validate thermal conductive heating (TCH) performance in fractured bedrock and develop guidelines for practitioners on how to apply TCH. Specific project objectives are listed and described in Section 1.2. This Cost and Performance Report summarizes cost and performance results of a TCH field application at the Naval Air Warfare Center (NAWC) fractured bedrock site in West Trenton, NJ.

TECHNOLOGY DESCRIPTION

In situ thermal desorption (ISTD) is the simultaneous application of TCH and vacuum to the subsurface. TCH's primary application uses thermal heating wells, along with extraction wells, which can be placed to almost any depth in virtually any media. During the TCH process, heat is applied to the subsurface using simple electrical heaters installed inside a casing in contact with the soil, so that radiation and thermal conduction heat transfer are effective near the heater. As a result, thermal conduction and convection occur in the bulk of the soil volume. During the TCH demonstration at the NAWC Trenton site, 15 TCH heater borings (HO) (designated HO-1 through HO-15) were installed in addition to 15 vapor extraction points (next to the heater wells, co-located in the borehole) and, eight temperature monitoring points.

During the course of the TCH demonstration, data were collected and compiled to monitor the performance of the TCH system. These data included energy expenditures for the target treatment zone (TTZ) and volumes for water and air removed from the subsurface. Furthermore, an energy balance was set up and maintained during operation to keep track of energy injected and extracted from the TTZ on a daily basis. The energy balance was used to optimize the thermal treatment.

Bedrock samples were collected from borings within the TTZ in order to evaluate TCH performance both before and after treatment. Three boreholes were cored prior to treatment in order to collect the rock samples and establish baseline conditions. Three boreholes were also cored after treatment in order to collect a similar set of rock samples. The pre- and post-treatment core locations were located approximately 2 to 3 feet (ft) apart to ensure that the post-treatment cores would not intersect fractures that had been filled with grout from the pre-treatment coring activities.

DEMONSTRATION RESULTS

Demonstration results from the bedrock samples indicate that the average reduction in TCE concentrations was 41-69%. However, careful examination of selected points in the rock matrix revealed that the rock matrix did not achieve targeted temperature in all locations (due mostly to contaminated groundwater influx through existing fractures). Since discrete sampling was done at 5 ft intervals, it was possible to identify at which depth there was incomplete heating and correlate that with observed fractures from a video log of the boreholes. Eliminating data from the locations where boiling water temperature was not achieved due to cool water influx, the average reduction was higher, at 94.5%. The 94.5% contaminant of concern (COC) mass removal rate is consistent with others findings. For example, in a literature survey conducted by Naval Facilities Engineering Command / Engineering Service Center (NAVFAC ESC) and Geosyntec Consultants under Environmental Security Technology Certification Program (ESTCP) project ER-200424, thermal technologies typically achieved levels of dense non-aqueous phase liquid (DNAPL) mass removal ranging between 94% and 96% (Lebrón et al., 2012). McGuire and others also reported in 2005 that thermal treatment exhibited a median reduction of 95% or greater in parent compounds.

The data also show that most rock concentrations were lowered to around 0-5 milligrams per kilogram (mg/kg), but that higher concentrations were maintained at distinct depth intervals. These depths correlated reasonably well with the depths showing the highest trichloroethene (TCE) concentrations prior to heating. The total amount of TCE removed (vapor and liquid) was estimated to be between 530 pounds (lb) of TCE (based on daily photoionization detector [PID] readings) and 680 lbs (based on analytical data).

All costs associated with the TCH Field Demonstration were tracked. In general, TCH cost depends primarily on the size and depth of the treated subsurface volume. A secondary parameter is the type of rock or sedimentary deposit, particularly its porosity and heat capacity. These parameters determine the amount of energy necessary to heat the target volume to the treatment temperature. In fractured rock, mineralogy of the rock, organic matter content, fracture rinds and fracture patterns and permeability are also important parameters.

TerraTherm utilized its proprietary cost model to produce cost estimates for three treatment scenarios with the same design parameters, but with different treatment areas and volumes to demonstrate the range of treatment costs dependent upon the treatment volume. Sites are classified as follows:

- Small: treatment zone approximately 12,500 cubic yards (yd^3);
- Medium: treatment zone approximately 50,000 yd^3; and,
- Large: treatment zone approximately 250,000 yd^3.

The total remediation time frame for each of the three volume scenarios is approximately 200 days. In fact, this figure is consistent with published literature; for example, McDade et al., 2005 found that the average duration of thermal remediation is 228 days. Costs for three different TCH treatment volumes have been presented in Table 10. In the cost model scenarios the cost per cubic yard ranges from \$269/yd^3 for the Small Site scenario to \$91/yd^3 for the Large Site scenario.

IMPLEMENTATION ISSUES

The key implications of this work for practitioners include:

1. System design must take into account the induced flow of cool groundwater into the treatment volume;
2. Consider the use of larger-diameter vapor extraction points to reduce the potential for liquid entrainment in the extracted steam;

3. Consider smaller-scale testing prior to full-scale deployment to identify potential problems and refine full-scale designs and operations;
4. Consider longer treatment times and/or higher temperatures than those used at this site, to remove contaminants from difficult regions; and
5. Attention should be given to groundwater influx into the treatment zone to determine whether boiling can achieved, and the length of heating time required to achieve boiling.

At the NAWC Trenton site, cooling associated with the substantial water flow through the fractures and the continual influx of contaminants from the bedrock surrounding the TTZ is believed to have limited the remedial efficiency in the bedrock close to such fractures. Use of larger diameter vapor extraction points or grouting in the heater borings and use of separate vapor extraction points would have significantly reduced the amount of water produced by eliminating the percolation effect seen at the vapor extraction points during operation. This percolation effect is created because the steam cannot bubble through the standing water without pushing it out, and the resulting liquid entrainment induces more flow into the TTZ. Using larger vapor extraction points would have likely limited the water extraction rate to the rate of in situ steam production from the fractures and the matrix, thereby limiting the rate of contaminant and cold water flux into the TTZ and enabling efficient heating and treatment of the TTZ. Another potential remedy for full-sale applications would be the use of steam injection to heat the fractures and minimize groundwater inflow from outside of the TTZ.

This page left blank intentionally.

1.0 INTRODUCTION

1.1 BACKGROUND

The removal of dense non-aqueous phase liquids (DNAPL) and associated dissolved phase compounds is challenging in fractured rock given permeability, matrix diffusion, and fracture connectivity issues In fact, in 2005, the National Research Council (NRC) concluded, that: *"Most of the technologies [used to treat DNAPLs] are not applicable in fractured materials"* (NRC, 2005). Yet, despite the fact that there have been no reported cases of DNAPL sites where remediation has achieved drinking water standards, there is still regulatory pressure to achieve strict remedial goals and absolute objectives at DNAPL sites (NRC, 2005).

In a survey conducted by the Navy and Geosyntec Consultants (Geosyntec), 29% of the 118 cases evaluated were fractured media sites (Naval Facilities Engineering Command / Engineering Service Center [NAVFAC ESC] and Geosyntec, 2004). Fractured rock settings offer rather unique challenges, resulting in consumption of a much larger ratio of U.S. Department of Defense (DoD) financial resources. In fractured rock settings, unique challenges arise from the difficulty of characterizing the fracture and flow patterns, and the diffusion of contaminants into the rock matrix where fluid flow is negligible.

Unless treatment removes mass from the matrix, back-diffusion of contaminants can continue for hundreds of years following removal of DNAPL from the open fractures. Therefore, a successful fractured rock remediation technology must target contaminants in both the open fractures and the porous rock matrix.

In August 2001, the DoD Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) sponsored a workshop in which research and development needs for cleanup of chlorinated solvent sites were identified. The panel reached consensus that in situ thermal treatment: 1) is the emerging technology most in need of research (assessment based on the promise of the technology and the uncertainties regarding implementation); and 2) has the potential to remove a very large fraction of the DNAPL mass and may be able to treat even the less permeable areas within the source zone as opposed to technologies relying on hydraulic delivery of reagents (SERDP and ESTCP, 2001).

In 2005, a panel put together by the National Academy of Sciences concluded that *"There's limited field experience applying conductive heating below the water table. If water inflow can be limited, then conductive heating would be expected to be effective in all granular media. However, achieving adequate capture of vapors and liquids and limiting water inflow may be more difficult as heterogeneity increases. There is no experience with conductive heating in saturated fractured media or karst. As control of water inflow may be problematic in fractured media and karst, and capture of contaminants may be difficult, effectiveness is expected to be limited in these settings"* (NRC, 2005).

Thus, ESTCP project ER-200715 was conducted to improve our understanding of thermal treatment in fractured bedrock, both in terms of what is achievable in situ and how the physical properties of fractured bedrock environments affect its performance. The project was funded with the objective of evaluating the efficiency of thermal conductive heating (TCH) to treat DNAPL at a well-characterized fractured bedrock site.

The focus of the field demonstration was to validate the heating strategy, achievable heating rates and fluid control, as well as matrix heating and de-saturation. The on-site application took place at the former Naval Air Warfare Center (NAWC) in Trenton, NJ. The conceptual model for the site is that trichloroethene (TCE) mass is held tightly in the rock matrix, and potentially in some of the fractures at the site. The TCE has dissolved, diffused, and adsorbed to the solid rock matrix (silt and mudstones).

Although TCH had been proven effective for DNAPL removal from fractured clay settings (LaChance et al., 2004), its effectiveness had not yet been demonstrated in bedrock, the most challenging geological setting, at the start of this project. Therefore, TCH was selected for the demonstration as it is the only thermal technology that can reach temperatures in excess of 100 degrees Celsius (ºC) (boiling) between heater borings installed into intact bedrock. There is a continued need for demonstration and validation (DEM/VAL) of successful DNAPL remedial technologies from bedrock sites and determine what type of performance should be expect from the technology.

TCH involves the placement of heater wells that have the capacity of operating at temperatures as high as 800ºC, thereby raising the temperature of the surrounding rock to a target temperature through conductive heating. TCH uses simple electrical heaters suspended inside a cased borehole to deliver energy to the surrounding formation. The heat migrates away from the heater borings by a combination of thermal conduction (driven by a temperature gradient) and convection (migration of steam produced by boiling ground water). Heater borings are typically located in a triangular pattern, using a spacing of 10 to 20 ft. In porous media, DNAPL is treated by heating the target volume to a minimum of the boiling point of water combined with vapor extraction.

1.2 OBJECTIVE OF THE DEMONSTRATION

The goal of the ER-200715 project was to demonstrate and validate TCH performance in fractured bedrock and develop guidelines for practitioners on how to apply TCH. Demonstration objectives are discussed in Section 3.

Specifically, DEM/VAL objectives for the on-site TCH demonstration included:

a) Demonstrate the feasibility of TCH to heat the target volume of rock and water to steam distillation temperatures and the boiling point of water via energy applied to vertical TCH borings. This included evaluating the cooling influence of inflowing groundwater.

b) Validate the degree of heating to temperatures above boiling (100ºC) at different distances from the heater borings. This included validating whether the temperatures recommended for effective treatment in this particular geology (derived from the laboratory work) were achieved.

c) Demonstrate capture of steam and other fluids from the heated boreholes such that vaporized and mobilized contaminants are extracted from the available fractures.

d) Show that the surface equipment meets regulatory demands for contaminant reduction efficiency and emissions.

e) Collect detailed temperature data to support numerical simulations of the heating and effect on remediation progress.

f) Collect rock chip samples to demonstrate temporal changes in contaminant concentrations within the pilot test volume as a function of the TCH application.

g) Collect microbial characterization data to evaluate the effect of the heating process on the potential for natural attenuation or enhanced bioremediation at the site.

1.3 REGULATORY DRIVERS

In 1976, TCE was designated by the U.S. Environmental Protection Agency (USEPA) as a priority pollutant. The Safe Drinking Water Act Amendments of 1986 strictly regulate this chlorinated ethene at a maximum contaminant level (MCL) in drinking water of 5 parts per billion (ppb) (USEPA, 1996). When concentrations at a contaminated site exceed this criterion, remedial action is required to lower these concentrations and reduce the risk to human health and the environment.

This page left blank intentionally.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

In situ thermal desorption (ISTD) is the simultaneous application of TCH and vacuum to the subsurface. TCH's primary application uses thermal heating wells, along with extraction wells, which can be placed to almost any depth in virtually any media. TerraTherm's proprietary ISTD technology is an off-the-shelf remediation technology that has been demonstrated to be capable of remediating the full range of volatile organic compounds (VOC) and semi-volatile organic compounds (SVOC) to levels at or below typical regulatory agency clean-up standards (Stegemeier and Vinegar, 2001).

During the TCH process, heat is applied to the subsurface using simple electrical heaters (shown in Figure 1). As the heating progresses by thermal conduction, the heater wells are heated to temperatures around 500 to 800°C, creating significant temperature gradients in the formation around each heater. Since the thermal conductivity of soil materials only varies by a factor of 2 (Stegemeier and Vinegar, 2001), TCH can be considered to be very precise and predictable regardless of the permeability of the soil or its degree of heterogeneity.

Figure 1. Proprietary TerraTherm heater element.

The metal rod has a diameter of approximately 0.5 inches. The white beads are ceramic isolators. Electric power flows through the steel rod, causing it to heat resistively. Covered by one or more of the following: U.S. Patent Nos. 5,190,405, 5,318,116, 6,485,232 and 6,632,047.

As the heat front moves away from the heaters through the soil by thermal conduction and convection, the superposition of heat from the many heaters results in a temperature rise throughout the TTZ. As soil temperatures increase, contaminants and water contained in the soil matrix are vaporized. While locations close to heaters may achieve temperatures well above the boiling point of water, locations in between heaters need only achieve temperatures to the boiling point of water to accomplish steam distillation for effective removal of chlorinated VOCs (CVOC).

Heating the subsurface to temperatures around the boiling point of water can lead to significant changes in the thermodynamic conditions in the subsurface and can make CVOCs and non-aqueous phase liquid (NAPL) more mobile and removable. The major effects of heating are:

- The vapor pressure of the NAPL increases markedly with temperature. As the subsurface is heated from ambient temperature to temperatures in the range of 100ºC, the vapor pressure of the NAPL constituents will typically increase by between 10 and 30-fold (Udell, 1996).
- Adsorption coefficients are reduced moderately during heating, leading to an increased rate of desorption of CVOCs from the soil (Heron et al., 1998).
- Viscosity of NAPL is reduced by heating. The higher the initial viscosity, the greater the reduction. For TCE and other chlorinated solvents, the viscosity typically is reduced by about a factor of two.
- NAPL-water interfacial tensions are reduced (Heron et al., 2006), which can lead to improved recovery as a liquid, but can also present a mobilization risk if appropriate measures are not implemented. However, this change is very modest compared to the vaporization mechanism.
- Boiling of NAPL at temperatures below the boiling point of water (DeVoe and Udell, 1998). Heating the subsurface to above the boiling point of site contaminants will make the DNAPL thermodynamically unstable, causing it to boil and convert to a vapor. Thus, once the temperature throughout the saturated portion of the target treatment zone (TTZ) has reached the contaminant boiling point, NAPL will no longer be able to exist as a separate phase. Other mechanisms, as discussed below, will then work to remove the remaining contamination.

For chlorinated solvents such as TCE and perchloroethene (PCE), vaporization is the most important physical removal/remediation mechanism. In addition to the physical removal described above, biological and chemical degradation mechanisms may occur during and after thermal remediation. These mechanisms may include thermal destruction by oxidation and pyrolysis near heating elements (for thermal conductive heating) at temperatures around 400EC, microbial mineralization of NAPL components, and hydrolysis at elevated temperature (Baker and Kuhlman, 2002).

A simple sketch of a TCH system is presented in Figure 2. The major equipment used in a TCH installation includes:

- A transformer delivering power for the electrical circuits;
- A power distribution system with switches, meters, and controllers;
- Cables and wiring for the TCH heaters that are located in vertical borings (heater borings);
- The wells and borings:
    - Heater borings;
    - Vapor and fluid recovery borings/wells;
    - Monitoring points;
- Manifold and conveyance piping for extracted fluids; and,
- Treatment system for extracted fluids (vapor and liquids, as required).

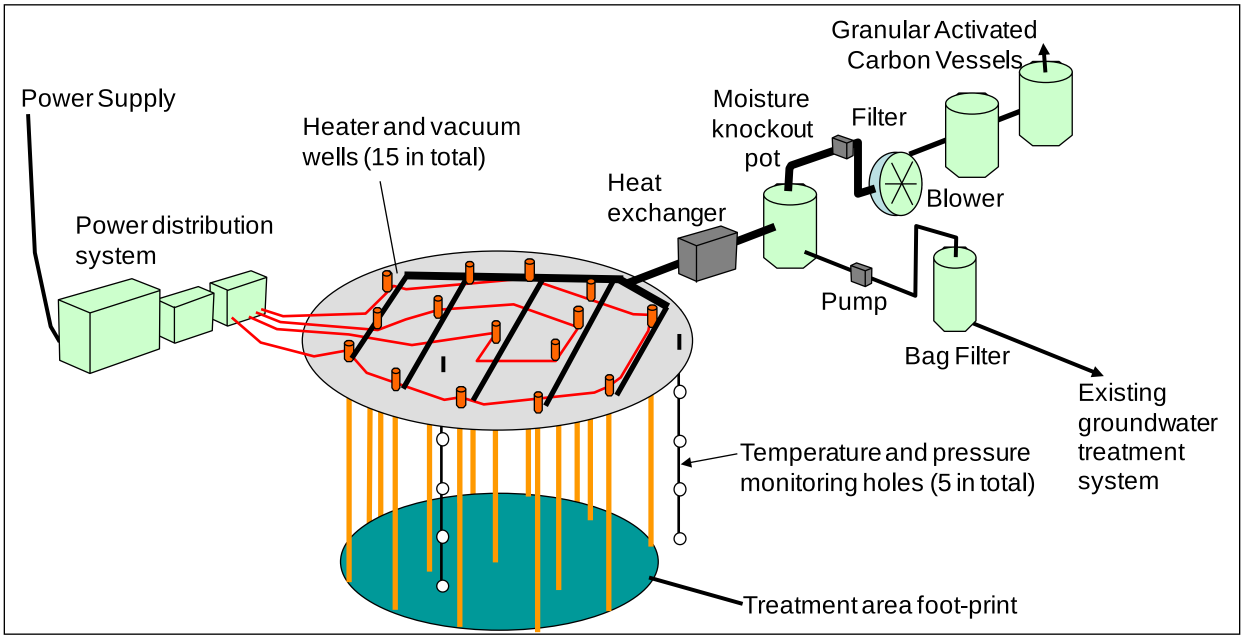


Figure 2. Sketch of TCH implementation.

