FINAL

ENLARGED ELECTRICAL RESISTIVE HEATING APPLICATION

CONSTRUCTION AND PERFORMANCE REPORT

BUILDING 181 TRICHLOROETHENE SOURCE AREA
AIR FORCE PLANT 4, FORT WORTH, TEXAS

JUNE 2004

Prepared for:
Air Force Center for Environmental Excellence
Brooks City-Base, TX

USAF Aeronautical Systems Center
Wright-Patterson AFB, OH

Contract Number: F41624-00-D-8028
Delivery Order: 0084
Project No: ACFJ20015006

Prepared by:
URS Corporation
9400 Amberglen Boulevard
Austin, TX 78729

Table of Contents

Page No.

Table of Contents (Continued)

Page No.

List of Figures

Page No.

List of Figures (Continued)

Page No.

List of Tables

Page No.

List of Acronyms, Abbreviations, and Symbols

%	percent
<	less than
>	greater than
° C	degrees Celsius
° F	degrees Fahrenheit
µg	microgram
AC	alternating current
AFCEE	Air Force Center for Environmental Excellence
AFP4	Air Force Plant 4
ASC	Aeronautical Systems Center
bgs	below ground surface
CATOX	catalytic oxidizer
CES	Current Environmental Solutions
cm	centimeter
CPVC	chlorinated polyvinyl chloride
CSM	conceptual site model
DNAPL	dense non-aqueous phase liquid
DTT	DNAPL Tracer Test
EPA	United States Environmental Protection Agency
EPL	East Parking Lot
ERH	Electrical Resistance Heating
FSP	Field Sampling Plan
ft	feet
gpm	gallons per minute
HSA	hollow stem auger
IRA	interim remedial action
ISO	International Organization for Standardization
kg	kilogram
kV	kilovolt
kW	kilowatt

List of Acronyms, Abbreviations, and Symbols (Continued)

L	liter
LM Aero	Lockheed Martin Aeronautics Company
lb	pound
MW	megawatt
mg	milligram
NOV	Notice of Violation
O&M	operation and maintenance
P&T	pump-and-treat
PCU	power control unit
PID	photoionization detector
PMA	photoacoustic multigas analyzer
POTW	publicly owned treatment works
ppmv	parts per million volume
psi	pounds per square inch
psia	pounds per square inch absolute
PVC	polyvinyl chloride
QA/QC	Quality Assurance/Quality Control
QAPP	Quality Assurance Project Plan
RAO	remedial action objective
ROD	Record of Decision
SAP	Sampling and Analysis Plan
SCFM	standard cubic feet per minute
SPH	Six-Phase Heating™
STL	Severn Trent Laboratories
SVE	soil vapor extraction
TCE	trichloroethene
TCLP	Toxicity Characteristic Leaching Procedure
™	Trade Mark
TMP	temperature/pressure monitoring point

List of Acronyms, Abbreviations, and Symbols (Continued)

TOC	total organic content
TRS	Thermal Remediation Services
UCL	upper confidence level
URS	URS Corporation
USAF	United States Air Force
VAC	volts alternating current
VOC	volatile organic compound

1.0 INTRODUCTION

URS Corporation (URS) has prepared this Construction and Performance Report for the United States Air Force (USAF) Aeronautical Systems Center (ASC) and the Air Force Center for Environmental Excellence (AFCEE). This report contains a description of the constructed system and evaluation of the effectiveness of Electrical Resistance Heating (ERH) technology at reducing trichloroethene (TCE) concentrations in the Building 181 source area (including reported dense non-aqueous phase liquid, [DNAPL]) at the Air Force Plant 4 (AFP4), Fort Worth, Texas site to below remedial action objectives (RAOs). The TCE DNAPL is believed to be the source of the East Parking Lot (EPL) groundwater plume at the site.

Selection of the ERH technology for this source removal was based on the findings of the pilot-scale test conducted at the site, as documented in the ***Six-Phase Heating™ Pilot-Scale Test Technology Demonstration Report*** (URS and Current Environmental Solutions [CES], May 2001). The ensuing ERH application was conducted according to the ***Enlarged Electrical Resistance Heating Application Work Plan, Sampling and Analysis Plan, and Engineering Submittal Package, Trichloroethene Source Area, Building 181, Air Force Plant 4, Fort Worth, Texas*** (URS and Thermal Remediation Services [TRS], January 2002a) and the ***Enlarged Electrical Resistance Heating Application Health and Safety Plan, Trichloroethene Source Area, Building 181, Air Force Plant 4, Fort Worth, Texas*** (URS and TRS, January 2002b).

1.1 Site Description and Operational History

AFP4 is located in Tarrant County, Texas, seven miles northwest of the City of Fort Worth (see Figure 1-1). The plant is bounded by Lake Worth on the north, Naval Air Station Fort Worth Joint Reserve Base on the east, the community of White Settlement on the south and west, and the City of Fort Worth on the west. The facility occupies 602 acres.

AFP4 is an active military aircraft manufacturing facility currently being operated by Lockheed Martin Aeronautics Company (LM Aero). Past management of waste oil, solvents, and fuels generated during the manufacturing operations have resulted in multiple separate sites of investigation, including landfills, fire training areas, underground storage tanks, and other miscellaneous areas.

The enlarged ERH application documented in this report addresses the source area associated with one of these sites of investigation – the EPL groundwater plume. The origin of the TCE source material is believed to be degreaser tanks in Building 181 that have since been removed. Building 181, the Chemical Process Facility, is part of the Assembly Building/Parts Plant. In May 1991, a TCE vapor degreaser tank in Building 181 was discovered to be leaking. A documented TCE release from tank T-534 was estimated at 20,000 gallons (Rust Geotech, 1995). On 15 June 1991, tanks T-544 and T-534 were removed from service.

On the basis of several subsequent investigations, it was found that releases of TCE had migrated through cracks in the concrete building floor, resulting in contamination in the unsaturated zone, including Terrace Alluvium and overlying fill soil under Building 181. Except for the one documented release, accurate information is not available on the historical amount of TCE that spilled or leaked from the tanks, how much TCE was in the unsaturated zone, or how much TCE was in the Terrace Alluvial groundwater (Rust Geotech, 1996). The contaminated unsaturated zone beneath Building 181 was thought to be a source of contamination to Terrace Alluvial ground-water, which flows in a northeast direction under Building 181 and the EPL. Contaminants are contained in the EPL by a series of groundwater extraction wells first operated in 1999.

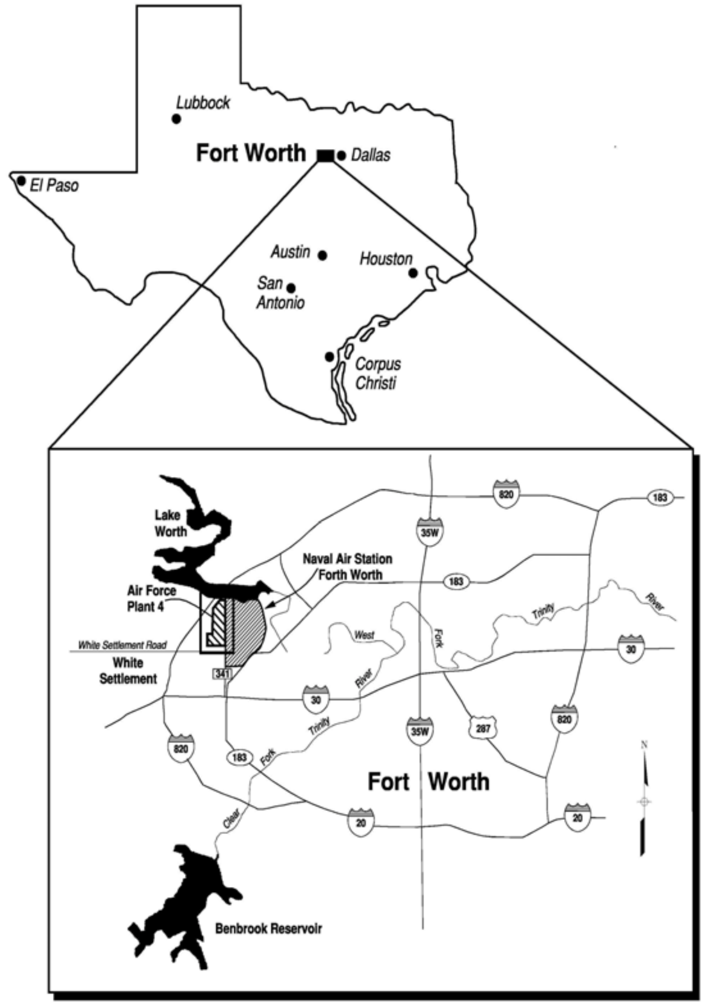


Figure 1-1. Location of Air Force Plant 4

1.2 Record of Decision Requirements

The TCE contamination that was the focus of the pilot test and the subsequent enlarged ERH application is addressed in the July 1996 Record of Decision (ROD) requirements for both the Building 181 and EPL sites. Following acknowledgement of the previously performed interim remedial actions (IRAs) at these two sites – consisting of soil vapor extraction (SVE) at

Building 181 and groundwater pump-and-treat (P&T) systems in the EPL – the ROD presents the selected remedies for the sites, which are:

- ***Building 181*:** A full-scale SVE system, with supplemental vacuum-enhanced groundwater extraction wells to collect perched groundwater situated above the underlying Terrace Alluvial groundwater; and

- ***EPL*:** Conventional P&T (additional wells over those installed in the IRA) with surfactant injection for DNAPL areas (assumed to be anywhere where groundwater concentrations are > 10 milligrams per liter [mg/L] TCE).

The ROD-specified Building 181 SVE system expansion was completed and began operation in 1999. The remedial action expansion of the EPL groundwater P&T system is currently ongoing.

The area of the enlarged ERH application, which has exhibited unsaturated zone and groundwater contamination, involves the selected remedies for both of these sites. Because ERH technology treats both the unsaturated and saturated zones, successful implementation would directly address the ROD source reduction provisions for the EPL plume and would also expedite the Building 181 remedial action. The ROD timeframe estimates for completion of these remedial actions are 15 years for the EPL (including surfactants, rather than ERH) and five years for the Building 181 SVE system. The successful implementation of ERH should significantly shorten these estimated remedial timeframes. The target TCE concentrations for the remedial actions, including the ERH source removal, are based on protecting downgradient compliance points rather than on risk factors associated with the Building 181 unsaturated zone or the EPL DNAPL.

1.3 Technology Description

ERH technology was selected for the Building 181 source area on the basis of the recommendation presented in the ***Preliminary (30%) Remedial Design, Dense Non-Aqueous Phase Liquid, Eastern Parking Lot Plume, Air Force Plant 4, Fort Worth, Texas***, (Radian International, 1999) and the successful pilot test. At AFP4, ERH was designed to work in conjunction with the existing SVE system. Thermally enhanced soil vapor extraction is a two-step process where the contaminated subsurface is heated to volatilize the contaminants (Step 1) and the contaminated soil vapor is extracted and treated above ground (Step 2). Because heat can be generated and conducted through soil regardless of permeability, thermally enhanced

SVE may be more effective in clayey soils than technologies that depend on flow pathways for removal or destruction of contaminants.

ERH heats the subsurface by passing an electrical current between electrodes through the soil matrix. The passage of current generates heat due to the electrical resistance of the soil. Heat is generated throughout the subsurface in the target area, and the temperature of the soil is increased to the boiling point of water (80 to 100 degrees Celsius [°C], depending on subsurface vacuum and the rate at which air is pulled through the target area by the SVE system). Soil moisture and volatile contaminants boil into steam and contaminated vapor that travels to recovery wells for removal.

For the enlarged ERH application at AFP4, the electrodes were installed vertically (or at angles when there were subsurface obstructions) to create an equilateral triangle pattern with electrode locations set approximately 19 feet (ft) apart at all points. Some movement of locations was necessary due to surface obstructions encountered within the ½-acre application area. In these cases, this could have resulted in diminished or increasing separation of electrode points by 1 to 2 ft. Each electrode conducts electricity with as many as six other nearby electrodes. In addition to flowing along the straight-line path between the electrodes, the current also fans out slightly as shown in Figure 1-2.

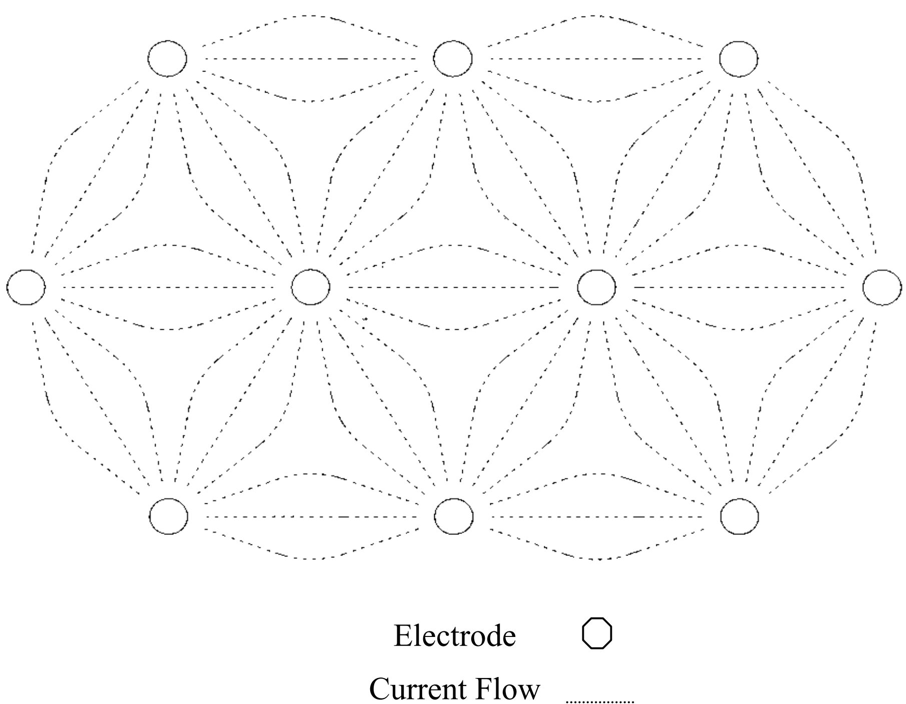


Figure 1-2. Representation of an Ideal ERH Electrical Current Distribution

The electrical current also fans out in the vertical direction, treating soil that lies in the conductive depth interval of the electrodes plus soil that lies up to 4 ft above or below the conductive interval. The result of this electrical current is very even heat generation in the subsurface that leads to uniform steam production and volatile organic compound (VOC) volatilization throughout the treatment volume.

Once the steam and contaminated vapors are collected, they are conveyed through an aboveground piping network to a condenser. The condenser uses non-contact cooling water to condense the steam and produce a contaminated vapor stream at ambient temperatures. The condensate is sent to an on-site air stripper before discharge to a publicly owned treatment works (POTW). The contaminated vapors are sent to the existing SVE system that includes an inlet knockout pot and a rotary lobe blower. Although a catalytic oxidizer (CATOX) was available, two vapor-phase carbon adsorption canisters configured in series were used to remove contaminants from the extracted vapors. Vapor phase carbon was used instead of the CATOX because of operational problems with the CATOX control logic, the relatively low mass-loading, and the short duration of the ERH application.

1.4 Remedial Action Objectives

Consistent with the ROD requirements and the goals of the preceding pilot-scale test, ERH was selected for its ability to satisfy the remedial action objectives presented in Table 1-1.

Table 1-1. ERH Performance Objectives

Performance Criteria	Performance Objectives	Methods of Measuring Performance
Subsurface temperatures in the treatment volume	Boiling point of TCE	Temperature monitoring point measurements
Soil - TCE Remediation Goal	< 11.5 mg/kg [1]	Pre- and post-application subsurface soil sampling
Groundwater - TCE Remediation Goal	< 10 mg/L [1]	Pre-application, interim and post-application groundwater sampling

[1] These performance objectives are equivalent to the ROD-based remedial action objectives for the soil and groundwater media and represent a > 99% reduction in TCE concentrations from the highest previous detections in the enlarged ERH application volume.

Section 5 of this report details the results of the ERH application and compares the results to the performance objectives listed above. For Building 181, the intent was to reduce the TCE concentration in soils to less than 11.5 milligrams per kilogram (mg/kg), which, based on leaching modeling (Rust Geotech, 1995), is the allowable soil concentration to prevent underlying groundwater concentrations from exceeding the respective RAOs. Extensive previous soil sampling performed in the vicinity of the enlarged ERH application revealed soil TCE concentrations of up to 2,770 mg/kg, but concentrations greater than 11.5 mg/kg were infrequent and distributed randomly. The Building 181 area that includes all known TCE concentrations in soil that were greater than 11.5 mg/kg is approximately ½-acre. This is the target remediation area for the current Building 181 SVE system, and is also considered the source area for the EPL groundwater plume.

The EPL RAO for groundwater is based on protection of the deeper Paluxy drinking water aquifer. This deeper aquifer is in hydraulic communication with the shallow Terrace Alluvial aquifer through an area (termed "Window Area") without the typically intervening aquitard (see Section 2.1 for a detailed hydrologic description). TCE groundwater concentrations less than 10 mg/L should help protect the underlying Paluxy aquifer by ensuring that DNAPL does not migrate beyond the EPL P&T containment system. The 10 mg/L value (which is roughly 1% of the aqueous solubility of free-phase TCE) is often used as a preliminary indication of DNAPL presence. For the ROD, the mapped extent of dissolved-phase TCE groundwater concentrations greater than 10 mg/L (approximately 6 acres) was used as a basis for the estimated extent of DNAPL presence, and hence, DNAPL-related remedial activities. However, the mapped extent of 10 mg/L TCE in groundwater is likely less than that for saturated zone DNAPL (if present). With source area groundwater concentrations of TCE of over 100 mg/L, dilution/dispersion processes alone could readily account for the current downgradient expanse of the TCE plume with concentrations greater than 10 mg/L.

Figure 1-3 shows the known extent of soil contamination beneath Buildings 5 and 181 and EPL groundwater with TCE concentrations greater than 10 mg/L. Also shown on the figure are the former locations of the removed degreaser tanks T-544 and T-534 that are believed to be the source of the TCE contamination. Their central location relative to the identified soil contamination supports their source designation.

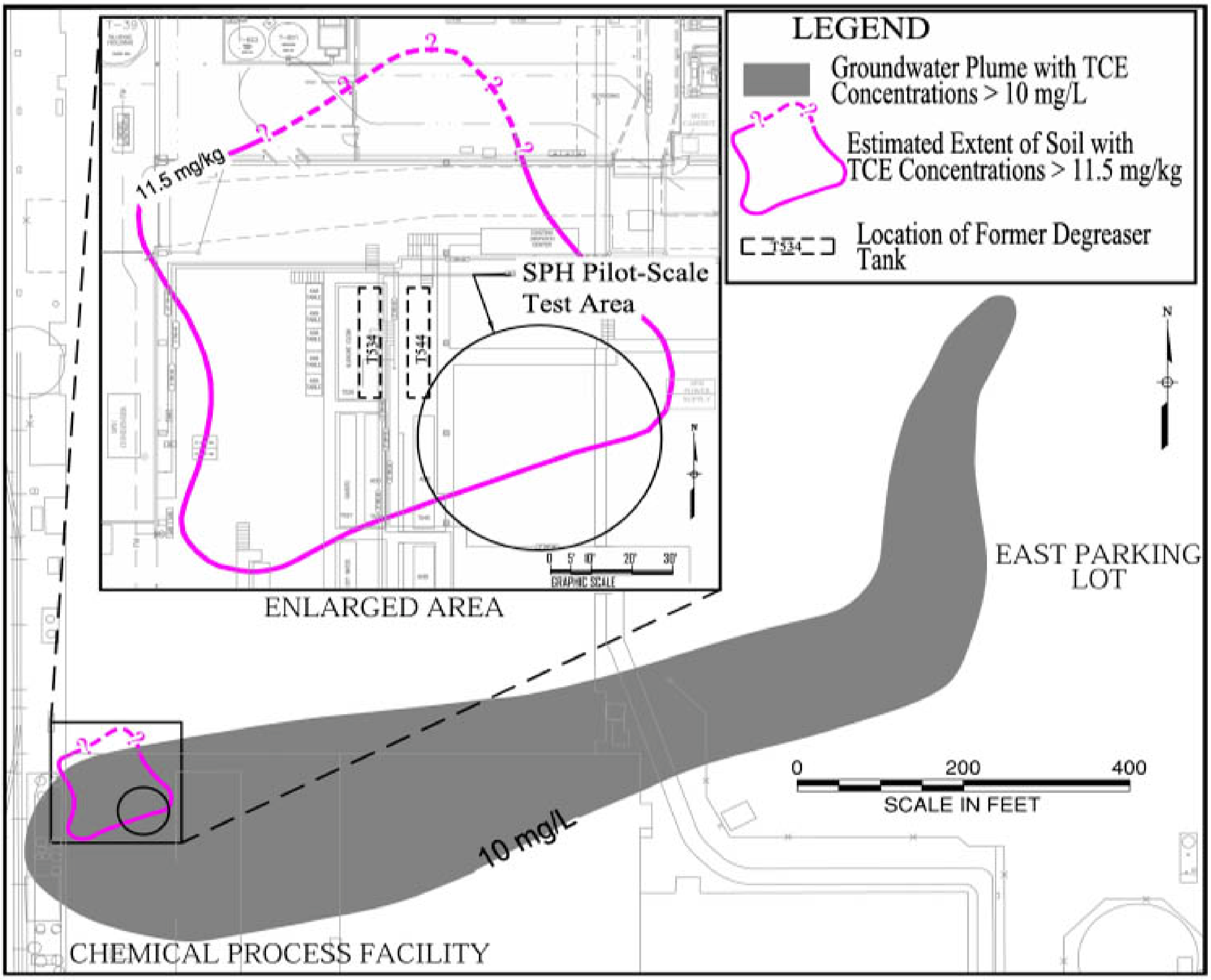


Figure 1-3. Soil and Groundwater Condition Before Pilot Test

2.0 CONCEPTUAL SITE MODEL

The information used to further develop the conceptual site model (CSM) was gathered from several existing reports, most notably the:

- ***Record of Decision*** (Rust Geotech, 1996);
- ***Remedial Alternatives Evaluation*** (Jacobs, 1998b);
- ***Draft East Parking Lot/Window Area Technical Report*** (Jacobs, 1998a);
- ***Technical Report on the Geology of Air Force Plant 4 and Naval Air Station Fort Worth Joint Reserve Base*** (Parsons, 1998);
- ***DNAPL Tracer Tests, Air Force Plant 4*** (Eckenfelder, 1998); and
- ***Six-Phase Heating Pilot-Scale Test Technology Performance Report*** (URS and CES, 2001).