Typically, an office trailer is used for housing data management computers and other monitoring equipment. The entire process is usually automated, with operators overseeing the system and collecting data and samples during the daytime. As the site is heated, fluids are extracted, cooled, separated, and treated. The subsurface process is monitored using temperature and pressure sensors and detailed sampling and analysis of subsurface fluids.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The major advantages of TCH include:

- Readily predictable heating due to simplicity of the conductive heating approach.
- Uniform heat distribution and treatment.
- No practical limitation on treatment depth or area. The TCH technology is used for enhanced oil recovery applications to depths >1,000 ft and for volumes exceeding 100,000 cubic yards (yd^3).
- Shorter treatment duration. Average treatment duration is 228 days (McDade, et al., 2005).

Potential disadvantages include:

- Energy demand. Typical sites require on the order of 120 to 300 kilowatt-hour (kWh)/yd^3 treated. This equals an energy cost of \$10-30/yd^3. Also, the energy consumption, depending on the source of electricity, may contribute to emissions of carbon dioxide, which contributes to global warming.

- The technology requires invasive drilling and on-site construction activities, which may disrupt site activities temporarily.
- Sensitivity to groundwater flow and cooling. Excessive flow through the heated volume can slow heating, or in some cases prevent certain fracture areas from getting to the target temperature.

For fractured rock sites, any in situ treatment technology will be faced with the upfront challenge of defining the three-dimensional treatment volume. This is particularly important for highly effective technologies such as TCH.

Figure 3 shows the TCH system installed at the NAWC site.

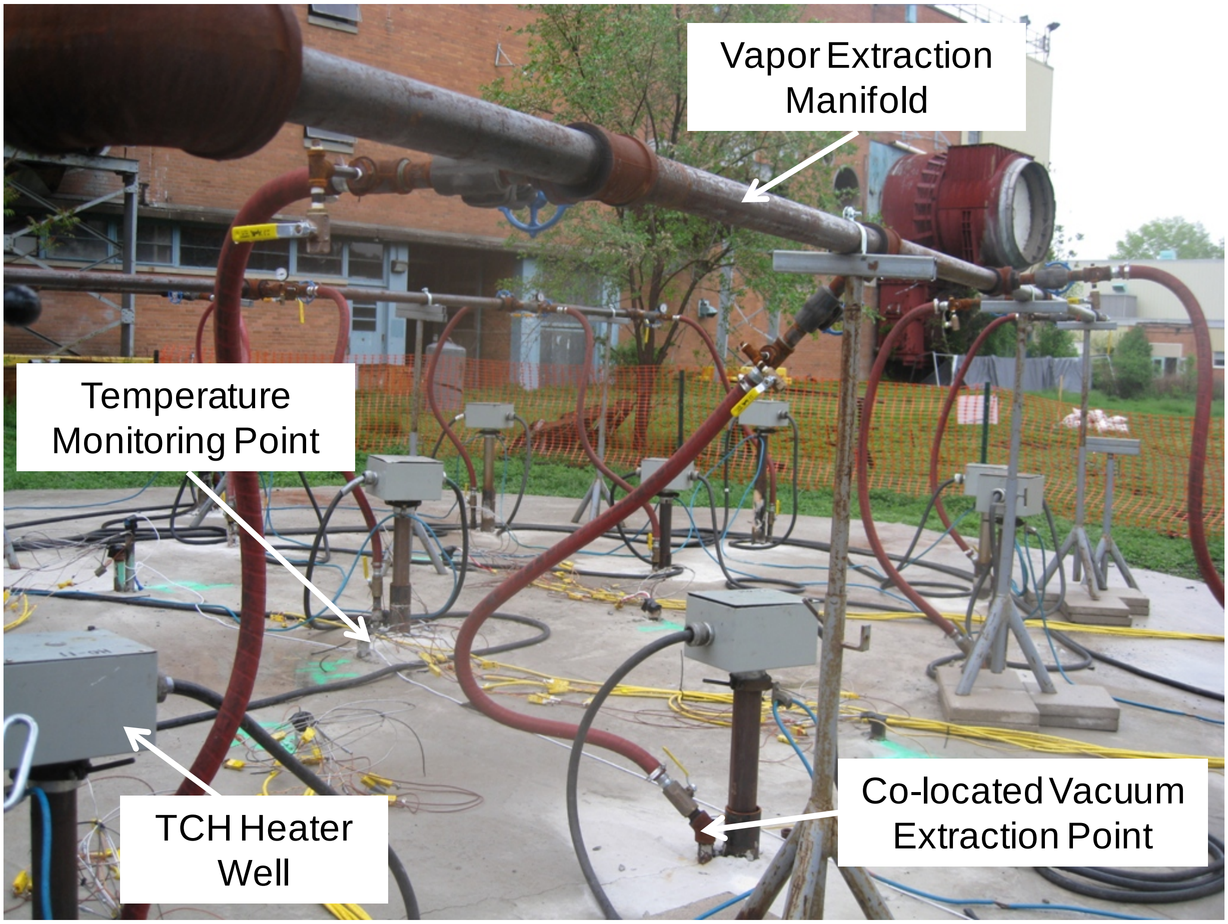


Figure 3. TCH system installed at NAWC site.

3.0 PERFORMANCE OBJECTIVES

This section contains a summary of the performance objectives, identification of whether the objectives were met or not and if the objectives were not met, then an explanation of the reason for failure. A summary of these details are provided below in Table 1.

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Qualitative Performance Objectives			
Faster remediation	• Collection of rock-chip TCE concentrations data before thermal treatment. • Quantification of the mass of TCE removed during thermal treatment. • Collection of rock-chip TCE concentrations data after thermal treatment. • Calculations of changes in average TCE concentrations, and changes in TCE concentration in the larger matrix blocks within the demonstration volume.	Document that contaminant of concern (COC) mass in the rock can be substantially reduced in months or few years of operation.	Objective met. Approximately 530-680 lbs of TCE were removed in 3.5 months of operation. Rock chip concentrations were reduced by 41-69% on average in the rock samples close to fractures where cooling influence hindered complete heating; 94.5% removal accomplished in the samples where target temperatures were achieved.
Achieve acceptable concentrations	• Source area TCE concentrations before and after thermal treatment. • Modeling of groundwater impacts of the treatment.	Reach endpoints faster by reducing mass discharge from source area.	Objective not met. Due to small test volume surrounded by contaminants, and influx of fluids to the treatment zone, end-points could not be validated. Results are consistent with Kingston, et al., 2010, i.e., *"worse performance occurs when the treatment footprint is smaller than the extent of the source zone."* Further, results are also consistent with Kingston, et al in that one to two orders of magnitude (10X to 100X) reductions in dissolved groundwater concentrations are achieved with in-situ thermal systems.
Ease of combining with existing operations	Observation of operations at the thermal test site and the existing pump and treat (P&T) system.	No upset of existing P&T systems including acceptable treatment of vapors and liquids.	Objective met. TCH system successfully operated with existing P&T system.
Ease of use operator acceptance	Recording of operation up-time. Observation of any operational challenges or difficulties.	Successful operation of TCH system with >95% uptime.	Objective met. TCH system successfully operated with 95% uptime.

Table 1. Performance objectives (continued).

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Achieve and maintain target treatment temperatures	Thermocouple data from eight locations, each with approximately 10 sensors (76 sensors total), recorded at least daily.	Achieve and maintain >95ºC above the water table and 100ºC below the water table in target treatment volume.	Objective met in the upper 35 ft of the volume, but not in the bottom 15 ft. Higher than expected groundwater flow at these depths prevented target temperatures from being achieved at the bottom 14 ft.
Reduce COC mass in rock matrix	• Collection of rock-chip TCE concentrations data before thermal treatment. • Collection of rock-chip TCE concentrations data after thermal treatment. • Calculations of changes in average TCE concentrations, and changes in TCE concentration in the larger matrix blocks within the demonstration volume.	Reduce contaminant concentration and mass inside the inner treatment volume in matrix >99% or below 0.1 mg/kg in rock matrix.	Objective not met. Rock chip concentrations were reduced by 41%-69% on average in the rock samples close to fractures where cooling influence hindered complete heating; 94.5% removal accomplished in the samples where target temperatures were achieved.
Assess magnitude and impact of cooling due to groundwater flux through treatment volume	Thermocouple data collected weekly during cool-down inside treatment area and in downgradient wells.	Support observations and interpretation of heating progress, and the impact of groundwater flow on the overall performance.	Objective met. Groundwater flux documented to be 5-10 times higher than expected during treatment. Liquid entrainment caused heating at the bottom 10-15 ft and in major fractures to be slower than expected. Cooling data was obtained during 8.5 months after thermal treatment. Regional groundwater flow, vapor extraction and fractures possibly created during sonic drilling are believed to have exacerbated cooling.
Estimate contaminant mass in the contaminated zone while quantifying mass recovered from demonstration area	Mass flux and totals calculated using flow rate and concentration data for vapor and water streams conveyed to treatment system; based on data collected from the cooled streams.	Maintain water and vapor balances, obtain TCE concentration data, and estimate mass removed.	Objective met. Approximately 500-650 lbs of TCE removed in the vapor phase, and 33 lbs in the liquid phase.
Estimate hazardous materials generated	NAPL recovered from condensing effluent vapors.	Quantify any NAPL collected.	Objective met. No NAPL was collected.
Estimate waste generated	Drilling, construction and demobilization wastes.	Quantify or estimate all major waste streams.	Objective met. Drilling waste (soil and rock cores) disposed of or archived, demobilization waste quantified.
Factors affecting performance	Groundwater flow through treatment zone (interpreted). Rock type, porosity, organic carbon content. Contaminant boiling point and hydrophobicity.	Data to be collected throughout implementation.	Objective met. Estimated effect of groundwater flow through treatment zone, rock type impact, porosity, Organic carbon content and contaminant boiling point and hydrophobicity.

4.0 SITE DESCRIPTION

The TCH field demonstration was conducted at a TCE impacted fractured rock site (U.S. Geological Survey [USGS] Chlorinated Solvents in Fractured Sedimentary Rock Research Site at the NAWC) in West Trenton, NJ (resources available at: http://toxics.usgs.gov/sites/nawc_page.html). The NAWC site was ideal for this demonstration as it is well characterized, having in excess of 100 wells (at least 70 bedrock wells and 30 shallow wells). Several other technology demonstrations have been hosted at the site as well.

These other demonstrations include:

- Single-well hydraulic testing to measure transmissivity,
- Assessment of contaminant distribution,
- Gauging evidence of intrinsic biodegradation and natural processes,
- Assessing efficacy of biostimulation and bioaugmentation, and
- Long-term monitoring tools.

Future and on-going work at the NAWC site includes:

- Estimating matrix diffusion, porosity and transport pathways,
- Understanding relationships between microbial degradation and rock geochemistry,
- Carbon isotope analysis,
- Geophysical time lapse monitoring, and
- Modeling.

All demonstrations at the NAWC site (present and future) complement and did not duplicate the efforts of this project.

4.1 SITE LOCATION AND HISTORY

The NAWC site was a U.S. Navy jet engine testing facility for military aircraft from the mid-1950s until the late 1990s. As a result of the activities at the facility, TCE, jet fuel, and other chemicals leaked into the subsurface.

The conceptual model for the site is that TCE mass was held tightly in the rock matrix, and potentially in some of the fractures at the site. The TCE had dissolved, diffused, and adsorbed to the solid rock matrix (silt and mudstones). The demonstration location at the site is shown on Figure 4.

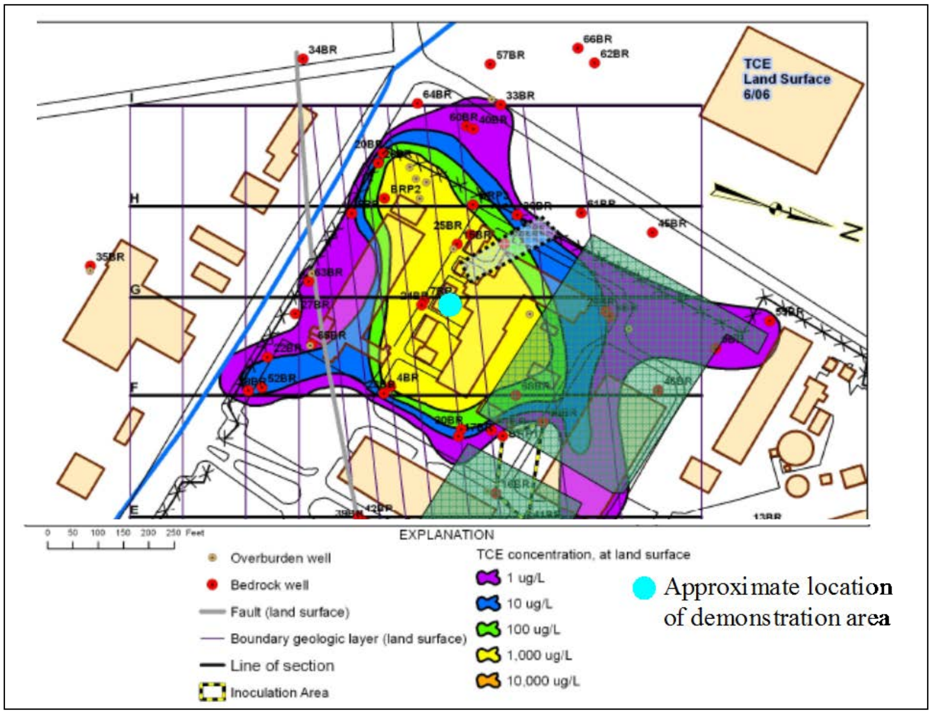


Figure 4. Map showing TCE concentration contours in groundwater and the approximate location of field demonstration area (courtesy of USGS)**.**

4.2 SITE GEOLOGY/HYDROGEOLOGY

The site subsurface is dominated by sedimentary rocks, with silt- and mudstone making up the majority of the sequence. The rocks are heavily weathered from land surface to a depth of about 5 ft and as a result, this portion of the bedrock behaves like an unconsolidated aquifer. Bedrock from 5 to 50 ft ranges from very weathered to unweathered. Water is transmitted in heavily weathered zones and in succinct fractures and partings. At depths greater than 50 ft below land surface, the bedrock is generally unweathered and water is transmitted via succinct fractures or partings. The unstressed regional hydraulic gradient in the bedrock aquifer is southward toward the west branch of Gold Run, but the ground-water flow direction is westward toward the spring. The cone of depression caused by pumping of contaminant and recovery wells at the site is asymmetric with a ratio of at least 4:1. The preferential flow directions in the bedrock aquifer are along bedding, strike, and dip.

4.3 CONTAMINANT DISTRIBUTION

In the TCH field demonstration area, CVOC plume consists of TCE, and its degradation products *cis*-dichloroethene (*cis*-DCE) and vinyl chloride (VC). Water samples from wells 07 borehole (BR) and 24BR, located less than 50 ft from the TCH field demonstration site, have TCE concentrations that range from 5000 to 60,000 micrograms per liter (µg/L) during the past 3 years. *Cis*-DCE concentrations range from 10,000 to 25,000 µg/L and VC concentrations range from 500 to 2000 µg/L. At present, the major CVOC contamination plume is 75 to 125 ft below ground surface (bgs). Excavation, P&T, and monitored natural attenuation (MNA) have reduced the aqueous phase TCE in the fractures. It is unclear the extent of the aqueous phase in the primary porosity or as DNAPL.

5.0 TEST DESIGN AND OPERATIONAL CONDITIONS

5.1 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The TCH remediation process entails the use of equipment installed above and below ground for the treatment of subsurface contaminants. The major underground and aboveground operating components of the TCH system are described in general terms in the sections below.

5.1.1 TCH Well Installations

The total number of borings installed for the field demonstration was as follows:

- 15 TCH heater borings (designated HO-1 through HO-15);
- 15 vapor extraction points installed next to the heater wells (co-located borehole); and
- 8 temperature monitoring points.

Sonic drilling was used to install the wells at the site. The boreholes at the site were installed as close as 1.2 ft apart. The heater well spacing was as close as 5 ft for the demonstration. On a full scale TCH project the heater spacing is typically 12 to 15 ft. The combination of the close well spacing and the vibrations induced to the rock formation during drilling may have created additional fractures and have caused the hydraulic conductivity of the fractured bedrock in the demonstration area to increase.

5.1.2 Heater Borings with Co-Located Vacuum Extraction Points

The heaters were used to apply energy to the TTZ. A total of 15 heater borings were installed at NAWC in a cylindrical area approximately 20 ft in diameter. Each heater boring consisted of a 3-inch diameter, non-perforated carbon steel casing with a bottom seal, installed to a depth of ~6 ft bgs. Each vacuum extraction point consisted of 1-inch diameter, stainless steel screen with bottom seal, installed in the same borehole as a heater well, to a depth of ~54 ft and screened from 5 to 54 ft. The heater borings with co-located vacuum extraction points are conceptually shown in Figure 5.

A single ISTD heater element was placed inside each stainless steel liner and set inside the heater can. Groups of heater wells were wired in series to deliver up to approximately 350 watts per foot of heated length to the subsurface at full power. A silicon controlled rectifier (SCR) power controller and remote temperature controllers were used to regulate the power application to the ISTD heaters based on temperature input from thermocouples (TC).

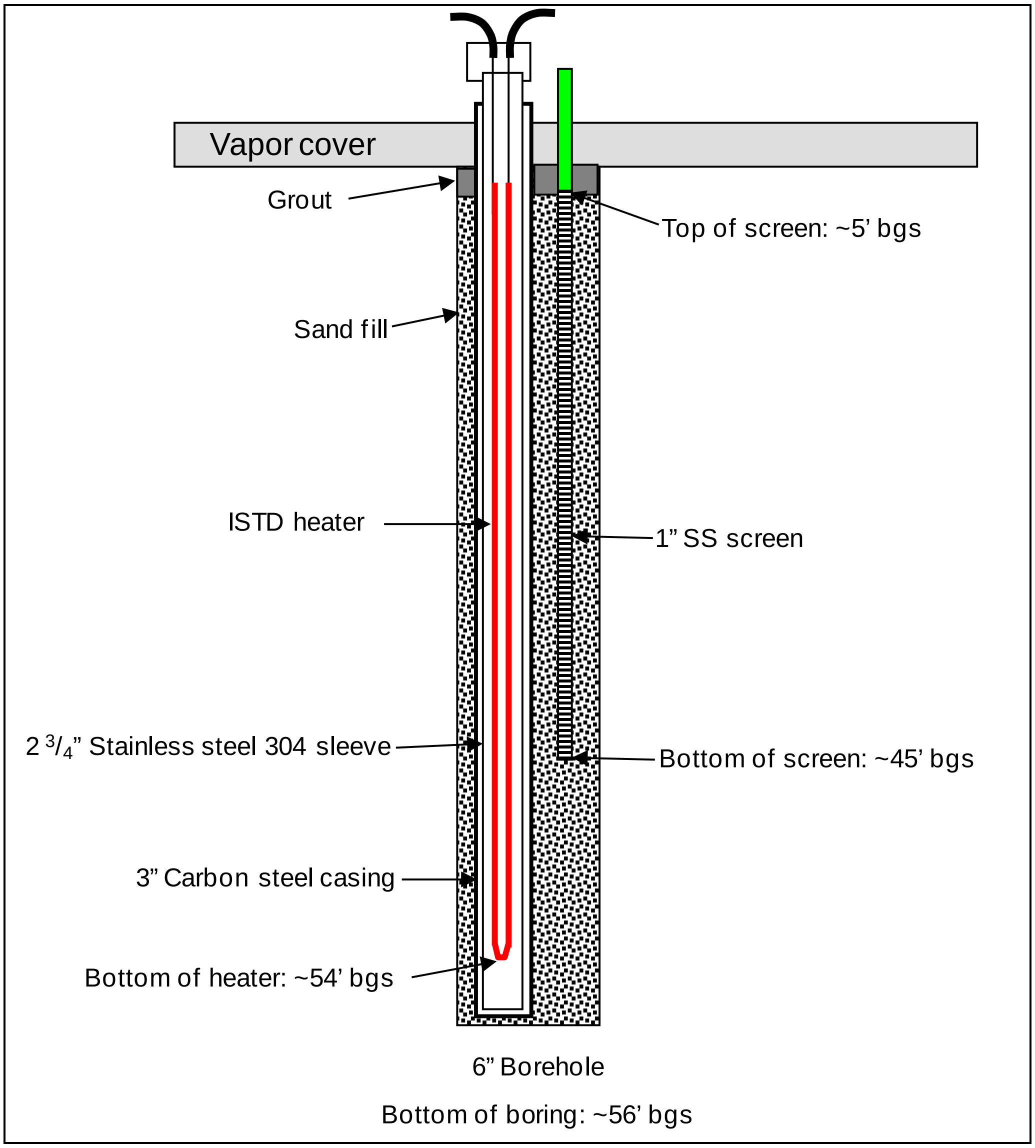


Figure 5. TCH heater boring with co-located vacuum extraction point.

5.1.3 Temperature Monitoring System

The temperature monitoring system was used to monitor heating progress during and after treatment. A total of 8 monitoring points were installed for the field demonstration. Each temperature monitoring well had approximately 10 TCs located 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 ft bgs.

5.1.4 Vapor Handling/Treatment Equipment

The aboveground vapor collection and treatment system to treat extracted vapors included:

- Graphite Block Heat Exchanger
- Chiller
- Knockout Pot

- Transfer Pumps
- Vapor Phase Carbon Vessels

Steam, vapors, and liquid droplets were extracted from the 15 vapor extraction points, passed through a heat exchanger and separated in the knockout pot. The extracted vapors passed through the knockout pot for subsequent treatment, while the separated liquids were pumped to the existing groundwater treatment plant operated by ECOR Solutions, who operates the site's P&T system.

An aerial view of the completed process treatment equipment for the TCH field demonstration is shown in Figure 6 below.

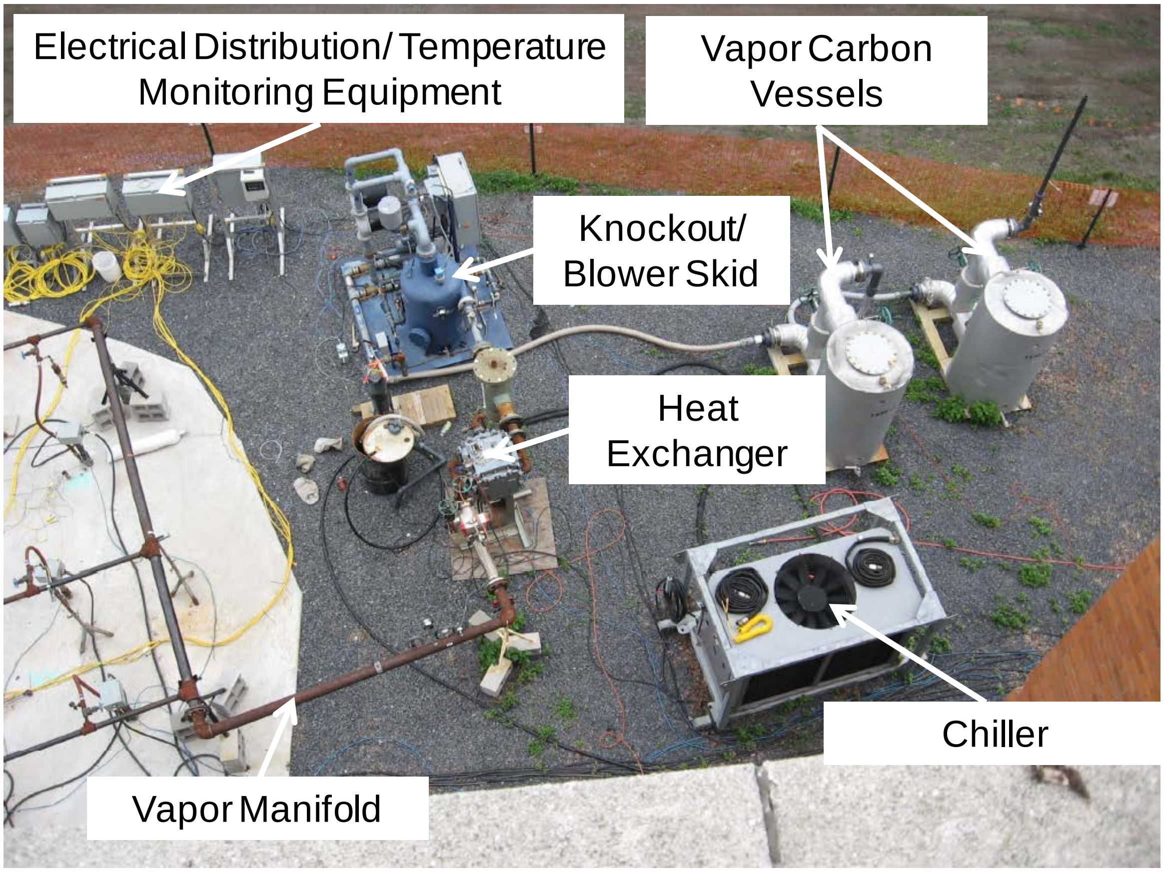


Figure 6. Aerial view of completed process treatment system (courtesy of USGS)**.**

5.1.5 System Controls

A programmable logic controller (PLC) manufactured by EOS Research, Ltd. operated and monitored the heating and vapor collection system functions. The PLC was connected to a telephone line for remote monitoring and for automated alarm notifications in the event of system faults. This PLC also had the capability to remotely shut down the vapor and liquid extraction and treatment systems if necessary.

5.2 BASELINE CHARACTERIZATION

Baseline characterization specific to the TCH site involved the following:

- Collection of three sonic drilling cores.
- Collecting samples to determine the following rock parameters: matrix porosity, organic carbon, pore throat distribution and bulk density.
- Geophysical logging. The 15 HO boreholes were gamma-ray logged to compare with the locally developed geologic framework.
- Water levels were monitored in 18 intervals in a network of nine bedrock wells within 200 ft of the TCH research site.
- Video inspection of three boreholes (BR1, BR2 and BR3) with a downhole video camera to determine the location and size of fractures in each of the three boreholes.
- Each of the three boreholes BR1, BR2 and BR3 were pressure tested with water at four depth intervals during drilling to gain data to determine a depth specific hydraulic conductivity.

5.3 LABORATORY TESTING AND MODELING

Numerical modeling was carried out as part of this project to evaluate the influence of inflowing cold groundwater on the ability to heat fractured rock, and to evaluate the influence of various rock properties on the ability to achieve boiling in the rock matrix using TCH.

The results of this modeling indicate that careful attention should be given to groundwater influx into a target treatment zone in order to determine whether the boiling of water can be achieved, and the length of heating time required to reach boiling. Calculating the groundwater influx at a fractured rock site is typically carried out using measurements of bulk rock hydraulic conductivity and hydraulic gradient. Given the likely variability of flow rate amongst individual fractures in a treatment zone (flow proportional to fracture aperture cubed), more accurate assessment of the influence of inflowing cold groundwater can be determined on the basis of knowledge of individual fracture apertures and fracture spacing. Groundwater influx may prevent or delay the heating of fractured rock during application of TCH. When bulk groundwater influx is high, temperatures in the fractures are influenced by the aperture and spacing of fractures. For medium and low values of influx, fracture properties do not appear to be as important in determining the temperature in fractures. In these cases, it appears not to be important to characterize discrete fracture features in the treatment zone; only a quantification of the total groundwater influx through the treatment zone is necessary.

The performance of TCH in fractured rock environments is expected to be strongly dependent on the hydraulic properties of the rock matrix (permeability, porosity), aperture, and spacing of fractures. If complete removal of all liquid water is the goal of thermal treatment, treatment time will be strongly governed by the magnitude of the pressure spike that occurs in the rock matrix during heating. When the rock matrix has a low permeability, high porosity, or sparse fracturing, this pressure rise may be enough to significantly raise the boiling point of water in the matrix, thus delaying treatment. Because a clear temperature plateau may not be observed in the matrix during boiling, it may be difficult to determine if boiling has occurred throughout a treatment area from temperature measurements alone.

Modeling results also showed that variations in material properties (rock density, rock thermal conductivity, and rock heat capacity) amongst rock types do have a small effect on the early-time temperature distribution in the rock, but on the whole are less significant than variations in hydrogeological parameters (hydraulic gradient, fracture aperture, and fracture spacing). It is noted that the range of variation in material properties is much smaller than the range of hydrogeological properties, which may vary by several orders of magnitude. This stresses the need for proper site characterization.

Low matrix permeability, high matrix porosity, and wide fracture spacing can contribute to boiling point elevation in the rock matrix. Consequently, knowledge of these properties is important for the estimation of treatment times. Because of the variability in boiling point throughout a fractured rock treatment zone and the absence of a well-defined constant temperature boiling plateau in the rock matrix, it may be difficult to monitor the progress of thermal treatment using temperature measurements alone. This is particularly relevant in low matrix permeability rock where thermal expansion of groundwater leads to pressure increases, which in turn result in elevated boiling points for water. Due to the importance of fracture spacing in determining the pressure rise in the matrix, a discrete fracture model is more appropriate than an equivalent porous medium model for simulating boiling in this context.

Furthermore, semi-analytical transient solutions were developed as part of the project to evaluate what level of fractured porous media (e.g., bedrock or clay) matrix clean-up must be achieved in order to achieve compliance of fracture pore water concentrations within a specified time at specified locations of interest. The developed mathematical solutions accounted for forward and back diffusion in a fractured porous medium where the initial condition comprises a spatially uniform, non-zero matrix concentration throughout the domain. Illustrative simulations incorporating the properties of mudstone fractured bedrock demonstrate that the time required to reach a desired fracture pore water concentration is a function of the distance between the point of compliance and the upgradient face of the domain where clean groundwater is inflowing. Shorter distances correspond to reduced times required to reach compliance, implying that shorter treatment zones will respond more favorably to remediation than longer treatment zones, in which back-diffusion dominates the fracture pore water response. For a specified matrix clean-up goal, compliance of fracture pore water concentrations will be reached sooner for decreased fracture spacing, increased fracture aperture, higher matrix fraction organic carbon, lower matrix porosity, shorter aqueous phase decay half-life, and a higher hydraulic gradient. The parameters dominating the response of the system can be measured using standard field and laboratory techniques.

5.3.1 Laboratory Treatability Studies Results

Laboratory studies conducted in support of this project included:

- Bench scale evaluations to identify optimum temperatures (*temperature profile* testing) and duration (*duration profile* testing) on different types of rock; three types of mudstone (found at the NAWC site), siltstone, limestone, sandstone and dolostone.
- Microbial enumeration both before and after heating to determine the effect of the heating on on-site microflora and if that effect was temporary.

The seven rock types were employed to assess the relationships between temperature, heating duration and degree of contaminant mass removal. Core samples of each rock type were cut to provide 40 discs (total of 280 discs) measuring 1 centimeter (cm) in thickness and 5 cm in diameter. A total of 28 discs were retained for heating experiments involving TCE and PCE for each of the seven rock types, while 12 discs were retained for physical characterization measurements (Figure 18) for each of the seven rock types.

Results indicate that heating duration had a greater effect on the degree of TCE and PCE mass removal compared to heating temperature. In heating *duration profile* tests, the majority of contaminant mass removal was achieved in the early stages of heating. In samples of sandstone, dolostone, limestone and siltstone further heating did not lead to a significant decrease in contaminant concentration. Heating *temperature profile* tests required final target temperatures of 200°C to remove the majority of the contaminant mass. In thermal field applications, extending treatment duration under standard operational temperatures beyond the boiling point of water would, therefore, be more effective than elevating temperatures above the boiling point of water. The removal of TCE and PCE from the rock matrix by heating was not found to be sensitive to the chemical properties of the compounds.

Rock properties had a significant effect on contaminant mass removal during heating experiments. It was determined that the rock properties observed in samples of sandstone and dolostone, such as high porosity and low fraction organic carbon, contributed to the increase in contaminant mass removal during the heating tests. In field applications, fractured bedrock with higher porosities and lower fraction organic carbon would favor the performance and effectiveness of thermal treatment in the removal of TCE and PCE.

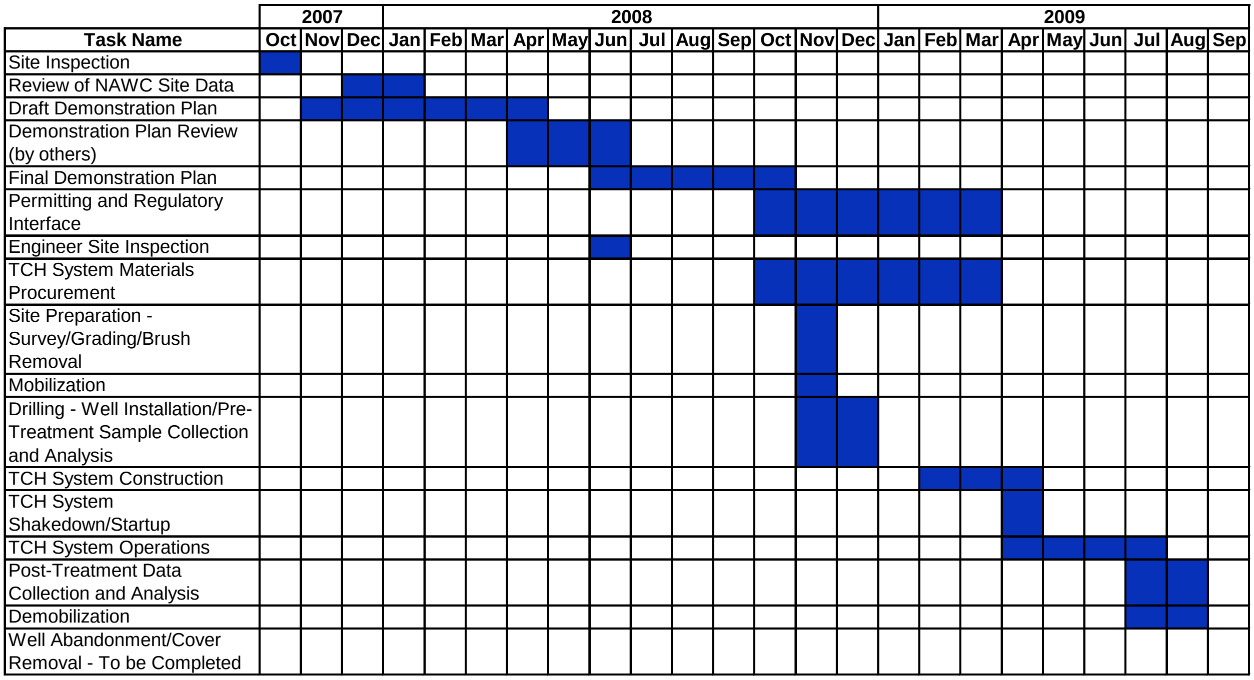
Principal component analysis (PCA) revealed that porosity favored the degree of contaminant mass removal from the rock matrix. In contrast, fraction organic carbon had a negative effect on the contaminant mass removal. Samples of sandstone and dolostone with a combination of higher porosity and lower fraction organic carbon exhibited higher degrees of contaminant mass removal. Samples of gray mudstone, limestone, red mudstone and siltstone had similar porosities and fraction organic carbon. The latter indicates that in a field application, such types of rock could present a similar contaminant mass removal under heat treatment at similar conditions. Finally, with a combination of lower porosity and higher fraction organic carbon, black mudstone (found at the NAWC site) exhibited the lowest degree of contaminant mass removal.