In addition to these reports, data gathered while installing the ERH system subsurface components and conducting the bedrock DNAPL site investigation were used to assist CSM development (the DNAPL site investigation was performed by the Shaw Group and is described in the following subsection). Table 2-1 presents a summary of the work performed and the types of data collected during the enlarged ERH application.

Table 2-1. ERH Field Activities Summary

Activity	Number
Soil Borings for Electrode/Vapor Recovery Well Installations	66
Soil Borings for Temperature Monitoring Points	10 (7 thermocouples in each)
Sample Soil from Six Temperature/Pressure Monitoring Points (TMPs) and Four Soil Boreholes	52 (pre-ERH) and 47 (post-ERH)
Groundwater Sampling	81 (varies over 10 rounds)
Sample Condenser Discharge	24
Sample Vapor Stream	37
Sample Drill Cuttings	8 (for waste characterization)
Sample Interior Building Air Quality	Continuous with INNOVA™
Perform Soil Vapor Survey	Roughly 150 locations each during pre- and post-ERH survey

2.1 Geology and Hydrogeology

During the Cretaceous period of the Mesozoic era, transgression and regression of the sea across north-central Texas deposited sediments on top of flat-lying Paleozoic age strata. Near the end of the Cretaceous period, regional uplift tilted the layers of sediment toward the east as seas withdrew toward the gulf. Subsequent transgression and regression of the sea deposited sediments of Tertiary and Quaternary age further to the east, as streams eroded the exposed land to the west and deposited Terrace and alluvial sediments there (Nordstrom, 1982).

At AFP4, Tertiary age Terrace Alluvium is exposed at ground surface, or lies beneath fill material that is generally comprised of the same Terrace Alluvium. Regionally, these sediments are characterized as heterogeneous or interbedded gravel, sand, silt, and clay mixtures. Drilling logs from Building 181 record the presence of silty clay deposits (with some sand and gravel) that range in thickness from 15 to 35 ft.

Beneath the Terrace Alluvium lie weathered and competent bedrock consisting of Cretaceous age Goodland Limestone Formation and Walnut Clay Formation, undifferentiated at the site. Regionally, the Goodland Formation is a white, fossiliferous, micritic limestone, and the Walnut Formation is a marl or marly limestone that contains fossilized oyster reefs. Together, these formations comprise the Fredericksburg Group, which functions as an aquitard overlying the Paluxy Formation of the Trinity Group aquifers (Baker, et al., 1990). Drilling logs from Building 181 record the presence of weathered limestone layers at 15 to 20 ft below ground surface (bgs) in the western portion of the site, and at 30 to 35 ft bgs in the east portion of the site. The logs consistently record the presence of competent bedrock at 30 to 35 ft bgs beneath the entire site. In the ERH coverage area, an approximately 5-ft thick fill layer underlies the building floor.

Two geologic cross-sections depicting the ERH application area are included in Figure 2-1 and 2-2 along with a plan view illustrating the cross-section lines. Copies of lithologic logs are included in Appendix A.

The hydrogeologic interval targeted by the ERH application includes the Terrace Alluvium and weathered bedrock to a depth of approximately 35 ft bgs. Well pump tests performed within this shallow aquifer yielded sustainable pumping rates ranging between 0.4 and 2.8 gallons per minute (gpm) and transmissivity values (calculated via Theis and Cooper-Jacob methods) ranging between 0.087 and 0.88 square ft/day (DNAPL Tracer Tests,

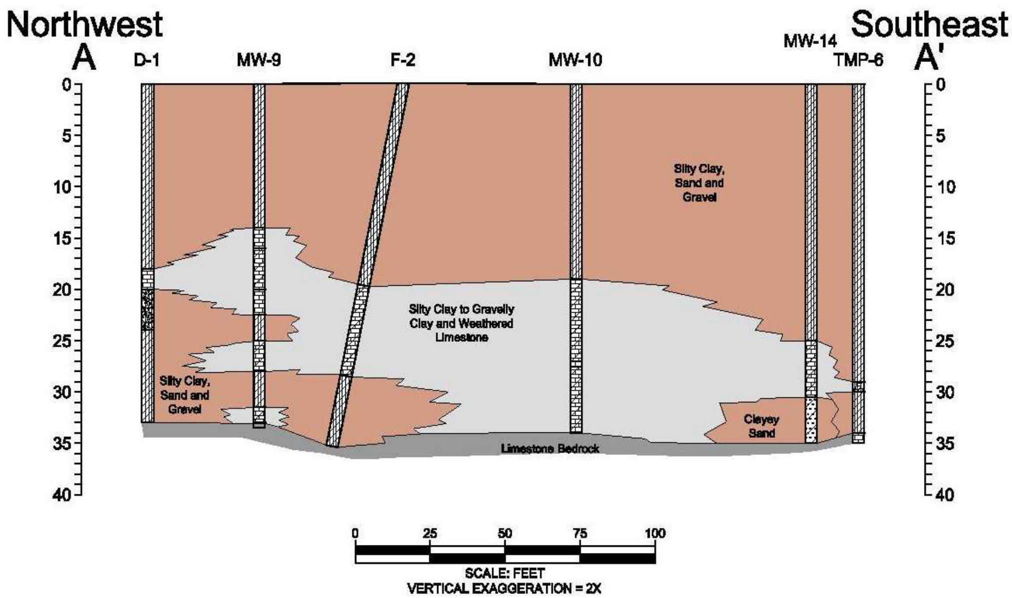
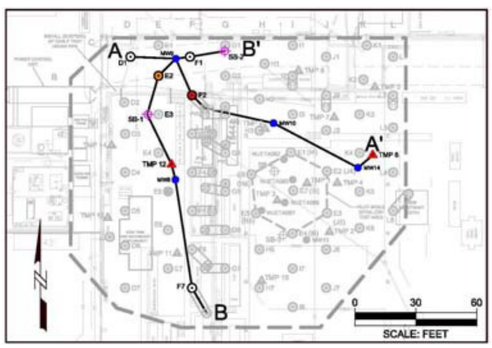


Figure 2-1. Cross-Section A-A'



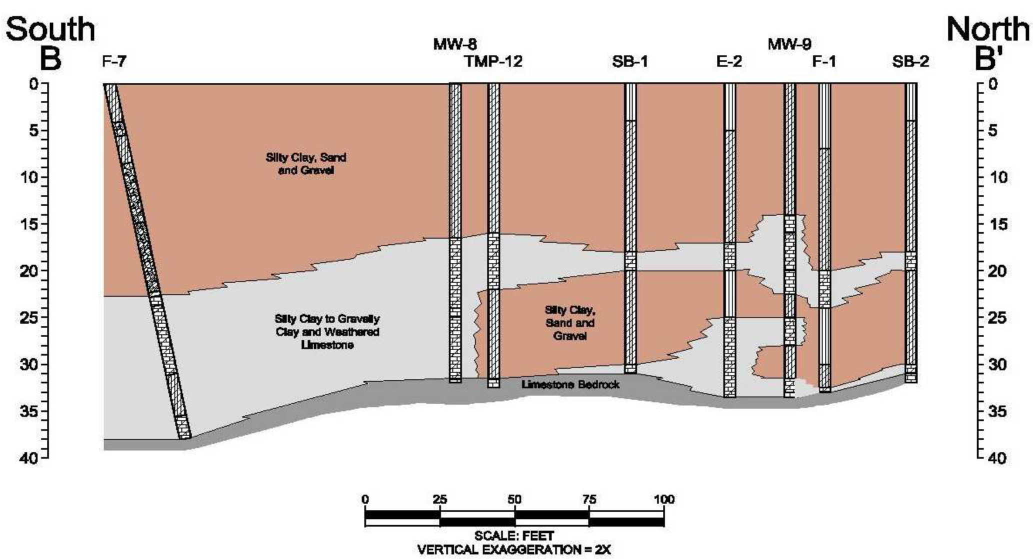


Figure 2-2. Cross-Section B-B'

Air Force Plant 4, Ft. Worth, Eckenfelder Inc., 1998). Based on site monitoring well gauging data, the depth to groundwater is approximately 25 ft bgs, with an east-northeast hydraulic gradient of approximately 0.008 ft/ft. Assuming the saturated thickness of the aquifer is approximately 10 ft, and based on the data above, corresponding hydraulic conductivity values for the aquifer range between 13 and 132 ft/day.

2.2 Source Zone Characterization

The original source of this contamination plume is believed to be the TCE degreaser tanks in Building 181 that have since been removed. Figure 2-3 shows an illustrative cross-section model illustrating the original TCE release, DNAPL migration, and dissolved phase groundwater contamination. Although previous reports describe the potential for several source areas, the main source area was presumed to be the former leaking tanks in Building 181 near the center of the enlarged ERH application area. The CSM depicts that from the release area, TCE