5.4 FIELD TESTING

TCH operations ran continuously for 106 days, 24 hours per day, 7 days per week without any major shutdowns other than shutdowns for scheduled maintenance and minor equipment replacement and granular activated carbon (GAC) change-outs.

The heating period lasted a total of 97 days, while the extraction system operated for 106 days. This included 6 days of startup, 97 days of operation, and 3 days of cool down.

A schedule of the field activities during the TCH on-site demonstration is presented in Figure 7 below.



	2007			2008											2009								
Task Name	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
Site Inspection	■																							
Review of NAWC Site Data			■	■																				
Draft Demonstration Plan		■	■	■	■	■	■																	
Demonstration Plan Review (by others)							■	■	■															
Final Demonstration Plan									■	■	■	■	■											
Permitting and Regulatory Interface													■	■	■	■	■	■						
Engineer Site Inspection									■															
TCH System Materials Procurement													■	■	■	■	■	■						
Site Preparation - Survey/Grading/Brush Removal														■										
Mobilization														■										
Drilling - Well Installation/Pre-Treatment Sample Collection and Analysis														■	■									
TCH System Construction																	■	■	■					
TCH System Shakedown/Startup																			■					
TCH System Operations																			■	■	■	■		
Post-Treatment Data Collection and Analysis																						■	■	
Demobilization																						■	■	
Well Abandonment/Cover Removal - To be Completed																								

Figure 7. TCH field demonstration schedule.

5.5 SAMPLING METHODS

The overall goal of the sampling and analysis program for the TCH demonstration at the NAWC site was to provide the data required for evaluation of the TCH system effectiveness on the impacted bedrock and groundwater at the site, and provide sufficient data for applying the technology to other sites in the future.

Specific objectives of the sampling were:

- Evaluate the effectiveness of the TCH technology in removing COCs from bedrock;
- Evaluate the effectiveness of the process treatment system;
- Evaluate the impact of treatment on the groundwater quality within the TTZ;
- Calculate COC mass removed from the subsurface;

- Provide data for site-specific validation of a heat conduction/steam migration model; and,
- Demonstrate that the Health and Safety Plan (HASP) criteria were maintained during operation of the TCH system.

To achieve these project objectives, the sampling and analysis program implemented the following activities:

- Collection of samples of the bedrock within the TTZ for quality analysis before and after treatment;
- Collection of samples of process vapor generated during operation of the TCH system to evaluate mass removal of COCs;
- Collection of process flow, pressures and process temperature data to ensure that the process treatment system was running properly and to gain data needed to evaluate the mass removal of COCs;
- Collection of samples of condensate generated during operation of the TCH system to evaluate mass removal of COCs;
- Collection of detailed temperature data during the project to support numerical simulations of the heating and its effect on remediation progress;
- Collection of rock samples for analysis of physical attributes before and after treatment;
- Collection of groundwater samples from bedrock borings within the TTZ before treatment; and,
- Monitoring of the ambient air quality to confirm that project-specific HASP criteria were not exceeded during construction or operation of the TCH system.

5.6 SAMPLING RESULTS

5.6.1 TCE Mass Removal

The data at the inlet to the vapor phase carbon units is shown in Figures 8 and 9. It was estimated that approximately 500 lbs of VOCs calculated as TCE were removed in the vapor stream alone based on observed PID readings and flow rates and by using the PID correction factor for TCE. The estimate of 650 lbs is based on total VOCs detected by the laboratory in the Summa canister samples.

The VOC mass removal rate based on photoionization detection (PID) was 4.7 lbs/day on average while the removal rate based on Summa canister samples was 6.2 lbs/average. The vapor mass removal rates were typically 2-10 lbs/day during operation. The mass removal of VOCs in the liquid phase was 0.3 lbs/day on average.

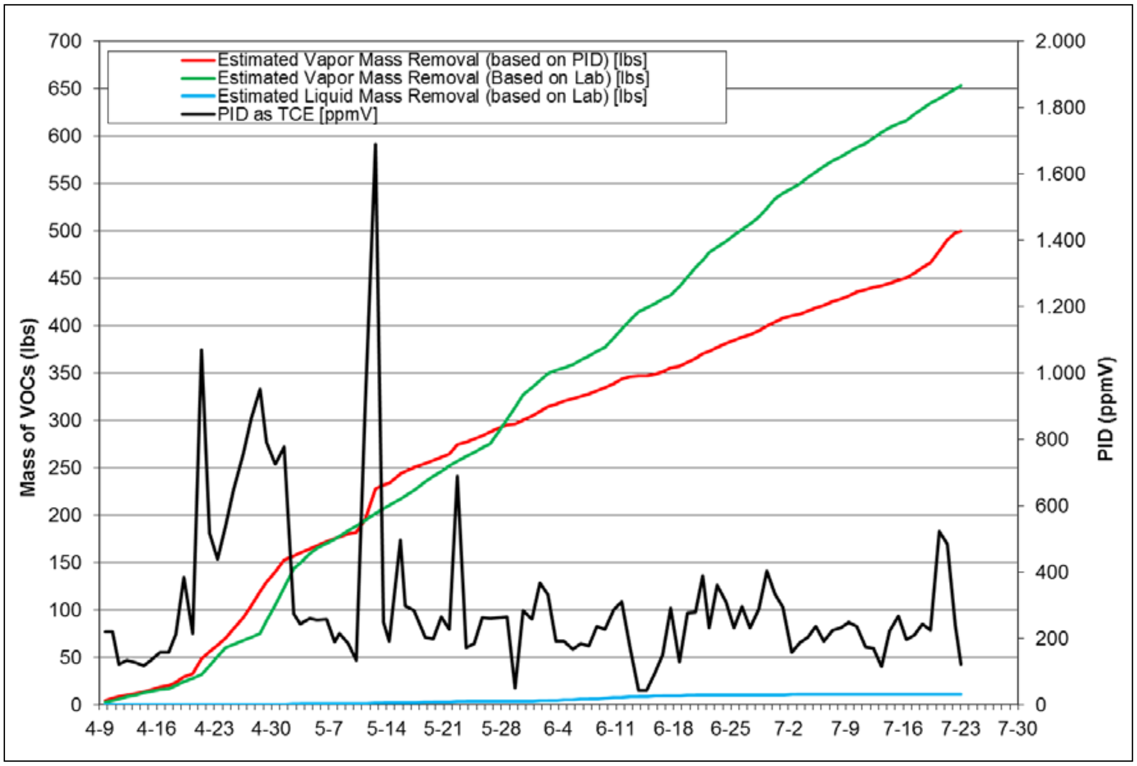


Figure 8. PID readings on vapor stream samples and associated mass removal estimate.

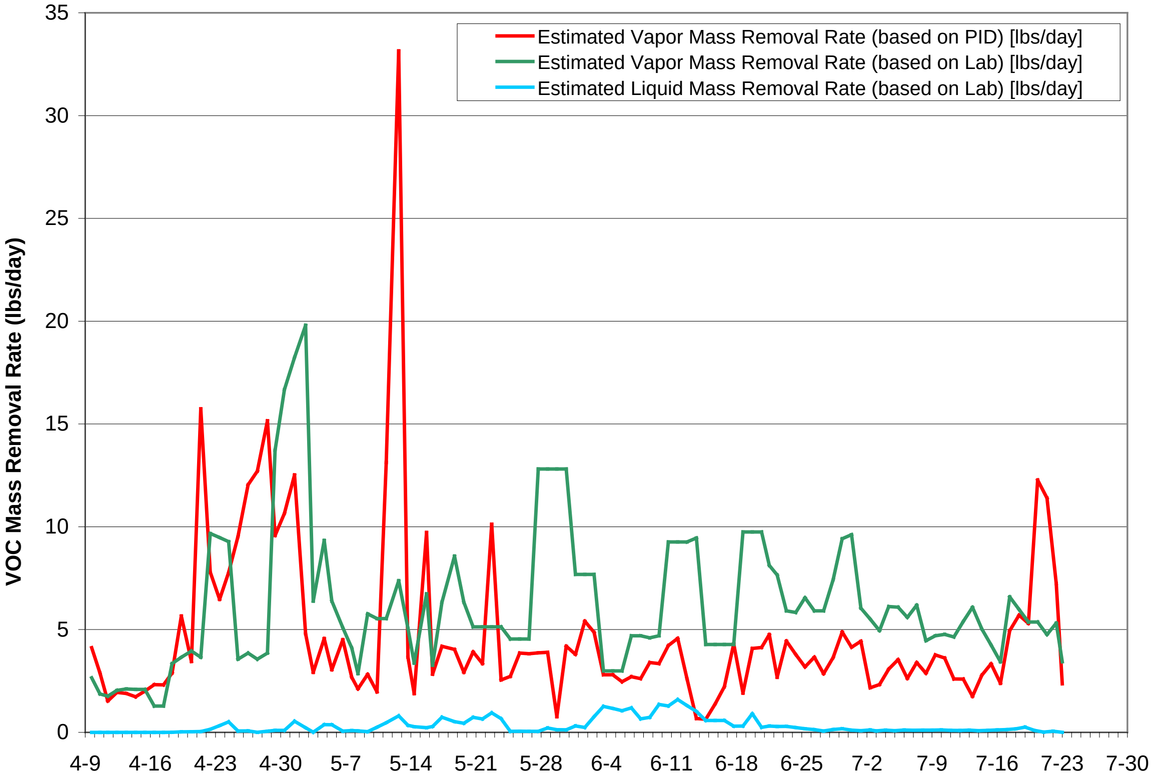


Figure 9. Estimated VOC mass removal rate during operations.

The laboratory data collected from the vapor stream show a similar trend as presented in Figure 10.

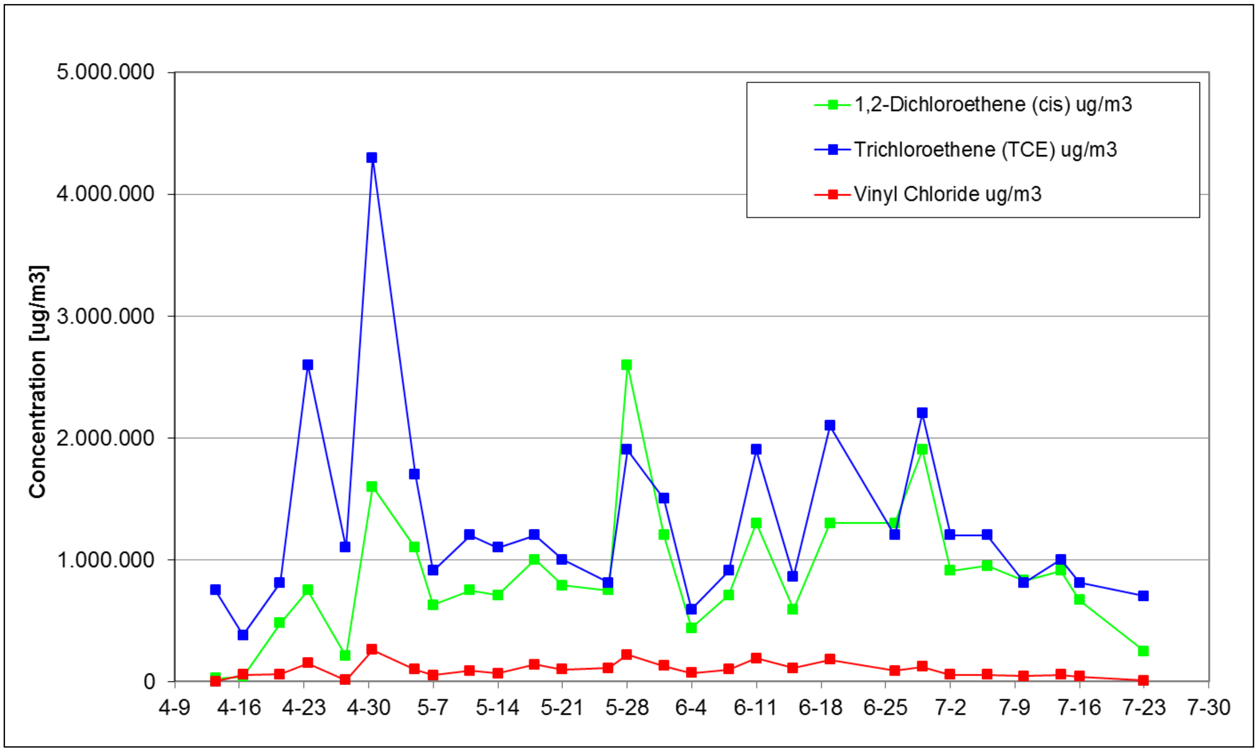


Figure 10. Vapor stream VOC concentrations for the dominant compounds.

The more or less consistent level of VOCs in the vapor stream during the last 2 months of heating indicates that VOCs are entering from outside the TTZ and supplying additional mass to the treatment area. As cold, contaminated water flows towards the heaters, the groundwater is heated by thermal conduction from the matrix, and while some of the VOCs are vaporized, the fracture zones remain cooler than the larger matrix blocks.

It is noteworthy that the VC concentration remains significant in the entire operations period. Since VC is the most volatile VOC at most sites, it is normally removed within the first month of heating. The persistent level of VC in the vapor stream indicates that groundwater flowing into the TTZ was providing a constant source of contaminant mass entering the TTZ.

The VOC concentrations in the entrained water from the TTZ are shown in Figure 11. The trends are similar to those seen for the extracted vapor. Based on these concentrations and measured liquid extraction rates, an estimated 33 lbs of TCE were removed in the liquid phase during TCH operations.

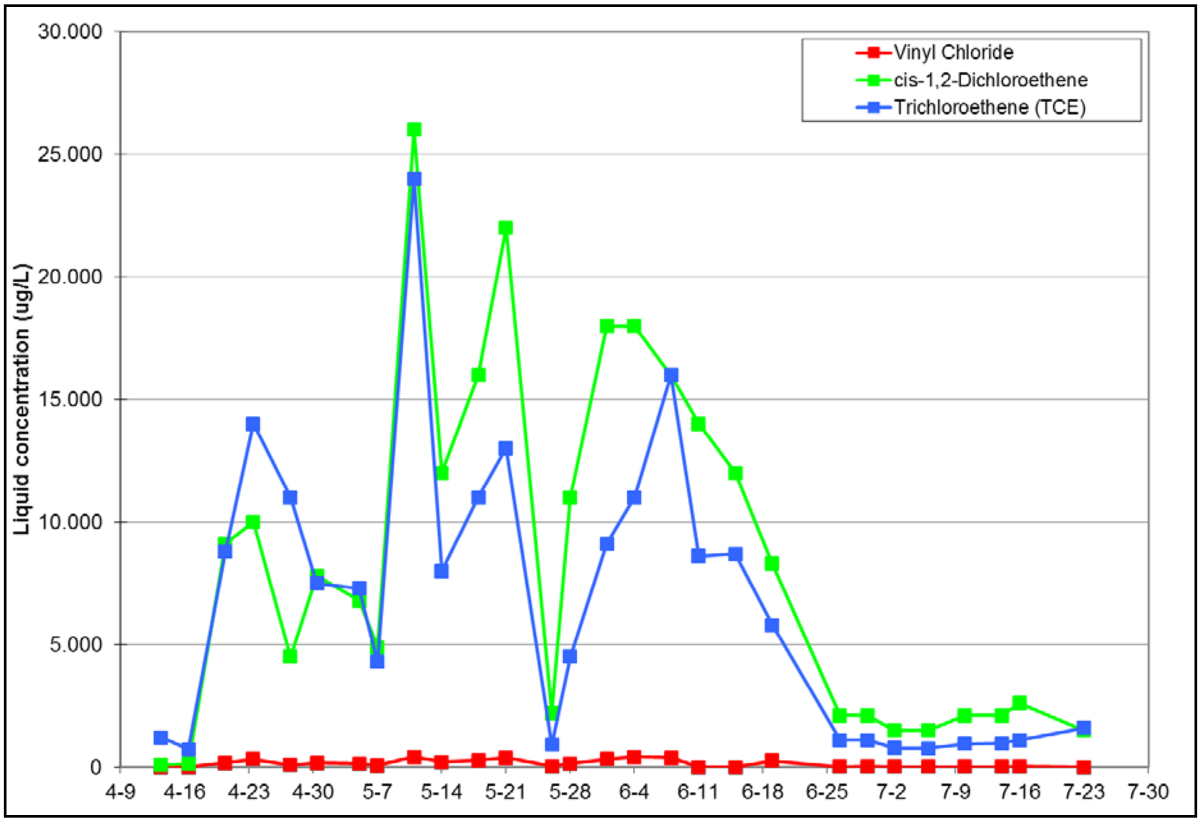


Figure 11. Liquid stream VOC concentrations for the dominant compounds.

The trend in the extracted water VOC content supports the theory that VOCs entered the treatment area via influent groundwater.

Based on these data, a total (vapor and liquid) of approximately 530 lbs based on daily PID readings and approximately 680 lbs based on analytical data of TCE was extracted from the site.

5.6.2 Bedrock TCE Concentrations

The rock concentration of TCE was measured at three locations inside the TTZ pre- and post-thermal treatment. Pre-treatment rock concentrations were collected from BR1, BR2, and BR3, all located in centroid points. After collecting the pre-treatment rock samples temperature monitoring point T1 through T3 were installed at the three sampling locations, respectively. Approximately one week after heating ceased post-treatment rock samples were collected from neighboring holes located less than 1 to 2 ft from the pre-treatment borehole. The three pre- and post-treatment rock sampling locations are shown in Figure 12.

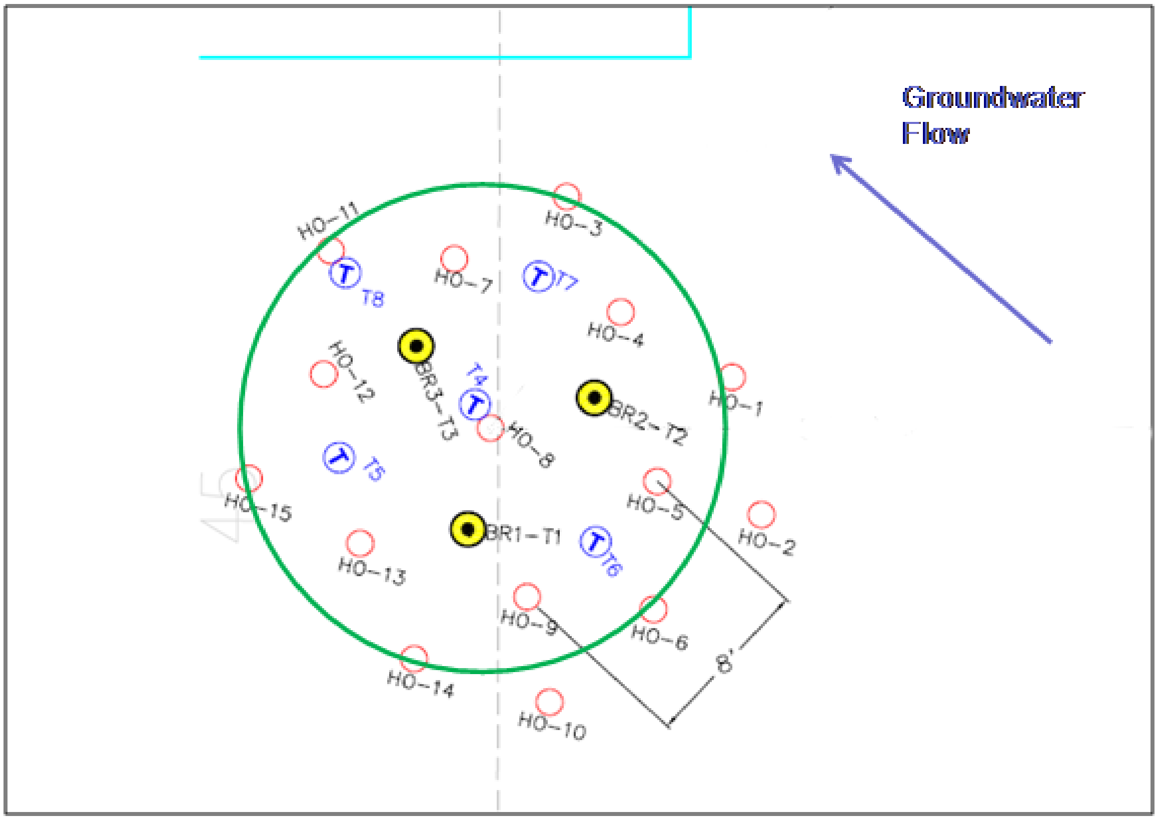


Figure 12. Pre- and post-treatment rock concentration sampling locations.

The performance of the thermal treatment has been evaluated using two different measures:

- Comparison of all pre- and post-treatment rock matrix and fracture concentrations at each of the three sampling locations, not taking into account that not all sampling locations have been sampled both post- and pre-treatment and not taking into account that some of the sample depths may represent rock fractures.
- Comparison of all pre- and post-treatment rock matrix sampling locations by excluding what is believed to be all sample locations close to the major rock fractures (locations directly affected by the influx of cool ambient groundwater with significant CVOC concentrations).

5.6.2.1 Pre- and Post-Treatment Rock Matrix and Fracture Concentrations

The following sections present the pre- and post-treatment rock concentration based on all samples collected at the site.

The rock samples collected from each of the three sampling locations pre- and post-thermal treatment are shown in Table 2. Note that additional samples were collected from BRP2 and BRP3 at the post-treatment sampling event, which explains the higher post-treatment sampling density.

Table 2. Number of pre- and post-treatment sampling locations.

Sampling Location	Pre-Treatment Samples	Post-Treatment Samples
BR1/BRP1	55	48
BR2/BRP2	10	46
BR3/BRP3	10	45

Pre- and post-treatment concentrations with depth for each of the sampling locations are presented in Figures 13 through 15. While BR-1 was sampled at a 0-ft increment for both pre- and post-treatment sampling, BR-2 and BR-3 were sampled at a 5-ft increment during pre-treatment sampling and a 1-ft increment during post-treatment sampling. This accounts for the greater resolution of the post-treatment data for these locations.

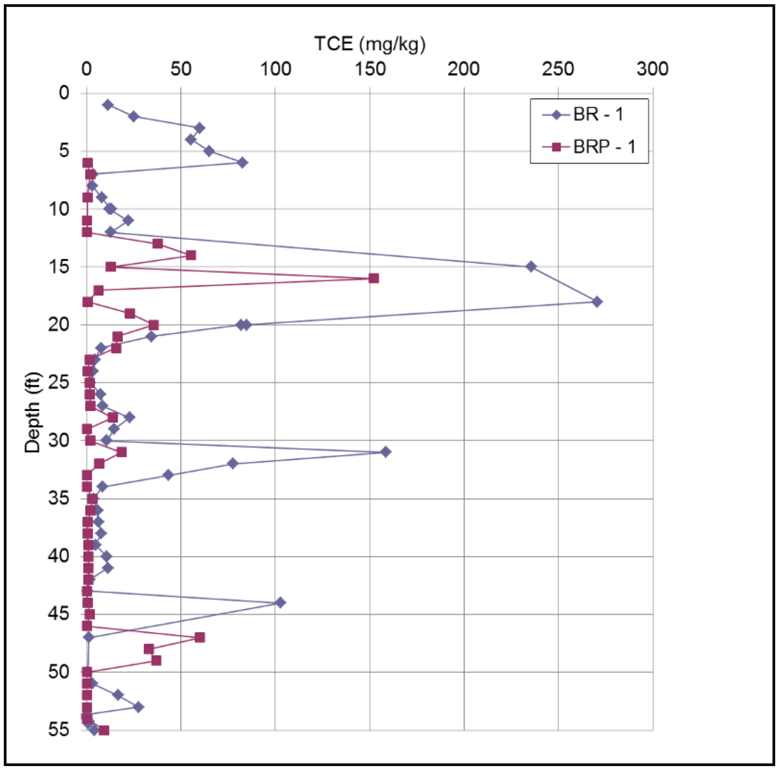


Figure 13. Pre- and post-treatment TCE rock matrix and fracture concentrations at sampling location BR1/BRP1.

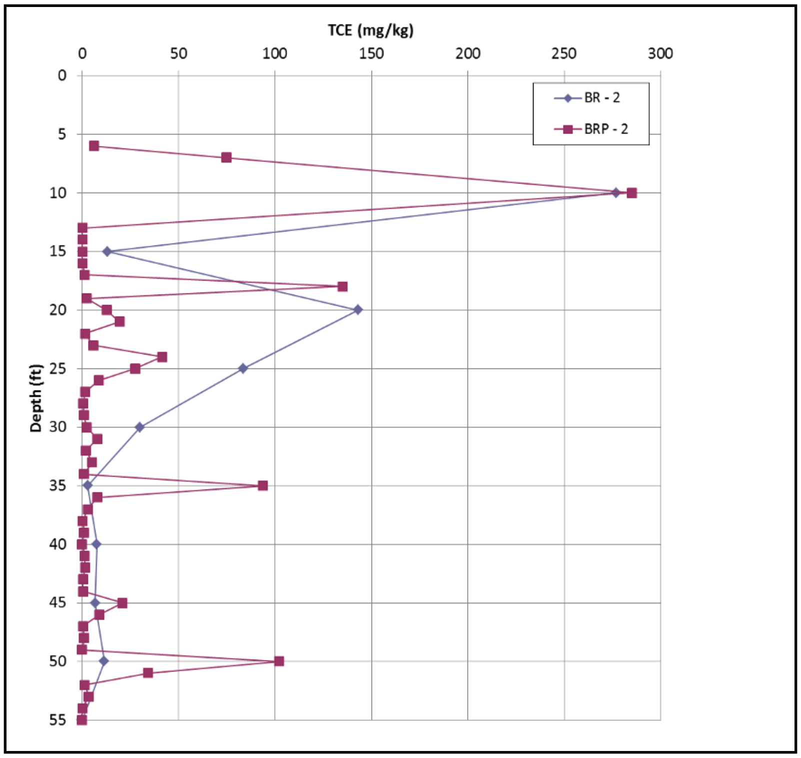


Figure 14. Pre- and post-treatment TCE rock matrix and fracture concentrations at sampling location BR2/BRP2.

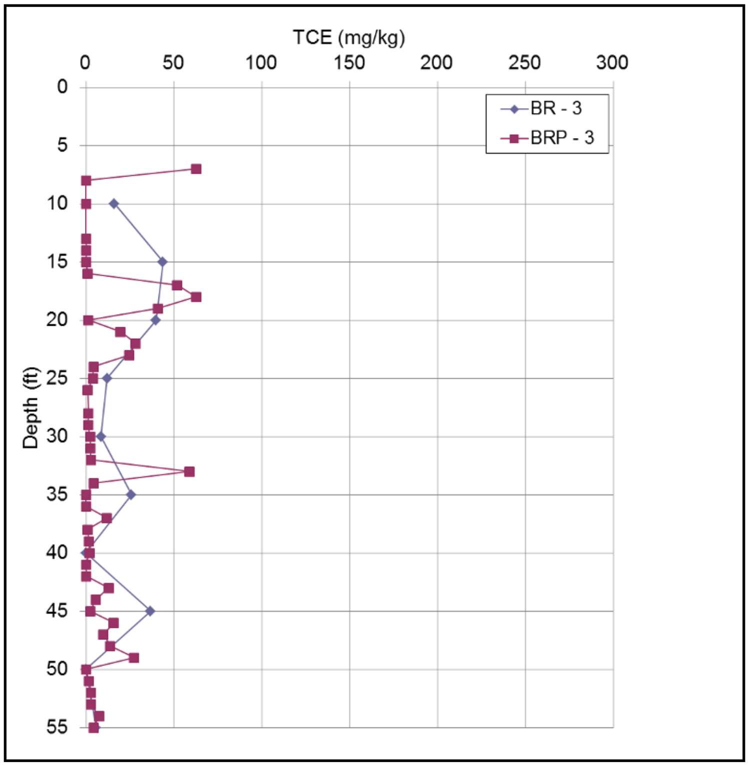


Figure 15. Pre- and post-treatment TCE rock matrix and fracture concentrations at sampling location BR3/BRP3.

While a general decrease is observed in the TCE concentrations, some apparent increases are also seen. However, these typically do not represent depths where pre-operational samples were collected. Therefore, rather than indicating an accumulation of TCE, the data show that post-treatment concentrations are high in some rock sections that were not sampled before the thermal treatment (i.e., the pre-treatment concentrations are unknown).

The average, maximum and minimum pre- and post-treatment TCE rock concentrations, based on all data collected at the site are shown in Table 3. Note that only samples collected inside the treated volume, e.g., from the surface and to 50 ft bgs, have been included in the comparison.

Table 3. Pre- and post-treatment TCE rock concentrations.

		BR1	**BRP1**	**BR2**	**BRP2**	**BR3**	**BRP3**
All samples	**Unit**	**Pre-treatment**	**Post-treatment**	**Pre-treatment**	**Post-treatment**	**Pre-treatment**	**Post-treatment**
Average	mg/kg	35.38	12.73	63.94	19.60	20.43	12.10
Max	mg/kg	270.77	152.00	276.93	285.00	43.85	63.00
Min	mg/kg	0.48	ND	2.86	ND	0.07	ND
No of samples	-	46	43	9	40	9	40
Average remedial efficiency	%	64%		69%		41%	

ND: Not detected at the laboratory reporting limit

The mass reduction indicated by the data in Table 3 is lower, reflecting a concentration reduction in the range of 41-69% when all rock data are considered. This will be discussed in the sections to follow.

5.6.2.2 Pre- and Post-Treatment Rock Matrix Concentrations

This section presents the pre- and post-treatment rock matrix concentrations for BR1/BRP1. Data that are believed to represent fracture concentrations are not included. The same analysis has not been conducted for BR2/BRP2 and BR3/BRP3, since the number of pre-treatment rock concentrations samples are limited.

During pre-treatment rock sampling the three open rock boreholes were inspected using a down hole video camera. The videos recorded were subsequently analyzed, and all fractures observed in the borehole were categorized from category 0 being none or a very small fracture not visible on the borehole video to category 4 being a large fracture.

An example of this analysis for borehole BR1 is shown in Figure 16. As shown in the figure, some depths were found to have a higher fracture density while the size of the fractures varied with depth.

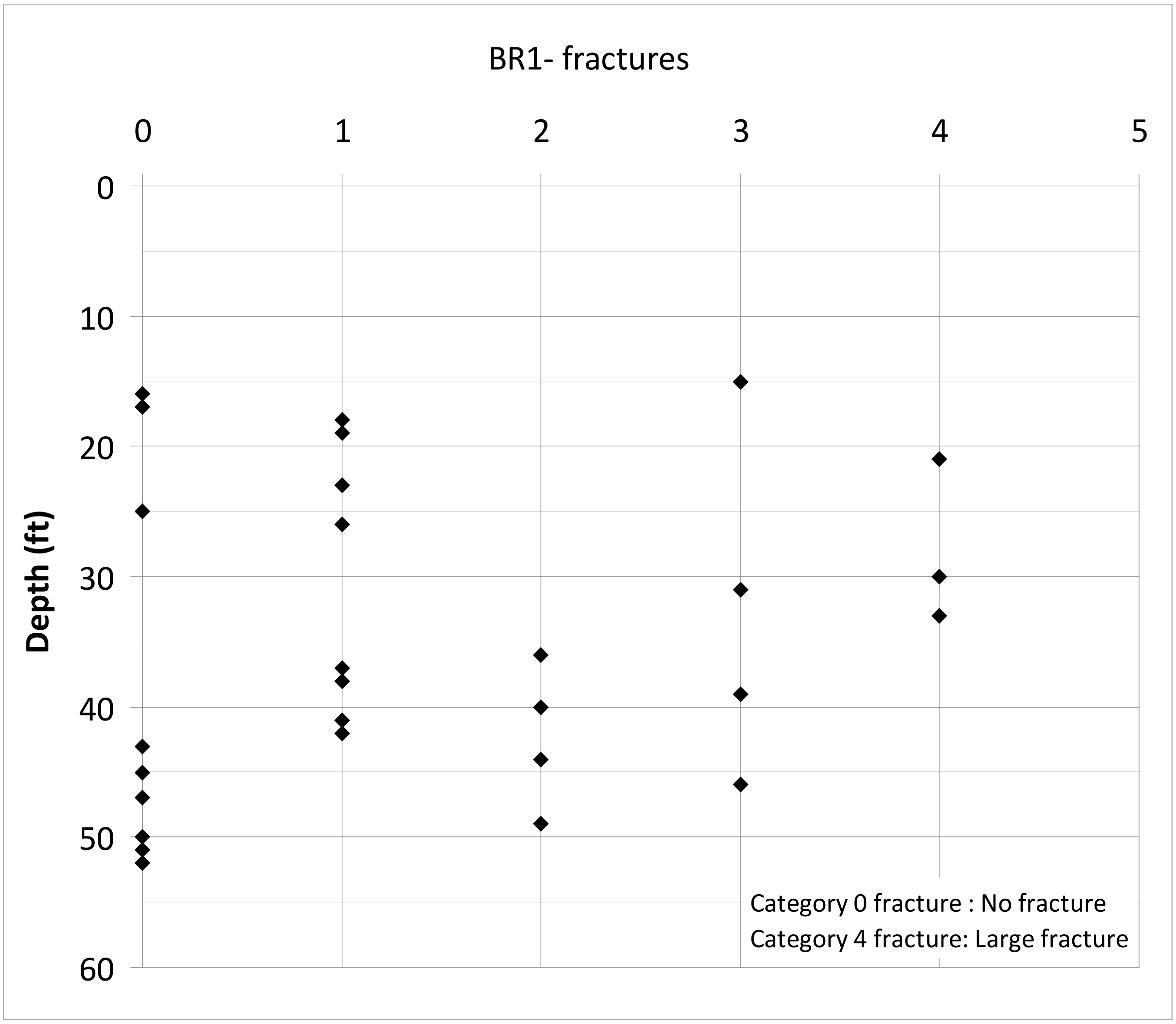


Figure 16. Location and size of fractures for BR1 based on borehole generally representing inspections in 1 foot increments.