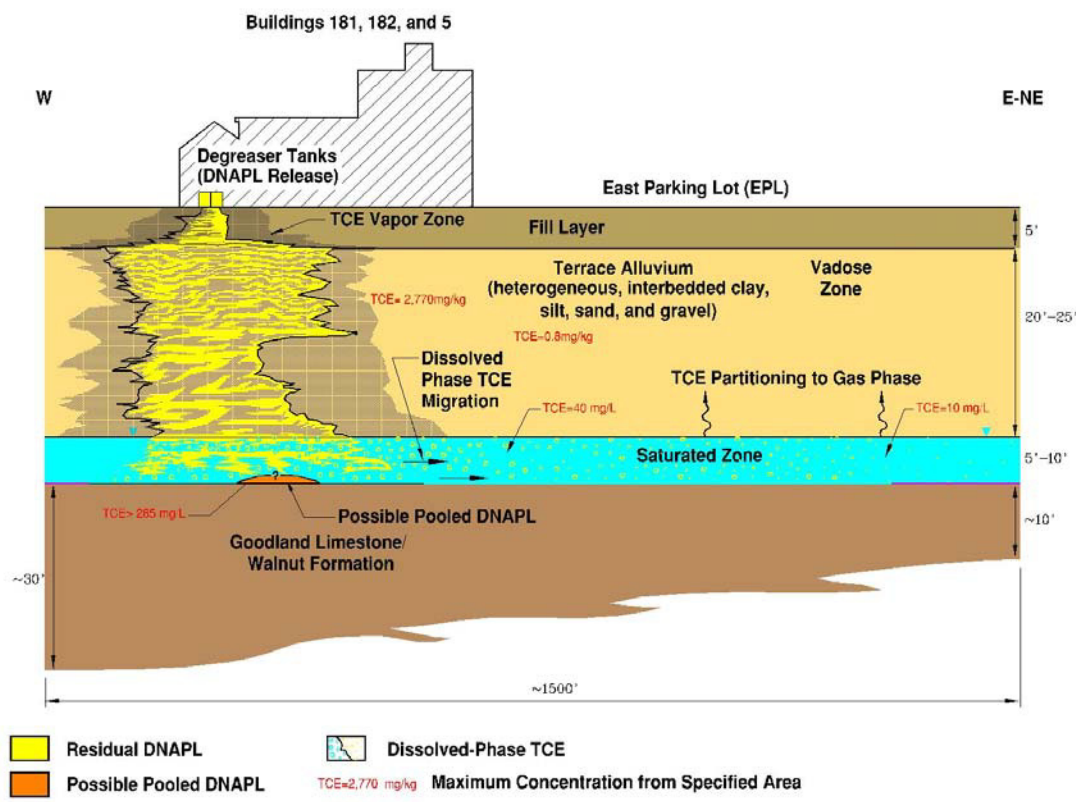


Figure 2-3. Conceptual Site Model Illustration

migrated through breaches in the concrete floor to the underlying fill. Much of the TCE accumulated at the interface of the fill layer with the underlying, lower-permeability Terrace Alluvium deposits. This premise was supported during investigational activities, during which the most elevated VOC field screening values occurred at this interface. From the fill/alluvium interface, the DNAPL likely migrated downward by gravitational force into the approximately 25-ft thickness of interbedded, primarily fine-grained sediments comprising the Terrace Alluvium. This downward migration was impeded, and likely diverted, by numerous lenses of finer-grained silts and clays. Some of the TCE was left as residual DNAPL in the unsaturated zone, where further movement was expected to be insignificant since the concrete floor of the building should prevent most infiltration of water that would entrain the TCE. It is assumed unsaturated zone contamination with residual DNAPL was limited to the vicinity of the former spills in Building 181.

The elevated TCE groundwater concentrations that were present in the main source area indicated that free-phase TCE reached the underlying water table. Once in the saturated zone, the free-phase TCE would have continued a primarily downward migration through the unconsolidated alluvium materials toward the more competent underlying limestone and shale. As in the unsaturated zone, some of the TCE would be left as residual in the saturated zone.

This interpretation would be consistent with the results of the DNAPL tracer test (DTT) performed in Building 181 (which used the same wells sampled for groundwater TCE concentrations during the pilot test and enlarged application), especially considering that the DTT is not geared for determining the mass of pooled DNAPL, and instead was performed to determine the mass of non-pooled, residual product.

Historical site groundwater concentrations of greater than 200 mg/L TCE are well above the 1% of TCE solubility rule-of-thumb that has been used as an indicator of DNAPL presence, and was used in the ROD to indicate DNAPL extent (i.e., DNAPL was assumed to be present beneath the water table everywhere that TCE groundwater concentrations were > 10 mg/L).

Bedrock DNAPL Presence

Prior to the implementation of the expanded ERH application, the Shaw Group (formerly the IT Corporation) drilled to bedrock at three select locations within the proposed ERH application area to attempt to find evidence of DNAPL. This study involved taking continuous core samples through the upper portion of the bedrock, examining the integrity of the bedrock, and performing field screening and laboratory analyses on the resulting samples. Analytical and field-screening results obtained during bedrock drilling indicate the bedrock has served as a deterrent to vertical DNAPL migration.

DNAPL Pooling Potential

Earlier interpretations of DNAPL distribution in the Building 181 subsurface assumed that the DNAPL migrated to the saturated zone in sufficient volume to allow pooling at the alluvium/limestone (bedrock) interface. It was conceptualized that, once pooled, the DNAPL migrated along lows in the bedrock upper surface to the mapped location of a nearby former stream channel, or paleochannel (approximately 150 ft south of pilot-scale test area). The paleochannel runs to the east-northeast, and usually contains the thickest accumulations of coarser-grained sands and gravel. Neither the occurrence nor the extent of lateral DNAPL migration in the paleochannel was understood, but migration was estimated as far as the east edge of the building complex.

More recent interpretation indicates there was insufficient DNAPL volume to pool at the bedrock interface, only residual DNAPL within the pore spaces of the aquifer. Evidence for the lack of pooled and mobile DNAPL was obtained from the numerous borings performed in the source area. For example, the ten DTT well borings were advanced to the underlying bedrock and hydrophobic dye was used where the most elevated PID readings occurred to try and detect DNAPL – none was observed visually or confirmed with the dye testing. In addition, there have been over 20 additional boreholes drilled to bedrock within the area without any visual observation or sampling confirmation of DNAPL. Including the numerous other boreholes drilled within Building 181 for investigative or well placement purposes, there has never been confirmation of pooled DNAPL below the water table.

2.3 Nature and Extent of Contamination

This document addresses the DNAPL associated with the EPL groundwater plume. Additional information regarding the downgradient extent of the contaminant plume is covered under the EPL interim measure and the long-term monitoring program. At this point, data have not been collected to determine the long-term effects of the source removal on the extent of contamination. However, data collected from within Building 181 indicate that the source zone mass was reduced by over 90 percent. Additionally, preliminary data from the EPL system monitoring indicate reduced contaminant concentrations downgradient from the source area. Continued monitoring will be necessary to determine the effect of the source removal.

2.4 Contaminant Fate and Transport

The enlarged ERH application should have a marked effect on contaminant fate and transport, if current trends continue. In the past, the Building 181 source area has provided a continuing source of contamination in the form of DNAPL dispersed as ganglia in the aquifer matrix. This residual source of contamination has slowly partitioned to groundwater. Continued monitoring will be necessary to determine the long-term effects of the source removal. This recommended monitoring is detailed in Section 7.

3.0 SYSTEM CONSTRUCTION

This section documents the constructed system and provides "as-built" type information for the above- and below-grade components of the system. The system was constructed, with some field modifications, according to the Engineering Submittal Package included with the Work Plan (URS and Beyke, 2002a). Some of the above-grade components were removed from the site after the application was completed. Figure 3-1 shows a conceptual diagram of the below-grade system construction.

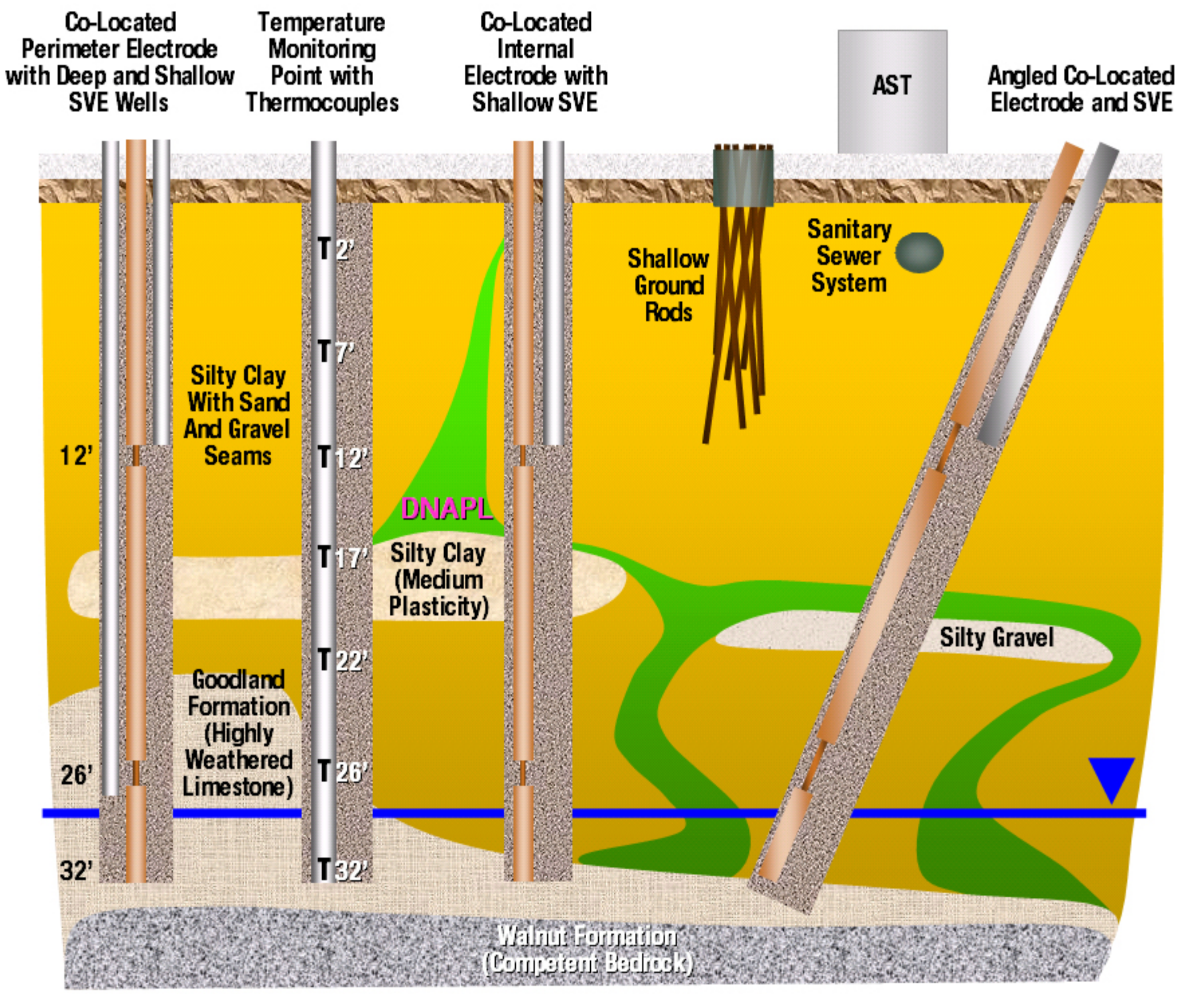


Figure 3-1. Below Grade System Construction Conceptual Diagram

3.1 Chronology of Events

Figure 3-2 shows the chronology of the construction phase of the project, defined as all work conducted between the initial field reconnaissance and system startup. The operation chronology is presented in Section 4.