Two screenshots from the borehole video for BR1, showing an example of a category 0 fracture and a category 4 fracture, are shown in Figure 17.

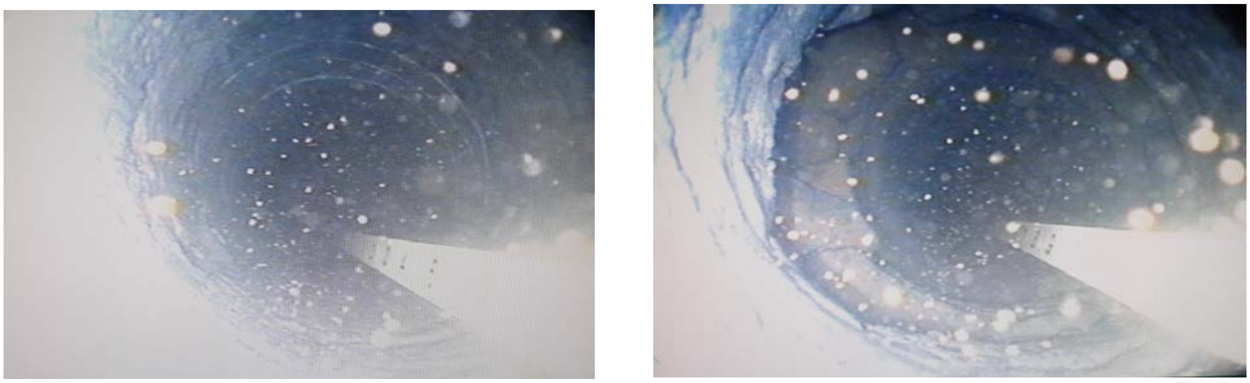


Figure 17. Screenshot from the video borehole logging showing a category 0 (left) **and a category 4** (right) **fracture.**

Based on the borehole inspection it was determined that all areas containing category 3 and 4 fractures did not represent rock matrix and had the potential to transport substantial amounts of water and contaminants from outside of the treatment area into the central parts of the treatment area. Therefore, all samples located at these depths were omitted to allow a comparison of pre- and post-treatment rock matrix concentrations.

Sample depths were estimated to represent fracture concentrations (red circles) as shown in Figure 18. The sample depths suggested to represent fractures were 15, 20, 21, 22, 30, 31, 32, 33, 39, and 47 ft bgs.

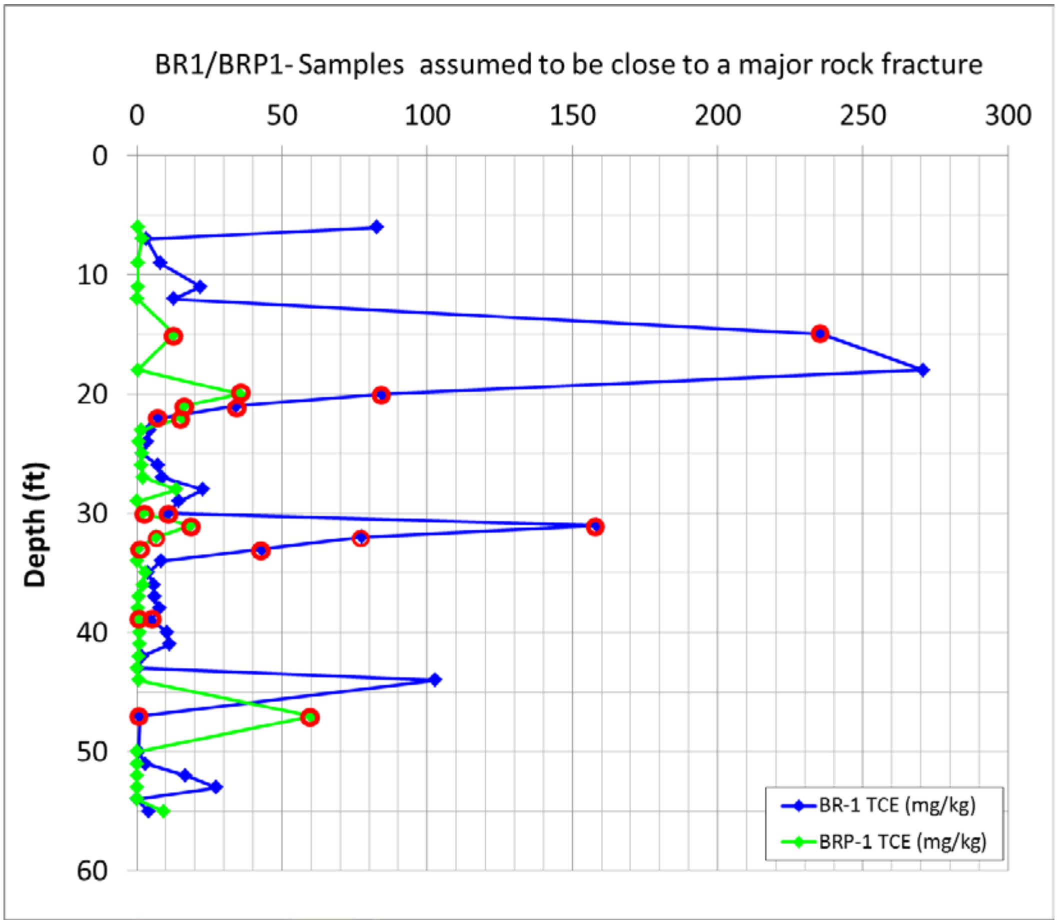


Figure 18. Vertical pre- and post-treatment concentration profile from BR1/BRP1 indicating samples close to a category 3 and 4 fracture (red circles)**.**

Pre- and post-treatment concentrations with depth for BR1/BRP1 after removal of expected rock samples representing fracture locations are shown in Figure 19.

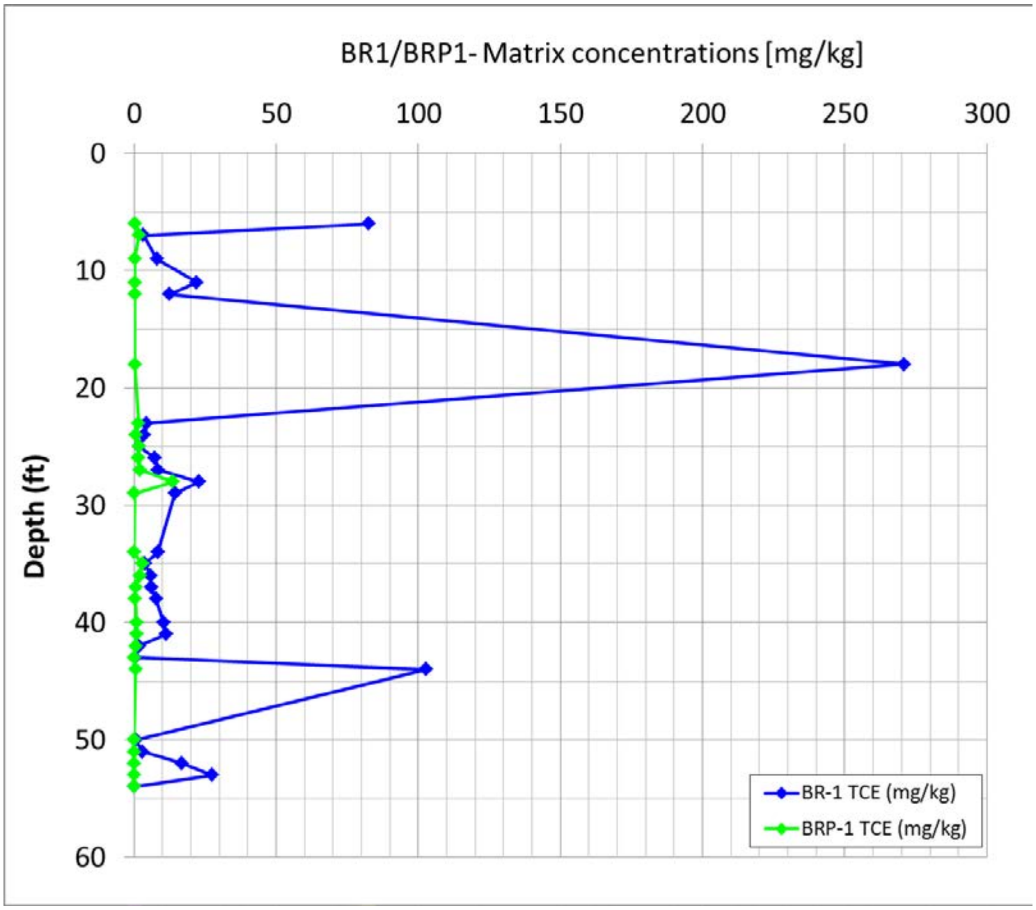


Figure 19. Pre- and post-treatment TCE rock matrix concentrations at sampling location BR1/BRP1.

A decrease in TCE concentration is observed in all samples. The decrease is as low as 6% at 25 ft bgs and as much as 99.4% at 44 ft bgs.

The average, maximum and minimum pre- and post-treatment TCE rock matrix concentration is shown below in Table 4. Note that only samples collected inside the treated volume, e.g. from the surface and to 50 ft bgs, have been included in the comparison.

Table 4. Pre- and post-treatment TCE rock matrix concentrations.

Rock Matrix	Unit	BR1 Pre-treatment	BRP1 Post-treatment
Average	mg/kg	25.90	1.43
Max	mg/kg	270.77	13.70
Min	mg/kg	0.48	ND
No of samples	-	24	24
Average remedial efficiency	%	94.5%	

ND: Not detected at the laboratory reporting limit

An average mass reduction in the 95% range is closer to the usual performance expected during a thermal remediation (NRC, 2005; NAVFAC ESC and Geosyntec 2004; and Lebrón et al., 2012).

6.0 PERFORMANCE ASSESSMENT

Results from the bedrock samples indicate that the average reduction in TCE concentrations was 41-69%. However, careful examination of selected points in the rock matrix revealed that the rock matrix did not achieve targeted temperature in all locations (due mostly to contaminated groundwater influx thru existing fractures). Since discrete sampling was done at 5-foot intervals, it was possible to identify the depths where there was incomplete heating and correlate that information with the observed fractures from a video log of the boreholes. If we eliminate from the performance data the points where boiling water temperature was not achieved due to cool water influx, the average reduction was higher at 94.5%. A detailed performance assessment follows.

Cooling associated with the substantial water flow through the fractures and the continual influx of contaminants from the bedrock surrounding the TTZ is believed to have limited the remedial efficiency in the bedrock close to such fractures. Use of larger diameter vapor extraction points or grouting in the heater borings and use of separate vapor extraction points would have significantly reduced the amount of water produced by eliminating the percolation effect seen at the vapor extraction points during operation. This percolation effect is created because the steam cannot bubble through the standing water without pushing it out, and the resulting liquid entrainment induces more flow into the TTZ. Using larger vapor extraction points would have limited the water extraction rate to the rate of in situ steam production from the fractures and the matrix, thereby limiting the rate of contaminant and cold water flux into the TTZ and enabling efficient heating and treatment of the TTZ. Another potential remedy for full-sale applications would be the use of steam injection to heat the fractures and minimize groundwater inflow from outside of the TTZ.

With respect to the “percolation effect,” steam extracted from the wells should never be viewed as having a negative impact, as it is the major mechanism for extraction and recovery of the vaporized contaminants. However, the “percolation effect,” essentially when steam is flowing in a small pipe at a velocity high enough to entrain groundwater and “pull it along” is unfortunate in some settings where this groundwater extraction is undesirable. When the wells “percolate,” it indicates that more than the desired flow of cool water is entering the treatment zone, which in turn means cooling of the fractures where it is flowing. As a result, target temperatures cannot be maintained.

The data also show that most rock concentrations were lowered to around 0-5 mg/kg, but that higher concentrations were maintained at distinct depth intervals. These depths correlated reasonably well with the depth showing the highest TCE concentrations prior to heating. A total (vapor and liquid) of approximately 530 lbs based on daily PID readings and approximately 680 lbs based on analytical data of TCE were extracted from the site.

The more or less consistent level of VOCs in the vapor stream during the last 2 months of heating indicates that VOCs are entering from outside the TTZ and supplying additional mass to the treatment area. As cold, contaminated water flows towards the heaters, the groundwater is heated by thermal conduction from the matrix, and while some of the VOCs are vaporized, the fracture zones remain cooler than the larger matrix blocks.

It is noteworthy that the VC concentration remained significant in the entire operations period. Since VC is the most volatile VOC at most sites, it is normally removed within the first month of heating. The persistent level of VC in the vapor stream indicates that groundwater flowing into the TTZ was providing a constant source of contaminant mass entering the TTZ.

System performance was likely impacted by groundwater flow (both regional and induced by the vapor extraction system), which is likely responsible for the cooling that led to ineffective TCE remediation. In addition, the flow of contaminated water into the TTZ continuously supplied TCE and other VOCs to the field demonstration area. This finding is consistent with NRC findings in 2005, i.e., *"There is limited field experience applying conductive heating below the water table… As control of water inflow may be problematic in fractured media and karst, and capture of contaminants may be difficult, effectiveness is expected to be limited in these settings. If water inflow can be limited, then conductive heating would be expected to be effective in all granular media."* Furthermore, Kingston et al., reported in 2010 that, *"Better performance might be achieved if system footprints are over-designed to extend beyond the source zone boundaries."*

The relatively smooth temperature profiles during cool-down indicate that regional groundwater flow may not have dominated the cooling. The high groundwater extraction rates observed during the thermal treatment are hypothesized to have been caused by liquid entrainment within the extracted steam. These rates were quickly reduced during cooling, as no more steam was flowing out of the vapor extraction points. In fact, it is believed that the induced flow of cool groundwater into the demonstration volume through the dominant fractures was the result of the design of the vacuum extraction system.

The results of a microbial presence treatability tests demonstrated that, as expected, heating groundwater to approximately 200°F resulted in sterilization. However, the results also indicated that the aquifer was rapidly reseeded with microorganisms, and that both numbers of microorganisms and microbial activity in groundwater just 4 months after thermal treatment were actually greater than prior to treatment. These results show that, while thermal treatment does decrease both numbers and activity of microorganisms in the short term, the aquifer quickly regained its ability to support microbial populations as well as microbial activity.

7.0 COST ASSESSMENT

7.1 COST MODEL

All costs associated with the TCH Field Demonstration were tracked including labor hours, materials, supplies, rental equipment, consumables and capital costs.

The cost elements that were tracked for the demonstration are documented below in Table 5.

Table 5. Cost tracking.

Cost Category	Subcategory	Data Tracked During the Demonstration	Costs
Startup costs and design	TCH design including: • Review of existing site data • Site selection • Site inspection • Prepare draft/final demonstration plans	• Personnel required	$67,000.00
	Permitting and regulatory interface	• Personnel required • Permit fees	$9800.00
	Engineering site inspection	• Personnel required and associated support labor	$1200.00
	Site preparation – survey/grading/brush removal, power drop	• Personnel required and associated support labor • Materials • Rental equipment	$51,100.00
	Mobilization	• Personnel required and associated support labor	$6200.00
	Drilling – well installation/pre-treatment sample collection and analysis	• Personnel required and associated support labor • Materials • Rental equipment • Subcontractor costs • Permit fees	$226,000.00
	TCH system construction and system shakedown/startup	• Personnel required and associated support labor • Materials • Rental equipment	$42,000.00
Capital costs	TCH system materials procurement	• Costs included above in TCH system construction and system shakedown/startup	$29,900.00
Operating costs	TCH system operations	• Personnel required and associated support labor • Materials • Rental equipment • Analytical laboratory costs	$170,700.00

Table 5. Cost tracking (continued).

Cost Category	Subcategory	Data Tracked During the Demonstration	Costs
Direct environmental activity costs	Post-treatment data collection and analysis	• Personnel required and associated support labor • Materials • Rental equipment • Subcontractor costs • Overhead expenses • Analytical laboratory costs	$31,500.00
	Well removal	• Personnel required and associated support labor • Materials • Rental equipment • Subcontractor costs	$62,500.00
	Utilities	• Power drop and electrical usage expense	Power drop costs are site specific. Power drop costs for the TCH Demonstration were $50,500.00 and are included in the Site Preparation Task above. Power usage costs for the TCH demonstration are estimated to be $55,000.00.
Indirect environmental activity costs	Waste manifesting (if any) and disposal	Costs included below in Demobilization	$19,200.00
	Environmental and safety training	NA	NA
	Occupational Safety and Health Administration (OSHA) sampling (if any)	NA	NA
Other	Demobilization	• Personnel required and associated support labor • Materials • Rental equipment	$33,500.00
	TCH system installation, construction, operation, post-treatment sampling, system demobilization overhead expenses, project management, project engineering, project accounting	• Overhead expenses such as per diem/living expenses, office trailer rental, shipping charges, etc.	$193,800.00
	Project trips, as necessary	• Personnel required and associated support labor • Overhead expenses such as per diem/living expenses	$2100.00
	Final reporting	• Personnel required and associated support labor	$31,300.00

7.1.1 Interpretation of Costs and Scale

The costs tracked for the TCH field demonstration should not be used as a linear comparison to cost TCH remediation at other sites. Due to the relatively fixed capital equipment and personnel costs associated with a TCH remediation project, cost estimates must be done using site specific parameters. Due to the relatively incremental cost for heaters and extraction points to be installed into deeper borings, a general rule of thumb is that the deeper a site and the larger the volume, the lower the unit price per cubic yard.