Task Name	Start	Finish
Field Reconnaissance and Planning	Nov 26 '01	Dec 21 '01
Well Abandonment	Jan 7 '02	Jan 8 '02
TMP Installation	Jan 10 '02	Mar 18 '02
Trenching	Jan 14 '02	Feb 12 '02
Electrode and SVE Well Installation	Jan 9 '02	Mar 20 '02
Monitoring Well Installation	Feb 20 '02	Mar 11 '02
Soil Boring Installation	Mar 6 '02	Mar 12 '02
Power and Conveyance Installation	Mar 13 '02	Apr 5 '02
Treatment System Connection	Apr 8 '02	Apr 12 '02
Surveying	Apr 15 '02	Apr 19 '02
System Startup and Optimization	Apr 9 '02	May 6 '02

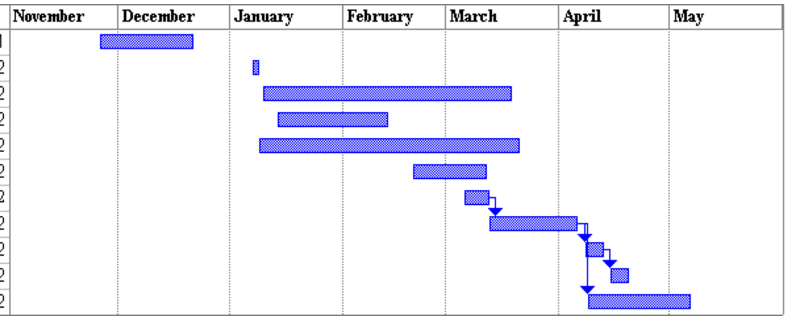


Figure 3-2. ERH Construction Chronology

3.2 Groundwater Monitoring Network

For the purpose of monitoring groundwater TCE concentrations before, during, and after ERH system operation, a network of 12 monitoring wells was established as shown in Figure 3-3.

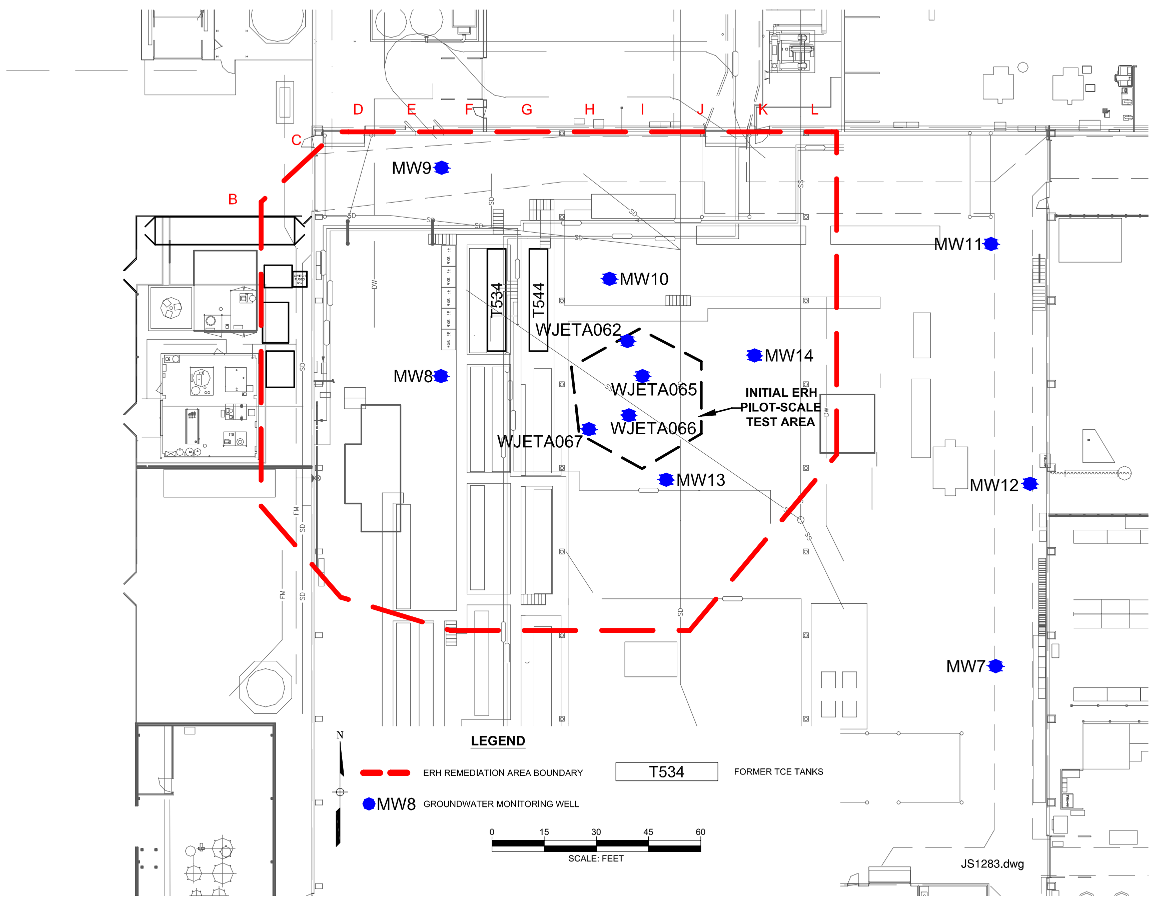


Figure 3-3. ERH Groundwater Monitoring Network in Building 181

This network consists of five pre-existing monitoring wells (MW-7, WJETA-062, WJETA-065, WJETA-066, WJETA-067) and seven newly installed monitoring wells (MW-8 through MW-14) that were installed during ERH system construction. Monitoring wells MW-7, MW-11, and MW-12 were to the east of the ERH treatment area and served as downgradient wells. A diagram of the typical well construction is shown in Figure 3-4, and specific construction details for each well are summarized in Table 3-1. Well construction logs are included in Appendix B.

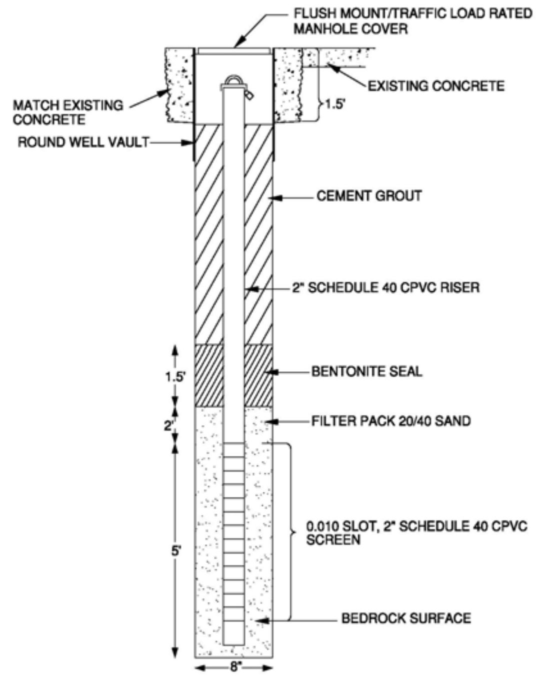


Figure 3-4. Typical Monitoring Well Construction

Table 3-1. Monitoring Well Construction Details

Well ID	Date Drilled / Installed	Total Depth of Well (ft bgs)	Well Screen Interval (ft bgs)	Well Diameter (in)	Grout (ft bgs)	Bentonite Seal (ft bgs)	Filter Pack (ft bgs)	Bentonite Backfill (ft bgs)
MW-7	2/29/92	34.5	19.5-34.5	4	0-14	14-16	16-34.5	NA
MW-8	2/20/02	18	13-18	2	0-9	9-11	11-19	19-32
MW-9	2/27/02	31	26-31	2	0-22	22-24	24-31	31-33.5
MW-10	3/11/02	33	28-33	2	0-23.5	23.5-26	26-34	NA
MW-11	3/8/02	35	30-35	2	0-25.5	25.5-27.5	27.5-35.5	NA
MW-12	2/23/02	33	28-33	2	0-24	24-26	26-35	NA
MW-13	3/10/02	35	30-35	2	0-25.5	25.5-28	28-35	NA
MW-14	3/9/02	34.5	29.5-34.5	2	0-22	22-25	25-35	NA
WJETA-062	12/8/97	33	24.9-29.9	4	0-19	19-22	22-33	NA
WJETA-065	12/9/97	32	24.9-30.4	4	0-19	19-22	22-32	NA
WJETA-066	12/9/97	32	24.7-30.2	4	0-19	19-23	23-32	NA
WJETA-067	12/9/97	32	25.5-30.5	4	0-19	19-22	22-32	NA

bgs – below ground surface NA – Not Applicable

3.3 Temperature/Pressure Monitoring Network

For the purpose of monitoring soil temperature and pressure conditions during ERH system operations, a network of 14 site TMPs was established as shown in Figure 3-5. This network consisted of four TMPs (TMP-1 through TMP-4) that were installed during the pilot-scale test and ten TMPs (TMP-5 through TMP-14) that were installed during ERH system construction. Each TMP was constructed to include two components: 1) a series of electrical

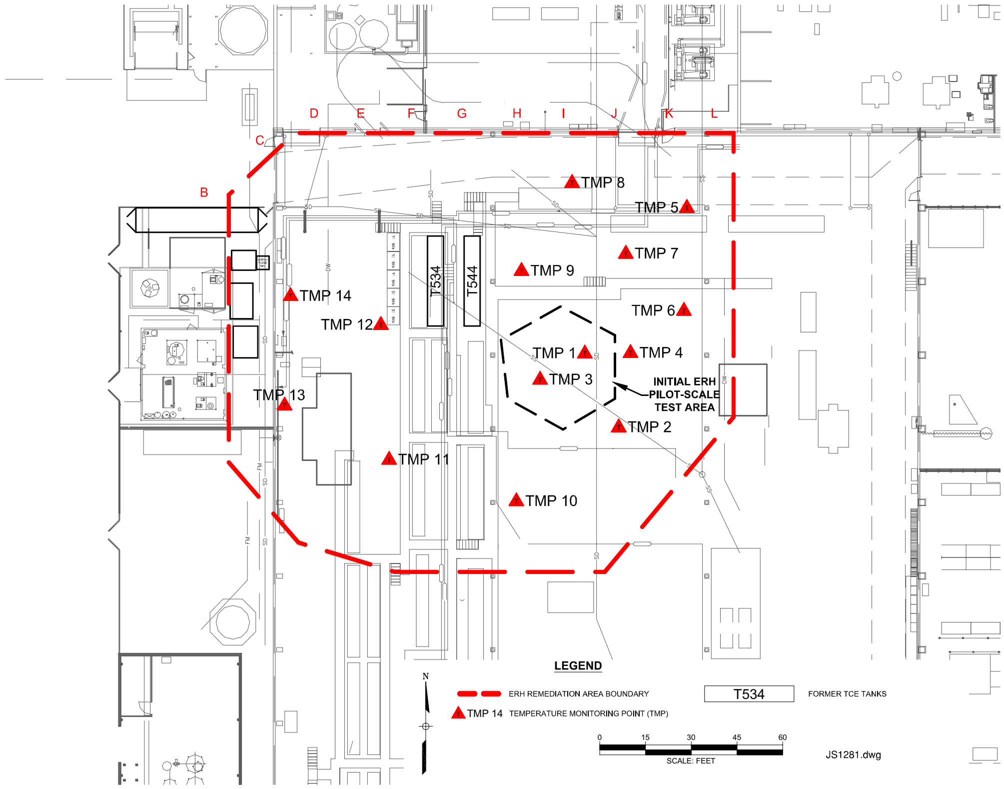


Figure 3-5. ERH Temperature Monitoring Point Network

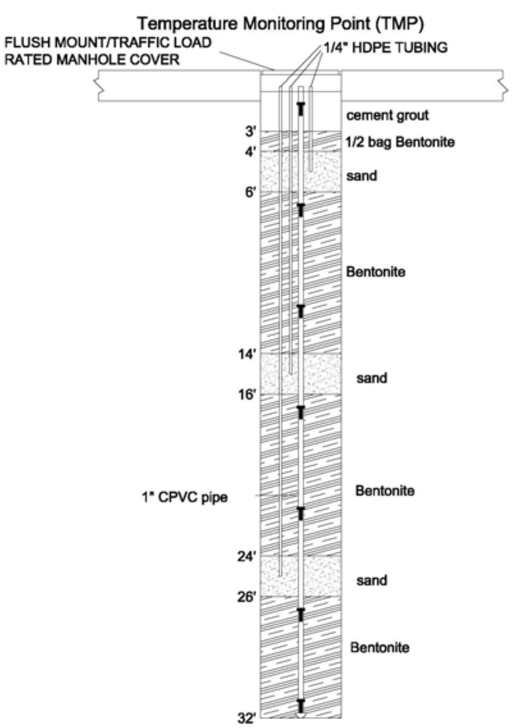


Figure 3-6. Typical ERH Temperature Monitoring Point Construction

thermocouples connected to a data acquisition computer for recording soil temperature at various depths; and, 2) a series of pressure piezometers to be monitored manually for recording soil vacuum pressure at various depths. A diagram of the typical TMP construction is shown in Figure 3-6.

3.4 Electrode Construction

In order to implement ERH technology at the site, a network of 73 electrodes was established as shown in Figure 3-7. This network consisted of 7 electrodes that were installed during the pilot-scale test, 64 electrodes that were installed during ERH system construction, and 2 electrodes that were installed during ERH system operation for the purpose of enhancing heat generation in target areas. Three groups of electrodes were connected to each of three phases of

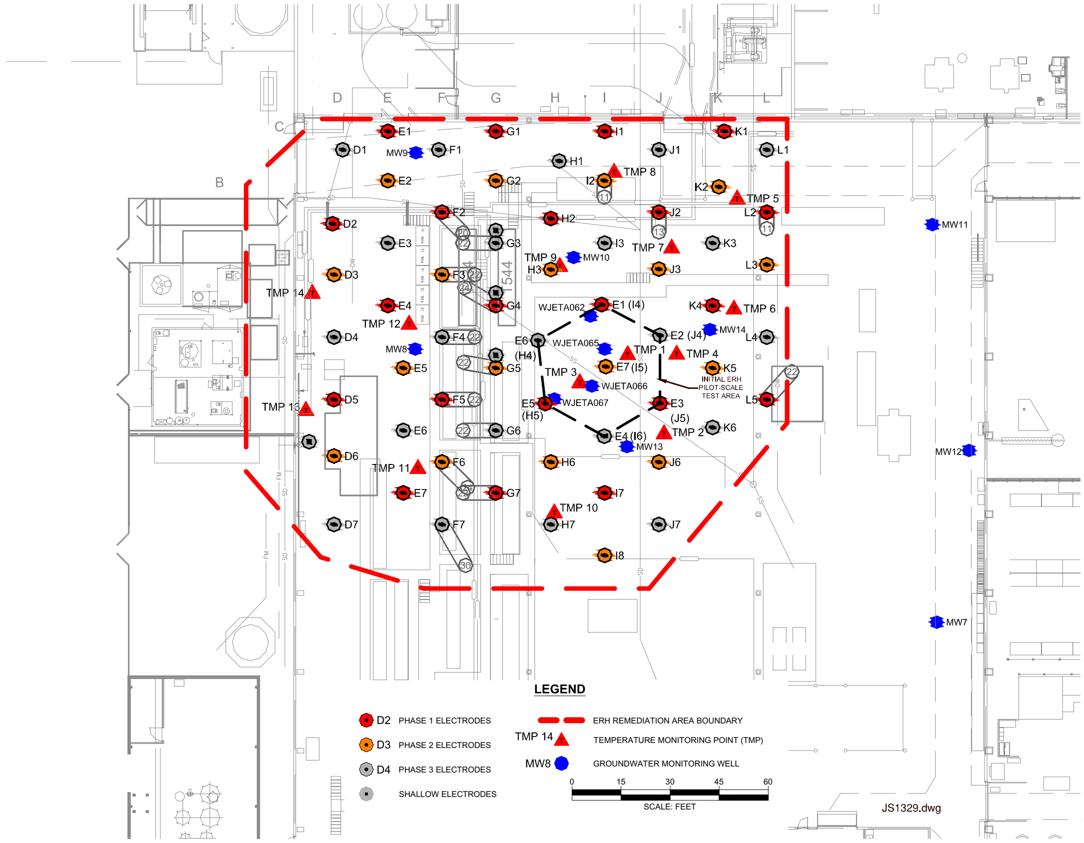


Figure 3-7. ERH Electrode Array

electricity in order to induce electrical current to pass through the soil to generate sufficient heat to convert VOCs and groundwater into steam. In conjunction with electrode construction, an SVE network was established. While many SVE wells were co- located in vertical or angled electrode boreholes, some SVE wells were independently located. The angled drilling (Figure 3-8) was necessary to avoid surface obstructions. In an attempt to maintain proper electrode spacing within the network, the upper intervals of the electrodes were installed as vertical grounding rods. This caused minor variations in the spacing of the electrodes, which could have caused uneven heat distribution. A diagram of the typical electrode construction is shown in Figure 3-9. Electrode construction logs are included in Appendix C.

3.5 Power Delivery System

The above-grade portion of the power delivery system consisted of the power control unit (PCU), transmission wire installed from the electrical substation to supply the PCU, and electrical cables to deliver power in three separate phases from the PCU to the electrodes. None of these appurtenances remain at the site as they were removed during demobilization.

Figure 3-8. Installation of Angled Electrodes

The cable from the substation to the PCU was a 5-kilovolt (kV) shielded power cable with an aluminum sheath and copper conductors. This cable had a 5 thousandths of an inch (mil) uncoated copper tape shield, a corrugated aluminum sheath, and a yellow sunlight resistant polyvinyl chloride (PVC) jacket.

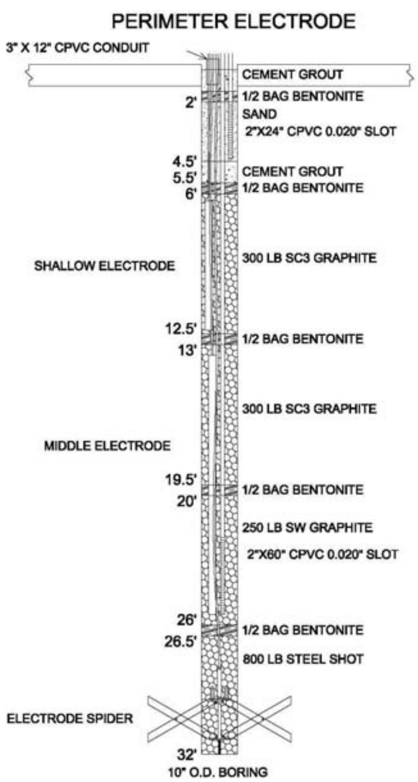


Figure 3-9. Typical ERH Electrode Construction

The ERH PCU conditioned electrical energy for optimum subsurface heating. The PCU, contained in a 40-ft International Organization for Standardization (ISO) shipping container, has a set of 60 hertz transformers rated for constant power output of up to 2,000 kilowatt (kW). The ERH PCU required input power be provided at 100 amps at 12,500-13,800 volts alternating current (VAC) 3-phase.

The PCU was equipped with numerous automatic shut-off components to prevent unwanted exposure to hazardous voltages. Emergency stop buttons were located both remotely and locally in the event a personnel or equipment hazard was identified. An electrical diagram is presented as Figure 3-10.

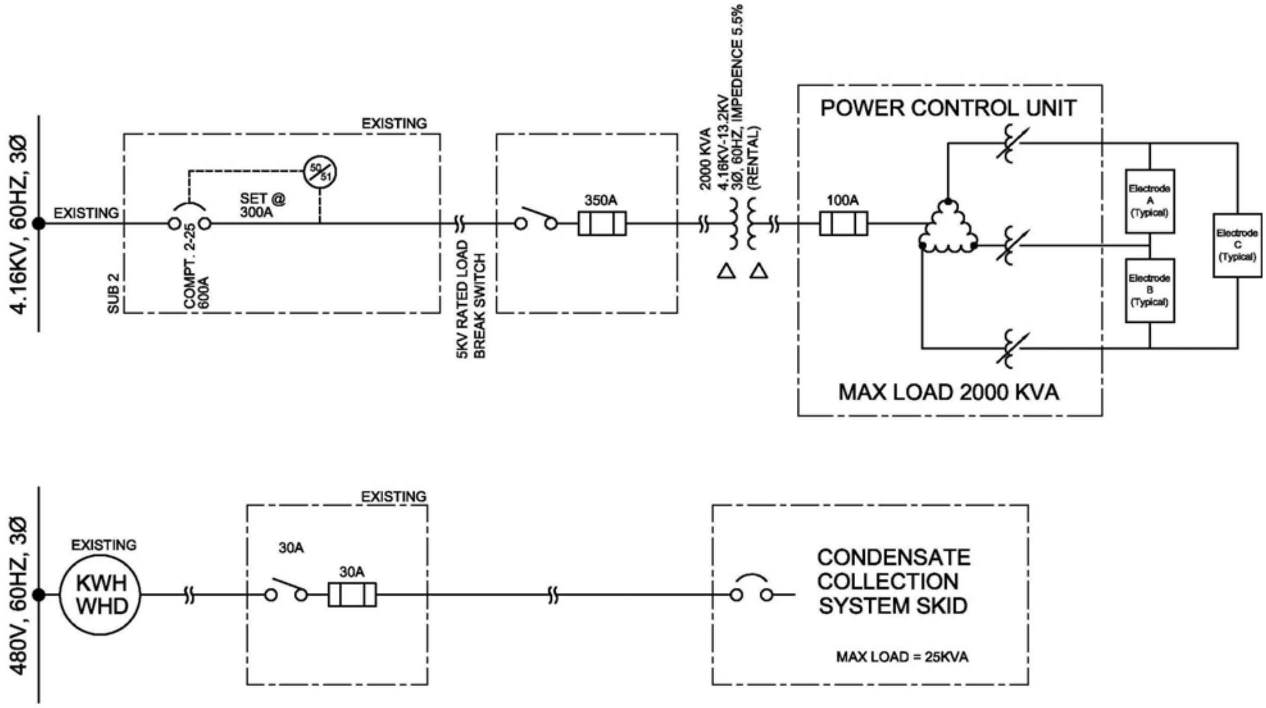


Figure 3-10. Electrical Schematic

The ERH PCU was connected to the electrodes through a series of insulated power cables. The cables were run above ground on the concrete floor or in overhead cable trays.

At the end of the run, cables were connected to the electrodes above grade or were placed in trenches cut through the concrete floor (and re-patched) for electrode connections in high traffic areas. Some cables were run in pairs or triplets, splitting as appropriate in the vicinity of the electrodes. Single cables were also used in some cases.