Additionally, as the availability of utilities and the cost for utilities can vary widely for remediation projects in different regions, the cost to install utilities and the cost for utilities is a site-specific cost. Assumptions can be made for estimating purposes, but site-specific costs should be evaluated when preparing a cost estimate.

7.2 COST DRIVERS

The cost of the TCH technology depends primarily on the size and depth of the treated subsurface volume. This defines the volume to be treated, which in turn determines the number and depth of heater borings and extraction points, and the size and type of the process equipment. A secondary parameter is the type of rock or sedimentary deposit, particularly its porosity and heat capacity. These parameters determine the amount of energy necessary to heat the target volume to the treatment temperature.

In fractured rock, several other factors are important. These include:

- The mineralogy of the rock (important for matrix diffusion).
- Organic matter content of the rock and fracture rinds (determining the degree of adsorption and retardation).
- Fracture patterns and permeability (governs the flow of groundwater, which could slow heating).

Finally, the type of contaminant is important for the treatment cost. Volatile COCs, like TCE and PCE, are likely to be effectively removed at the boiling point of water (drying of the site not necessary), whereas less volatile COCs such as PCBs will require heating of the rock to higher temperatures for complete removal and may also require more aggressive aboveground vapor treatment technologies to comply with regulatory requirements.

Costs associated with the implementation of TCH are significantly impacted by the size of the area of concern to be treated. Because of the relatively fixed capital and infrastructure costs associated with the construction of process vapor and liquid treatment systems, the overall size and depth of the area of concern for which TCH will be used impacts the unit cost per volume for the TCH implementation significantly (i.e., the deeper the area of concern, the lower cost per unit volume). While the well head infrastructure cost for each TCH boring and vapor/liquid piping segment is fixed, the cost to extend heater borings and vapor extraction points to deeper depths to treat a larger volume is a relatively minor per foot incremental cost.

Due to the varying boiling points of COCs, those COCs with higher boiling points (e.g., chlorobenzenes, PCBs) will typically require more robust heating designs including closer well spacing and longer TCH operational durations to achieve site cleanup. Sites with high groundwater flux or site soils with high organic content (e.g., peat) also require more robust heating designs, typically requiring closer TCH well spacing, longer operational durations or both.

The closer well spacing can be used to heat the subsurface to target treatment temperatures more quickly and in some instances to provide a hydraulic barrier for the site (essentially boiling off groundwater as it enters the area of concern). Longer operational durations may be required to reach higher target treatment temperatures for those COCs with higher boiling points.

7.3 COST ANALYSIS

TerraTherm has utilized its proprietary cost model to produce cost estimates for three treatment scenarios with the same design parameters but with different treatment areas and volumes to demonstrate the range of treatment costs dependent upon the treatment volume at a specific site. TerraTherm's proprietary cost model is based on cost data from approximately 25 completed projects. We have classified the three scenarios as follows:

- Small: treatment zone approximately 12,500 yd^3;
- Medium: treatment zone approximately 50,000 yd^3; and,
- Large: treatment zone approximately 250,000 yd^3.

These cost scenarios are applicable to fractured bedrock as they incorporate assessment of groundwater flow and measures to reduce and manage the rate of flow, if necessary (e.g., design of vacuum extraction system, use of steam to prevent groundwater influx and pre heat groundwater, and use of groundwater hydraulic control). The design parameters used for the three different costing scenarios are outlined in Tables 6 and 7. One of the major lessons learned from this TCH field demonstration conducted under ER-200715 was the need for not only the utilization of TCH to treat the DNAPL source zone, but also the need for a method to adequately control the incoming flux of groundwater into the TTZ from bedrock fractures. TerraTherm has already incorporated such approach into their TCH applications, thereby transferring technology directly from an ESTCP project into implementation. To successfully control the groundwater influx, they have included not only multi-phase extraction wells to pump water from the TTZ, but they have also included steam injection well(s) in the design. Steam injection can be used to heat and treat permeable matrices, as well as to create a pressurized steam zone in the subsurface to effectively block the influx of cool water into the TTZ.

Table 6. Volume and heat capacity design input parameters.

Volume and Heat Capacity	Small	Medium	Large	Unit
Treatment area	2250	9000	45,000	ft^2
Upper depth of treatment	0	0	0	ft bgs
Lower depth of treatment	150	150	150	ft bgs
Thickness of overburden	50	50	50	ft
Thickness of bedrock	100	100	100	ft
Volume, TTZ	12,500	50,000	250,000	yd^3
Solids volume	10,625	42,500	212,500	yd^3
Porosity volume	1875	7500	37,500	yd^3
Soil weight	47,443,901	189,775,606	948,878,029	lbs soil
Water weight	2,794,688	11,178,752	55,893,759	lbs water
Soil heat capacity	11,860,975	47,443,901	237,219,507	BTU/F
Water heat capacity	2,794,688	11,178,752	55,893,759	BTU/F
Total heat capacity, whole TTZ	14,655,663	58,622,653	293,113,266	BTU/F

Table 7. Energy balance design input parameters.

Energy Balance	Small	Medium	Large	Unit
Steam injection rate	240	720	2880	lbs/hr
TCH power input rate	980	2217	8056	kW
Water extraction rate during heatup	3	11	52	gpm
Steam extracted, average	1105	2552	9355	lbs/hr
Energy flux into treatment volume	3,577,504	8,260,517	30,279,251	BTU/hr
Energy flux in extracted groundwater	207,916	763,655	3,614,744	BTU/hr
Energy flux in extracted steam	1,073,251	2,478,155	9,083,775	BTU/hr
Net energy flux into treatment volume	2,296,337	5,018,707	17,580,732	BTU/hr
Heating per day	3.7	2	1	F/day
Start temperature	50.0	50	50	F
Target temperature	212.0	212	212	F
Estimated heat loss, worst case	46.3	32	28	%

kW = kilowatt
gpm = gallons per minute
BTU/hr = British Thermal Units per hour
F = Fahrenheit

Site specific design outputs based on the parameters that were used for modeling the three treatment volume scenarios are provided in Tables 8 and 9. The total operational duration for each of the three volume scenarios is shown in Table 8. This operational time is only for the time spent “heating” the site.

Table 8. Total operational duration.

Operating Time	Small	Medium	Large	Unit
Shake-down	7	7	7	days
Heating to boiling point	70	103	145	days
Boiling and drying	70	121	167	days
Sampling/analysis phase	10	10	10	days
Post treatment vapor extraction	14	14	14	days
Total operating time	**170**	**255**	**343**	**days**

Table 9. Total number of wells.

Number of Wells	Small	Medium	Large
Heater borings	23	52	189
Vertical soil vapor extraction (SVE) wells	23	52	189
Steam injection wells	4	8	24
Multi-phase extraction wells	1	2	6
Temperature monitoring wells	7	12	35
Pressure monitoring wells	4	5	10

The total remediation time frame for each of the three volume scenarios is approximately 200 days. In fact, this figure is consistent with published literature (McGuire et al., 2009), which estimated average duration of thermal remediation is 228 days. Project duration, including treatment design, construction and operations, and final reporting is less than 3 years. Project durations by task for each of the three treatment scenarios are provided below in Figures 20 through 22. All schedules assume a project start date of January 1, 2012.

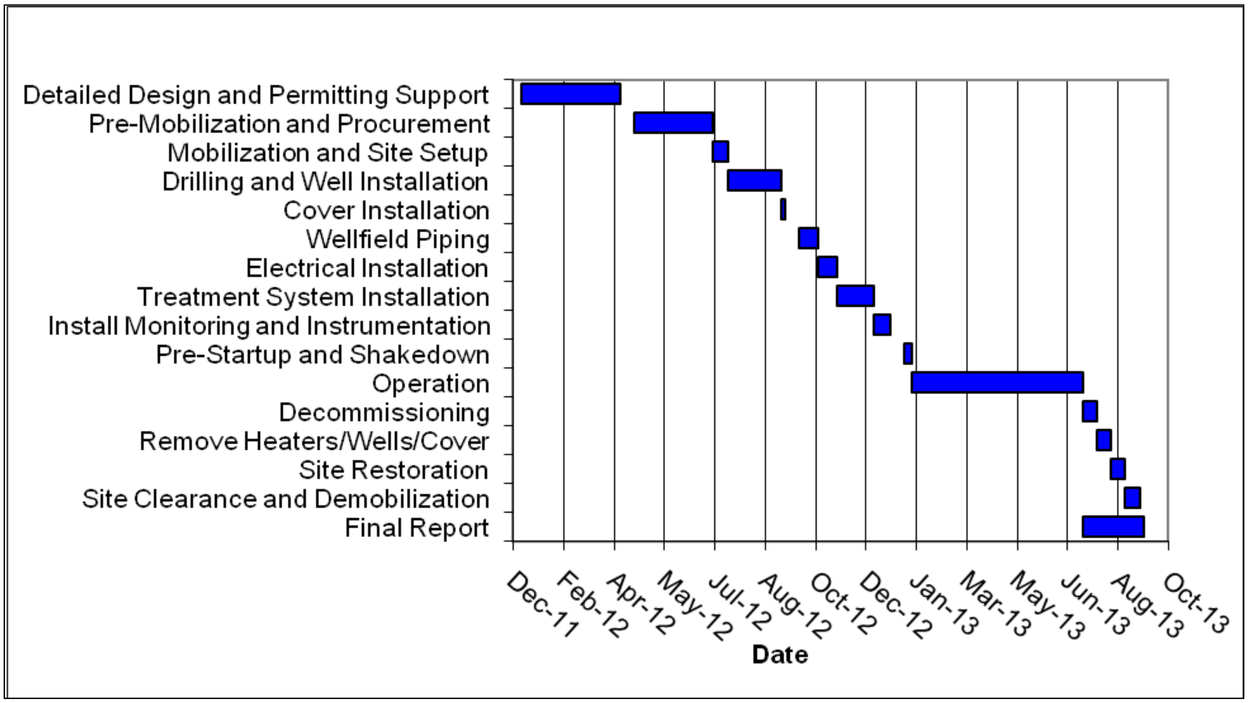


Figure 20. Project duration by task for small project implementation.

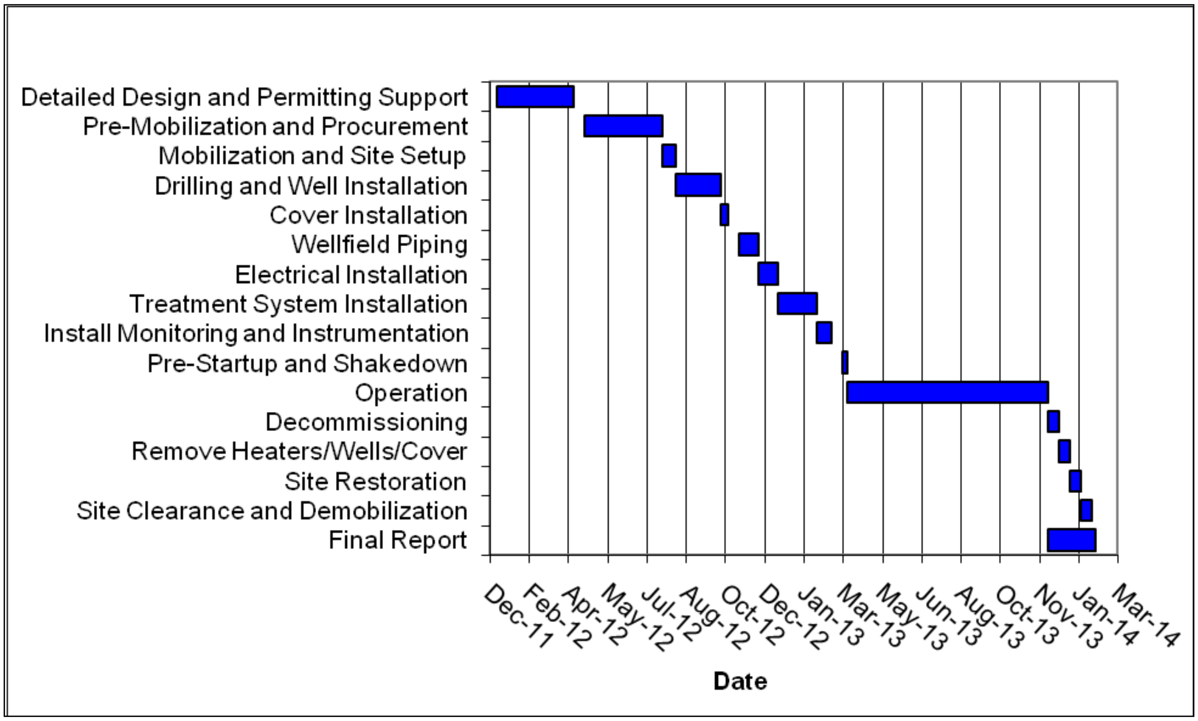


Figure 21. Project duration by task for medium project implementation.

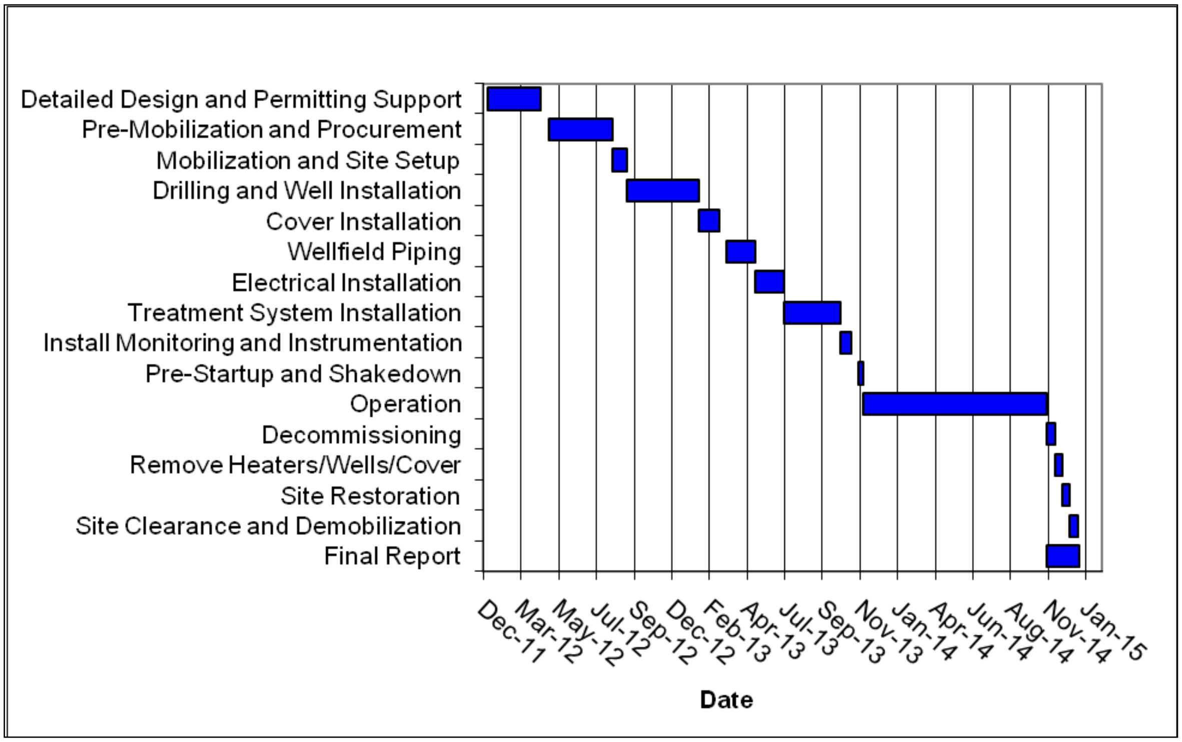


Figure 22. Project duration by task for large project implementation.

Costs for three different TCH treatment volumes have been presented below in Table 10. TerraTherm's proprietary design and costing model was used to generate the costs associated with TCH remediation of three sites with the same input parameters with the exception of the surface area of the treatment zone. By keeping all other input parameters constant, it allows us to examine the decrease in unit cost as the overall volume of the area of concern is increased. Because the total remediation time frame is less than 3 years for each of the scenarios, no discount rate was applied to the costs presented in Table 10 (White House Office of Management and Budget [OMB], 2010).

Table 10. Implementation costs for small, medium and large volume TCH projects.