3.6 Steam Extraction and Treatment System

Beginning on 19 March 2002 through 25 April 2002, a network of chlorinated polyvinyl chloride (CPVC) piping was installed to manifold the SVE wells together into a common inlet at the condenser, as shown in Figures 3-11 and 3-12. Using a 70-ton crane, the condenser skid and cooling tower were placed inside the fenced enclosure on the west side of Building 181 on 2 April 2002 (Figure 3-13). Over the course of the next week, the utility connections and process tie-ins were completed between the condenser, cooling tower (Figure 3-13), and the existing SVE system. A process flow diagram, Figure 3-14, is presented at the end of this section.

Figure 3-11. SVE Header Inside Building 181

Figure 3-12. SVE Header Entering Condenser Skid

Figure 3-13. PCU Placement

Figure 3-14. Condenser Cooling Tower

3.7 Air Monitoring Station

Indoor air-quality measurements were collected to ensure occupational health and safety and to detect any accidental releases of vapors from the subsurface or collection piping. To collect these measurements, an INNOVA™ Model 1312 photoacoustic multigas analyzer (PMA) was used along with a laptop computer, a modem, and software to enable measurements to be obtained remotely. For this long-term monitoring the PMA was placed indoors and collected air samples for analysis, via tubing, from a location near the center of the heating array. Discrete measurements were collected at times, but most measurements were collected on an automatic 5-minute cycle, 24 hours per day throughout the duration of the remediation. No TCE or other VOC detections occurred at a detection limit of 1 part-per-million volume (ppmv).

3.8 Communications

The PCU and the PMA were controlled locally (when personnel were present) through a computer installed for each unit. When personnel were not present, the PCU and PMA were controlled through a remote computer. Connectivity for both systems were set up and maintained with pcAnywhere™ produced by Symantec™. The PMA was dynamically linked to the PCU (and thus, the heating array) via interlock. If the PMA were to detect TCE above 5 ppmv, the PCU would then shut down the heating array.

4.0 SYSTEM OPERATION

This section details the chronology of ERH system operation and the parameters measured during the operation period. The methods and equipment for the various measurements are also discussed, as are the function and purpose of the various measurements as they relate to the performance metrics. The results associated with these performance metrics are discussed in Section 5.

4.1 Operations Chronology

Figure 4-1 shows the chronology of the operation phase of the project. The operation phase was all work conducted between the system startup and the verification sampling.

Task Name	Start	Finish
System Startup and Optimization	Apr 9 '02	May 6 '02
Initial Power Application	Apr 23 '02	Apr 23 '02
Daytime Testing	May 2 '02	May 2 '02
Operation	May 13 '02	Aug 15 '02
Deep Zone Targeted Operation	Aug 20 '02	Sep 10 '02
Northwest Targeted Operation	Sep 11 '02	Dec 19 '02
Shutdown	Dec 19 '02	Dec 19 '02
Soil Sampling	Feb 4 '03	Feb 7 '03
Groundwater Sampling	Apr 22 '02	Dec 6 '02

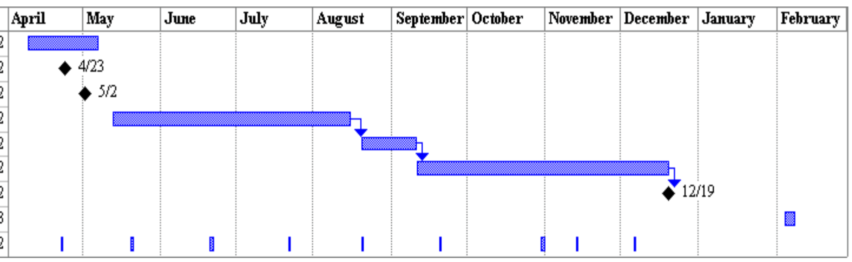


Figure 4-1. ERH Operations Chronology

4.2 Routine Operations and System Measurements

A variety of data were collected during the operation of the ERH system in order to assess, qualitatively and quantitatively, the affect of the system on soil and groundwater TCE contamination at the site. In addition, other data were collected to document the operation and maintenance of system equipment in order to optimize system efficiency. The subsections below describe the purpose and methods of data collection with respect to specific environmental media or ERH system components.

4.2.1 Voltage and Current

During the system startup and optimization period, the electrical delivery system was balanced to provide power to all portions of the array as equally as possible. The system was operated in this mode until unsaturated zone temperatures increased to the desired goal. Later in the operations period, electrical input was directed first to the deeper portions of the array (groundwater) and then specifically into the northwest portion of the treatment area.

Voltage and current were measured to achieve these desired combinations of power input. Since voltage for each phase was known from the PCU and did not vary considerably, amperes were measured in individual cables installed from the PCU to the specific electrodes.

Current measurements were obtained with a digital multimeter equipped with an ammeter loop. Power balancing was performed by manipulating the cable configuration. One cable could service more than one electrode if they exhibited the design resistance, however, if an electrode exhibited too little resistance it required a dedicated cable to handle the increased current. Finally, amperage measurements were collected to ensure that the capacity of the electrical cables was not exceeded.

Amperage measurements on specific cables were used for optimization only, not to calculate total power input or any instantaneous power delivery rate. The overall rate of power delivery was ascertained from the measurement devices built into the PCU.

4.2.2 Vacuum Pressure and Vapor Flow Rate

During ERH system operation, vacuum pressure and vapor flow rate readings were routinely collected from each SVE well and from various header pipes supporting some or all SVE network wells. The data were used to assess the performance of the vacuum blower and SVE network, and, in conjunction with laboratory analytical results for influent vapor samples, to calculate the mass of TCE removed from the subsurface over time. The data were also used to determine which system adjustments were needed to optimize steam extraction on a weekly basis.

Pitot tubes were used in conjunction with a digital manometer to collect vacuum pressure and vapor flow rate readings from ports located throughout the SVE network pipes. A computer spreadsheet was used to store recorded data and calculate TCE mass removal. As needed, valves located throughout the SVE network were manually adjusted to control the amount of vacuum and vapor flow at each SVE point.

4.2.3 Subsurface Vacuum Propagation

During ERH system operation, soil vacuum pressure readings were routinely collected from each TMP. The data were used to assess the cumulative affect of the vacuum blower and SVE network on surrounding soils at various depths. In conjunction with SVE vacuum pressure and vapor flow rate readings, the data were also used to determine which system adjustments were needed to optimize steam extraction on a weekly basis.

A digital manometer was used to collect soil vacuum pressure readings from co-located pressure piezometers that penetrated three different depths (approximately 5, 15, and 25 ft bgs) at each TMP. A computer spreadsheet was used to store recorded data. As needed, valves located throughout the SVE network were manually adjusted to control the amount of vacuum at each TMP.

4.2.4 Steam and Vapor Recovery

As part of the routine system measurements, recovered steam and vapor were measured at their respective locations downstream of the condenser skid. The condensate was pumped through a turbine-type totalizer (water meter) before it was sent to the equalization tank inside the SVE building. The operator would record the date, time, and totalizer reading so that the time-averaged flowrate of condensate could be calculated as:

(Totalizer Reading 2 – Totalizer Reading 1) ÷ (Time 2 – Time 1)

If no condensation occurs in the piping network before the condenser, then the condensate flowrate is equal to the steam recovery flowrate.

The vapor recovery rate was measured with a pitot tube downstream of the condenser, before the SVE knockout tank. Using measurements from a differential pressure gauge, a vacuum gauge, and the vapor outlet thermometer on the condenser, the vapor flowrate was calculated as follows:

$$Q = 128.8 \times K \times D^2 \times SQRT\{(P \times \Delta P) \div [(T + 460) \times S]\}*$$

Where:

Q =	Vapor flow, standard cubic feet per minute (SCFM);
K =	Flow coefficient = 0.67 for 8” Schedule 40 pipe;
D =	Inside pipe diameter = 7.941 inches for 8” Schedule 40 pipe;
SQRT =	Square root;
P =	Static pressure, pounds per square inch absolute (psia);
ΔP =	Differential pressure, inches of water column;
T =	Vapor temperature, degrees Fahrenheit (°F); and,
S =	Specific gravity with respect to dry air at 60 °F (assumed to be 1).
* Source:	Dwyer Instruments, Inc. Flow Sensor Bulletin F-50.

4.2.5 Water and Vapor Phase Concentration

Water and vapor phase concentrations were monitored by periodically collecting samples and sending them off-site for analysis. Condensate samples were collected from a sample port in the transfer line just before the equalization tank in the SVE building. The sample was analyzed for VOCs by US Environmental Protection Agency (EPA) Method 624 (as required by the POTW pretreatment permit).

Vapor phase samples were collected in a SUMMA canister that had been decontaminated and evacuated in the supplying laboratory. The canister was connected through stainless steel tubing and a needle valve to a sample port in the vapor line down stream of the condenser but before the inlet knockout pot of the SVE system. With the needle valve closed, the initial vacuum was measured with a vacuum gauge and recorded. The needle valve was opened slowly and vapors were collected inside the canister over a period of several minutes. When the pressure in the canister and the static pressure in the vapor line had equilibrated, the needle valve was closed and the final canister pressure was measured and recorded. The canister was shipped off-site for VOC analysis using EPA Method TO-14.

4.2.6 Groundwater Sampling

During ERH system operation, groundwater samples were periodically collected from the network of 12 site monitoring wells. The laboratory analytical results from groundwater samples were used to track the progress of groundwater remediation throughout the site. The methods used for sampling and sample analysis are defined in detail in the Sampling and Analysis Plan (SAP), which includes a Field Sampling Plan (FSP), a Quality Assurance Project Plan (QAPP), and an Addendum to the QAPP.

To reduce the risk to the sampling crew, the ERH system was deactivated a minimum of 12 hours prior to sampling. Water level measurements were collected at each monitoring well, after which a disposable bailer was lowered into the well to obtain a water sample. Using a peristaltic pump, the water sample was then pumped through a stainless steel coil submerged in ice to cool the water prior to filling sample bottles. Sampling logs were completed for each monitoring well. Sealed sample bottles were delivered or shipped, on ice, to Severn Trent Laboratories (STL) in Austin, Texas, to be analyzed for VOC concentrations using Method SW8260B.

4.2.7 Soil Sampling

During ERH system installation and after ERH system demobilization, hollow-stem auger (HSA) drilling was used to collect soil samples from various site locations (including monitoring wells, TMPs, and soil borings). The laboratory analytical results from soil samples were used to characterize and delineate the extent of initial soil contamination, as well as to record the extent of soil remediation throughout the site at the conclusion of ERH system operation.

The methods used for sampling and sample analysis are defined in detail in the SAP. In brief, continuous split-spoon soil sampling was completed using HSA drilling. Screening of soil for VOC content was conducted for each depth interval by using a photo-ionization detector (PID). Pre-remediation soil intervals with the highest VOC content based on PID screening were collected in EnCore™ containers. Post-remediation soil samples were collected from the same depths from boreholes drilled adjacent to the initial sample locations. Geologic boring logs, well construction logs (when applicable), and sampling logs were completed for each drilling location. Sealed sample containers were delivered or shipped, on ice, to STL in Austin, Texas, to be analyzed for VOC concentrations using method SW8260B.