Task	Subtask	Small Price ($)	Medium Price ($)	Large Price ($)
Design and preparation	Conceptual design and cost estimate	40,426	40,426	40,426
	Detailed design, permitting	162,000	162,000	162,000
	Procurement	100,000	163,000	458,000
Site activities pre-operation	Mobilization and site setup	44,000	76,000	246,000
	Power drop and transformer	Not included	Not included	Not included
	Drilling and well installation	725,000	1,483,000	5,012,000
	Vapor cover installation	46,000	141,000	591,000
	Wellfield piping	55,000	136,000	986,000
	ISTD power equipment installation	61,000	97,000	267,000
	Steam generation system installation	20,000	22,000	30,000
	Treatment system installation	363,879	578,858	2,216,477
	Electrical installation, wellfield and process	43,000	58,000	125,000
	Instrument and monitoring system installation	16,000	22,000	49,000
	Pre-startup and shakedown	33,000	45,000	100,000
Operation	ISTD power equipment rental	90,000	127,000	167,000
	Steam generation system rental	46,000	69,000	113,000
	Labor, travel, per diem	282,000	633,000	1,136,000
	Process monitoring, sampling and analysis	16,000	36,000	130,000
	Waste and GAC	27,000	110,000	1,000
	Repair/maintenance	61,000	91,000	123,000
	Tools, rentals and fees	23,000	34,000	46,000
Demobilization and other	Decommissioning	42,000	77,000	267,000
	Remove heaters/wells/cover	237,000	495,000	1,699,000
	Site restoration	-	-	-
	Site clearance & demobilization	17,000	33,000	118,000
	Reporting	41,000	41,000	41,000
Indirect costs	Field support	80,000	119,000	160,000
	Home office support	134,000	200,000	270,000
	ISTD licensing fees	90,000	157,000	456,000
	Total (not including electricity)	**2,895,000**	**5,066,000**	**14,693,000**
Utilities	Electricity	468,000	1,600,000	7,711,000
	Total (including electricity)	**3,363,000**	**6,846,000**	**22,721,000**
	Price (\$)/yd^3	**269**	**137**	**91**

The assumptions that were incorporated in the cost model generated costs are as follows:

- Due to the variability of utility availability, utility hookup charges have not been included in the costs.
- A rate of $0.12/kWh has been used for electricity usage charges.
- Permitting fees are excluded; details to support the permitting application process (handled by client) are included in costs.
- Power and other utilities are assumed to be available to the site with service available in a reasonable timeframe. Note that at most sites it is necessary to bring in power. This typically involves making a new connection (power drop) to an existing nearby power line. In most cases, this involves installing one or several poles, running wire, and bringing in and connecting a transformer of the appropriate size for the project.
- Discharge/disposal of treated effluents, drill cuttings and any GAC or NAPL produced during operation is excluded.
- Site will be free of any existing infrastructure not compatible with treatment temperatures or that would interfere with treatment application.
- Sufficient space is provided for unencumbered site construction and thermal operations.
- We have assumed that sacrificial GAC will be used for vapor treatment for both the Small and Medium scenarios. We have assumed that a GAC regeneration system will be used for vapor treatment for the Large scenario.

As seen in Table 10, the unit costs for TCH implementation vary greatly as a function of the total treatment volume of the site. In the cost model scenarios, the cost/yd^3 ranges from \$269/yd^3 for the Small 12,500 yd^3 scenario to \$91/yd^3 for the Large 250,000 yd^3 scenario. These cost ranges agree with other full-scale implementation costs as observed by TerraTherm at other TCH sites.

This page left blank intentionally.

8.0 IMPLEMENTATION ISSUES

The goal of the field demonstration was to develop useful guidelines so that practitioners could understand how to apply the TCH technology and to help avoid misperceptions regarding what is attainable with TCH, in terms of mass removal, reduction of aqueous phase contaminant flux, reduction of aqueous phase concentrations, and reduction in source zone lifespan. The field demonstration and the data generated help us to understand and evaluate the effectiveness of the thermal treatment of chlorinated ethenes in source zone contamination at bedrock sites.

Regional groundwater flow is believed to be partially responsible for the local cooling that led to ineffective heating, and therefore, ineffective TCE remediation. In addition, the flow of contaminated water into the TTZ continuously supplied TCE and other VOCs to the field demonstration area. Furthermore, field data corresponds well with the interpretation that elevated groundwater flows during thermal treatment were caused by the vapor extraction, and not solely by regional groundwater flow. In other words, groundwater moved much faster during the thermal operations, as a result of liquid entrainment occurring in the vapor extraction points as steam was extracted, and pulled large quantities of groundwater with it.

8.1 GUIDELINES TO PRACTITIONERS

For the TCH process to be effective in this setting, the flow of cold and contaminated groundwater into the TTZ must be limited and/or controlled. This finding is consistent with NRC findings in 2005, i.e., *"There is limited field experience applying conductive heating below the water table… As control of water inflow may be problematic in fractured media and karst, and capture of contaminants may be difficult, effectiveness is expected to be limited in these settings. If water inflow can be limited, then conductive heating would be expected to be effective in all granular media."* Furthermore, Kingston et al. reported in 2009 that *"Better performance might be achieved if system footprints are over-designed to extend beyond the source zone boundaries."* Though at full scale this mechanism will be much less pronounced, as the surface area to volume ratio decreases with the scale, it may be necessary to limit the influx of groundwater to limit the cooling effect that prevents target temperatures from being reached. Further, for full-scale applications, the treatment area would typically encompass the entire contaminated zone so that groundwater entering the treatment area would not re-introduce high VOC concentrations into the treatment zone as was observed at this site.

Other useful guidelines follow:

1. Careful attention should be given to groundwater influx into a target treatment zone in order to determine whether the boiling of water can achieved, and the length of heating time required to achieve boiling. Calculating the groundwater influx at a fractured rock site is typically carried out using measurements of bulk rock hydraulic conductivity and hydraulic gradient. Given the likely variability of flowrate amongst individual fractures in a treatment zone (flow proportional to fracture aperture cubed), more accurate assessment of the influence of inflowing cold groundwater can be determined on the basis of bulk rock hydraulic conductivity measurements carried out at smaller scales, rather than at larger scales. However, water inflow at a fractured bedrock site may be challenging, therefore an effective TCH application should include site-specific testing

to discover these issues and make modifications prior to full-scale treatment. In fact, practitioners should pay particular attention to the potential for groundwater influx when designing and implementing a TCH application in fractured bedrock.

2. System design must take into account the induced flow of cool groundwater into the treatment volume through the dominant fractures as a result of the vacuum extraction system.
3. Because of the variability in boiling point throughout a fractured rock treatment zone and the absence of a well-defined constant temperature boiling plateau in the rock matrix, it may be difficult to monitor the progress of thermal treatment using temperature measurements alone.
4. The combination of the close well spacing and the vibrations induced to the rock formation during the sonic drilling may have created additional fractures and caused the hydraulic conductivity of the fractured bedrock in the demonstration area to increase. Although not likely due to wider well spacing at full scale, drilling methods should be examined to reduce the possible amount of additional fracturing that may occur during well installation. A site manager must consider impacts of drilling techniques on the potential for water influx and a system design should include contingencies to limit or mitigate groundwater influx if cooling is detected. During this ER-200715 TCH demonstration, the ambient hydraulic characteristics of the TCH site were likely altered after installation of 23 boreholes at a site that is 22 ft diameter and 55 ft deep. Each borehole was drilled using a sonic drilling rig and a 6-inch drill bit. The closely spaced boreholes and the high vibrations created during sonic drilling caused a massive network of fracture in the field demonstration area and radically increased the hydraulic conductivity of the bedrock. The NJ licensed driller reported that the first completed borehole pumped at a maximum rate of less than 1 gpm. A pumping rate that is typical for many of the 105 monitoring wells located at the NAWC. The driller also reported an increased pumping rate for the last 3 or 4 boreholes. The average pumping rate of higher producing wells at the NAWC typically is 4 to 10 gpm.
5. Treatability tests demonstrated that heating duration had a greater effect on the degree of TCE and PCE mass removal compared to heating temperature. In heating *duration profile* tests, the majority of contaminant mass removal was achieved in the early stages of heating. In samples of sandstone, dolostone, limestone and siltstone further heating did not lead to a significant decrease in contaminant concentration. Heating *temperature profile* tests required final target temperatures of 200°C to remove the majority of the contaminant mass. In thermal field applications, extending treatment duration under standard operational temperatures at the boiling point of water would, therefore, be more cost-effective than elevating temperatures above the boiling point of water, which requires dewatering of the target volume.
6. The results of a microbial presence treatability test demonstrated that as expected, heating groundwater to approximately 200°F resulted in sterilization. However, the results also indicated that the aquifer was rapidly reseeded with microorganisms, and that both numbers of microorganisms and microbial activity in groundwater just 4 months after thermal treatment were actually greater than prior to treatment. These results show that, while thermal treatment does decrease both numbers and activity of

microorganisms in the short term, the aquifer quickly regained its ability to support microbial populations as well as microbial activity.

7. Use of larger-diameter vapor extraction points should be considered (so that steam can bubble through any standing water more easily). In addition, larger extraction points would reduce the steam velocity and the amount of entrained water being extracted from the points.
8. A TCH system should use separate heaters and vacuum extraction points. Grouting of the heater borings into the bedrock is recommended. Grouting the heater borings instead of backfilling the boreholes with sand would prevent the pressurization and steam drive of water out of the boreholes around the heaters.
9. Regional groundwater flow cooling can possibly be reduced using a hydraulic barrier such as a freeze-wall or a grout curtain.
10. TCH can also be combined with steam injection to enhance performance. The injection of steam into the water-bearing fractures, displaces groundwater and heats the fracture system.
11. A site manager should consider smaller-scale testing prior to full-scale deployment to identify potential problems and refine full-scale designs and operations.
12. Practitioners should consider longer treatment and/or higher temperatures to remove contaminants from difficult regions. In fact, a "Critical Evaluation of State-of-the-Art In Situ Thermal Treatment Technologies for DNAPL Source Zone Treatment" conducted under ESTCP Project ER-200314 states: *"The operating duration for most in situ thermal applications seems to arguably have been arbitrary, with cessation of heating after reaching and maintaining a target temperature for some pre-defined period of time. It seems that there is an opportunity here to better define operational endpoints based on metrics more closely related to the conventional cleanup goals (i.e., target soil and groundwater cleanup concentrations)."*
13. Hydraulic conductivity measurements should be taken at relatively small scales to assess individual strata or rock types. Further, as much as possible, fractures should be characterized as well as possible.
14. The impacts of different rock types present in the contaminated zone should be understood. The thorough technical approach employed in the ER-200715 validation allowed for laboratory tests that yielded valuable information for the field demonstration. Those treatability tests concluded that rock properties had a significant effect on contaminant mass removal during heating experiments. It was determined that the rock properties observed in samples of sandstone and dolostone, such as high porosity and low fraction organic carbon, contributed to the increase in contaminant mass removal during the heating tests. In field applications, fractured bedrock with higher porosities and lower fraction organic carbon would favor the performance and effectiveness of thermal treatment in the removal of TCE and PCE. Further, a two-way analysis of variance (ANOVA) with replication showed that the contaminant mass removal was significantly different for each type of rock throughout the heating process, regardless of the heating profile utilized during the heating tests (95% significance level). The PCA analysis revealed that porosity favored the degree of

contaminant mass removal from the rock matrix. In contrast, fraction organic carbon had a negative effect on the contaminant mass removal. Black mudstone (as in the case of NAWC), with a combination of lower porosity and higher fraction organic carbon, exhibited the lowest degree of contaminant mass removal.

15. Last, but not least, given the uncertainties intrinsic to site characterization and technology performance, both an adaptive management approach and a performance based contract may be appropriate if there is room for flexibility to adjust to unforeseen conditions. Clear objectives and goals should be established based on the site’s regulatory, stakeholder, and hydrogeological conditions, with options to adapt the system design. Performance based contracting is encouraged by DoD whenever possible (DoD, 2000).

9.0 REFERENCES

Baker, R.S., and M. Kuhlman, 2002. "A Description of the Mechanisms of In-Situ Thermal Destruction (ISTD) Reactions." In: H. Al-Ekabi (Ed.), *Current Practices in Oxidation and Reduction Technologies for Soil and Groundwater*. Presented at the 2nd International Conf. on Oxidation and Reduction Technologies for Soil and Groundwater, ORTs-2, Toronto, Ontario, Canada, Nov. 17-21, 2002.

DeVoe, C., and K.S. Udell, 1998. Thermodynamic and Hydrodynamic behavior of water and DNAPLs during heating, In *Proceedings from the First Conference on Remediation of Chlorinated and Recalcitrant Compounds*, May 18-21, Monterey CA, Battelle Press 1 (2): 61-66.

Department of Defense (DoD), 2000. Guidebook for Performance-Based Services Acquisition (PBSA) in the Department of Defense. http://www.acq.osd.mil/dpap/Docs/pbsaguide010201.pdf.

Heron, G., R.S. Baker, J.M. Bierschenk, and J.C. LaChance, 2006. Heat it All the Way - Mechanisms and Results Achieved using In-Situ Thermal Remediation. Paper F-13, in: Bruce M. Sass (Conference Chair), Remediation of Chlorinated and Recalcitrant Compounds—2006. Proceedings of the Fifth International Conference on Remediation of Chlorinated and Recalcitrant Compounds (Monterey, CA; May 2006). ISBN 1-57477-157-4, published by Battelle Press, Columbus, OH, www.battelle.org/bookstore.

Heron, G., M. Van Zutphen, T.H. Christensen, and C.G. Enfield, 1998. Soil heating for enhanced remediation of chlorinated solvents: A laboratory study on resistive heating and vapor extraction in a silty, low-permeable soil contaminated with trichloroethylene. *Environmental Science and Technology*, 32 (10): 1474-1481.

Kingston, J.L., P.R. Dahlen, and P.C. Johnson, 2010. Sate-of-the-Practice Review of In Situ Thermal Technologies. Ground Water Monitoring & Remediation, 30, 4. Blackwell Publishing Ltd. 1745-6592. http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6592.2010.01305.x/abstract;jsessionid=10715602059A6BE5E9CC67D4DBF80BDF.d02t01 64, 72. 2010.

LaChance, J.C., R.S. Baker, J.P. Galligan, and J.M. Bierschenk, 2004. "Application of 'Thermal Conductive Heating/In-Situ Thermal Desorption (ISTD)' to the Remediation of Chlorinated Volatile Organic Compounds in Saturated and Unsaturated Settings." Proceedings of Battelle's Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, CA, May 24, 2004.

Lebrón, C.A., D. Major, J. Konzuk, B.H. Keuper, and J. Gerhard, 2012. Contract Report CR-NAVFAC ESC-EV-1201, Development of a Protocol and a Screening Tool for the Selection of DNAPL Source Area Remediation.

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

Naval Facilities Engineering Command / Engineering Service Center (NAVFAC ESC), and Geosyntec Consultants (GeoSyntec), 2004 Assessing the Feasibility of DNAPL Source Zone Remediation: Review of Case Studies, April, 2004. NAVFAC ESC Report CR-04-002-ENV.

National Research Council (NRC), 2005. Contaminants in the Subsurface: Source Zone Assessment and Remediation. The National Academies Press, Washington, D.C.

SERDP and ESTCP, 2001. Workshop Report: Expert Panel Workshop on Research and Development Needs for Cleanup of Chlorinated Solvent Sites. SERDP and ESTCP, Alexandria, VA. http://serdp-estcp.org/content/download/8241/101242/version/1/file/Workshop-ChlorSolvCleanup-2001.pdf.

Stegemeier, G.L., and H.J. Vinegar, 2001. Thermal Conduction Heating for in-situ thermal desorption of soils. In Hazardous and radioactive Waste Treatment Technologies Handbook, Chang H. (ed.). CRC Press, Boca Raton, Florida. ch 4.6-1.

Udell, K.S., 1996. Heat and mass transfer in clean-up of underground toxic wastes. In *Annual Reviews of Heat Transfer*, Vol. 7, Chang-Lin Tien, Ed.; Begell House, Inc.: New York, Wallingford, UK: 333-405.

U.S. Environmental Protection Agency (USEPA), 1996. Method 8260B: Volatile Organic Compounds by Gas Chromatography/Mass Spectrometry (GC/MS). Test Methods for Evaluating Solid Waste, Physical/Chemical Methods. EPA/SW-846, Revision 2.

White House Office of Management and Budget (OMB). Circular A-94 Appendix C, Revised December 2010, Discount Rates for Cost-Effectiveness, Lease Purchase, and Related Analyses. http://www.whitehouse.gov/omb/circulars_a094/a94_appx-c. Retrieved August 10, 2011.

APPENDIX A

POINTS OF CONTACT

Point of Contact	Organization	Phone Fax E-Mail	Role In Project
Carmen A. Lebrón	NAVFAC ESC 1100 23rd Avenue Port Hueneme, CA 93043	Phone: 805-982-1616 E-Mail: Carmen.lebron@navy.mil	Project Manager
Gorm Heron	TerraTherm, Inc. 28900 Indian Point Keene, CA 93531	Phone: 661-823-1620 Fax: 978-343-2727 E-Mail: gheron@terratherm.com	Field Manager
Bernard Kueper	Queen's University Ellis Hall Kingston, ON Canada K7L 3N6	Phone: 613-533-6834 Fax: 613-533-2128 E-Mail: kueper@civil.queensu.ca	Treatability Study Director
Jim Galligan	TerraTherm, Inc. 151 Suffolk Lane Gardner, MA 01440	Phone: 978-730-1200 Fax: 978-632-3422 E-Mail: jgalligan@terratherm.com	Health and Safety Officer
John LaChance	TerraTherm, Inc. 151 Suffolk Lane Gardner, MA 01440	Phone: 978-730-1200 Fax: 978-632-3422 E-Mail: jlachance@terratherm.com	Quality Assurance Manager
Andrea Leeson	ESTCP 4800 Mark Center Drive Suite 17008 Alexandria, VA 22350-3605	Phone: 571-372-6398 E-Mail: andrea.leeson@osd.mil	Environmental Restoration Program Manager

ESTCP Office
4800 Mark Center Drive
Suite 17D08
Alexandria, VA 22350-3605
(571) 372-6565 (Phone)
E-mail: estcp@estcp.org
www.serdp-estcp.org