4.3 Optimization Efforts

Throughout the period of operation, continual attempts were made to optimize the various processes. The rate and distribution of energy input were routinely balanced by adjusting the size and the number of cables attached to the various electrodes. When it appeared that an electrode was receiving too much current, larger (or additional) cables were installed for additional capacity. As portions of the array exhibited the desired temperature for an adequate duration (i.e., the vadose zone), heating was targeted to the deep zone by disconnecting cables from the upper array. Subsequently, heating was targeted to the northwest deep zone specifically to address groundwater the area surrounding MW-9 and MW-10 where concentrations of TCE remained above the RAO. During this targeted heating in the northwest area, additional (redesigned) electrodes were installed to more efficiently deliver power to the subsurface.

In addition to optimization efforts for the power delivery system, optimization was performed on the steam extraction system. These efforts included cycling the wells to increase vacuum pressure and an attempt at well development by alternating positive and vacuum pressure. The results of power delivery and steam extraction system optimization are further described in Section 5.

4.4 Parameters Derived from System Measurements

Many of the measurements described above were used for diagnostics, electrical and vapor extraction optimization, and general health and safety. Portions of the system measurements previously described were used to calculate parameters to evaluate the performance and the ultimate success of the remediation. Table 4-1 shows the performance metrics and the associated measurements that were used to evaluate them. Section 5 presents the results for each of the performance metrics presented in the table.

Table 4-1. Performance Metrics and Measurements

Performance Metric	Objective	Measurements Required	Method
Input Power	To evaluate efficiency of power input and heating potential.	Power rate (voltage x current)	Direct reading in PCU.
Subsurface Temperature Results [(1)]	To evaluate the effect of the input power on subsurface temperature.	Temperature	Direct temperature reading through TMPs and thermocouples.
Vacuum Propagation	To determine if the steam extraction system is effectively capturing contaminated steam.	Vacuum pressure	Direct pressure reading through TMPs with hand-held instrument.
TCE Mass Removed	To quantify the actual mass of contamination removed.	Vapor phase concentration	SUMMA canister sample from process header.
		Temperature	Direct reading from thermocouple placed in process header.
		Vacuum pressure	Direct reading, hand held instrument from process header.
		Differential Pressure	Direct reading, hand held instrument from process header.
		Condensate concentration	Water sample collected from tap downstream from condenser.
		Condensate flowrate	Calculation from condensate discharge totalizer readings.
Soil Vapor Results	To evaluate the ERH application's effectiveness of lowering soil vapor concentrations of TCE.	*In situ* concentration	Conversion of direct PID measurement from soil vapor extraction wells and vapor monitoring points.
Soil Results [(1)]	To evaluate the ERH application's effectiveness of lowering soil concentrations of TCE.	TCE soil concentration	Laboratory analysis of samples collected from boreholes.
Groundwater Results [(1)]	To evaluate the ERH application's effectiveness of lowering groundwater concentrations of TCE.	TCE groundwater concentration	Laboratory analysis of samples collected from monitoring wells.

[(1)] One of the three primary performance metrics, based on the remedial action objectives, for evaluation of remediation success.

5.0 PROJECT RESULTS

This section presents the data that were collected to evaluate the performance metrics described in Table 4-1. These include:

- Input Power;
- Subsurface Temperature;
- Vacuum Propagation;
- TCE Mass Removed;
- Soil Vapor Results;
- Soil Results; and,
- Groundwater Results.

The performance metrics were developed to assess the overall effectiveness of the ERH application. Some of these metrics pertain directly to the three RAOs outlined in Section 1, which are repeated here:

- Reduce the mean and 95% upper confidence level (UCL) concentrations of TCE in soil to below 11.5 mg/kg;
- Reduce the mean and 95% UCL concentrations of TCE in groundwater to below 10 mg/L; and,
- Accomplish this by raising the subsurface temperature on the treatment volume to above the boiling point of TCE and removing TCE from the subsurface via the steam extraction system.

5.1 Input Power

The assumption during the design was that an input power rate of 1,300 to 2,000 kW would be achievable. The actual power delivery rate to the subsurface was much less than planned, averaging just over 400 kW (some of this was due to targeted heating, however, the maximum input rate was under 600 kW). Apparently, some subsurface areas in the enlarged application did not exhibit as much resistance (i.e., greater conductivity) as observed during the pilot test. This could have occurred due to varying soil types throughout the application area (some soil types offer more resistance than others), a better electrode design for the enlarged application that had less inherent resistance than those installed for the pilot test, or greater overall conductivity due to higher soil moisture. Since the electrodes were designed on the basis of the pilot-scale test, some of the downhole cabling was of insufficient size to handle the amperage required to achieve the design power input rate.

Figure 5-1 shows the relationship between planned and actual input power. The blue line represents the input rate planned, as demonstrated by the higher slope. The red line, or actual input power rate, exhibits a lower slope initially, and an even lower slope after targeted heating began during week 14. The lower rate (measured in MW) resulted in a longer remediation timeframe. The total amount of input power (measured in MW hours) was actually less than planned (1,899 vs. 2,710 MW hours). Since some improvements were made to the electrode design since the pilot-scale test, this indicates that the electrode construction was more efficient (than during the pilot test) at actually delivering power to the subsurface.

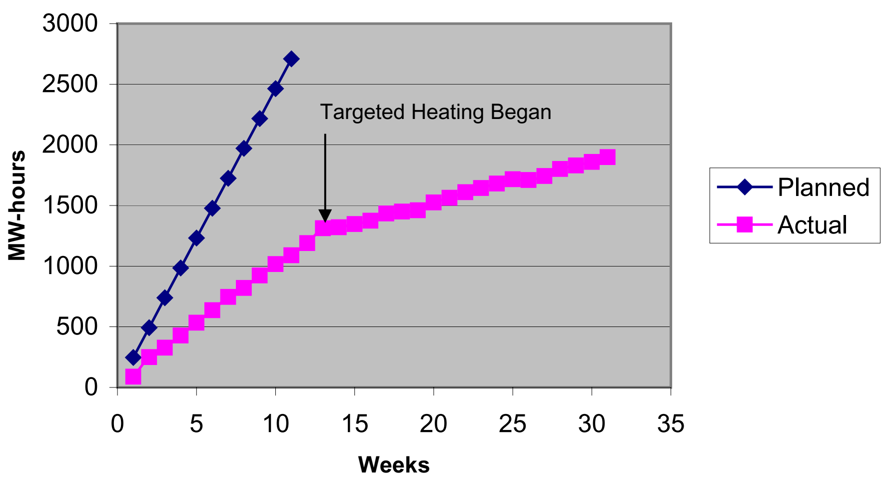


Figure 5-1. Input Power Rate – Planned vs. Actual

It is unclear what benefit a higher input power rate would have provided. In the unsaturated zone, appropriate temperature was reached in a reasonable amount of time. However, a higher rate may have been beneficial for the deeper zone (groundwater) and during the targeted heating in the northwestern portion of the site. In an attempt to optimize the power input to the areas that did not exhibit desired temperature, the above ground cabling was reconfigured to target only the deeper electrodes. Some of the deeper electrodes limited the power input rate to the network (since all electrodes were subjected to the same voltage, power input was dictated by the limiting electrode). After several weeks of operation on the reduced network, groundwater sampling and temperature measurements indicated that the northwest portion of the site required specific targeting.

Two new electrode "wells" were installed in the northwest area later in the program. These electrode wells were constructed of a continuous screen of galvanized steel with an insulating top. The electrical cable was installed through this insulator and connected directly to the galvanized screen, in effect, turning the entire well into a conductor of electricity. These wells exhibited much higher power input rates than the typical electrodes, but it could not be determined where along the screen the energy was dissipating. In the area of MW-9, however, temperature increased dramatically in the saturated zone following the installation of these electrodes.

5.2 Subsurface Temperature Results

Temperature was measured as described in Section 4 to evaluate the effect of the input power. Fortunately, the newer electrodes were more efficient at generating heat in the unsaturated zone, as the temperatures increased at a rate faster than what would be expected with the lower power input rate.

On the basis of data collected from the site TMP network, average subsurface temperature from 0 to 32 ft bgs measured 23.4°C on 30 April 2002 (prior to this date, only preliminary testing of the ERH system had occurred). ERH system operation began at full power on 7 May (Day 1) and average subsurface temperature increased to 36.4°C by 21 May (Day 15). When the first interim groundwater sampling event was conducted on 19 June (Day 44), average subsurface temperature had increased to 61.1°C. Recalculating the average for this date to exclude temperatures recorded between 0 and 4 ft bgs (which remained low throughout the ERH system operation due to upward heat loss through the concrete slab to the atmosphere), the average subsurface temperature measured 64.7°C. When the second interim groundwater sampling event was conducted on 23 July (Day 78), the average subsurface temperature had increased to 75.4°C. Recalculating the average for this date to exclude temperatures recorded between 0 and 4 ft bgs, the average site subsurface temperature measured 80.3°C. Two days before the third interim groundwater sampling event was conducted, the average subsurface temperature peaked at 80.1°C on 12 August (Day 98). Recalculating the average for this date to exclude temperatures recorded between 0 and 4 ft bgs, the average subsurface temperature measured 85.4°C. A graph of average subsurface temperature vs. time is shown in Figure 5-2.

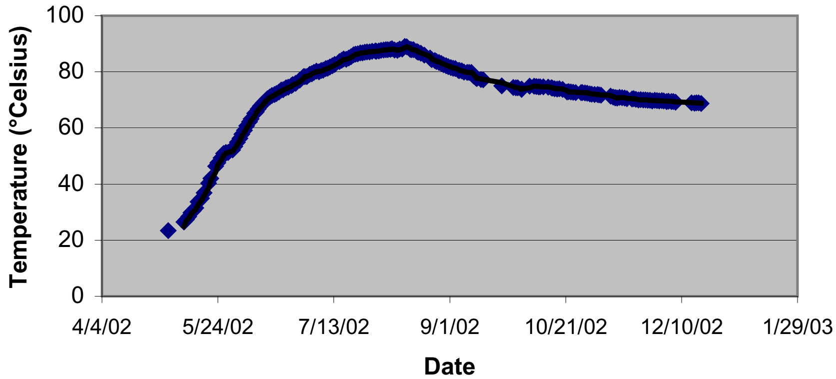


Figure 5-2. Average Site Temperature vs. Time (without Uppermost Interval)

It is important to note that subsurface heating did not occur uniformly throughout the site. The shallow depth interval (0 to 4 ft bgs) retained heat poorly owing to potential heat loss through the concrete building slab. The deep depth interval (29 to 34 ft bgs) failed to heat at a rate matching the unsaturated zone. On 16 August (Day 102), in response to this observation and after the unsaturated zone had reached an appropriate temperature, URS/TRS reconfigured the ERH system to transfer more power to the deep depth interval across the site. As a result, average subsurface temperature decreased throughout the site for the remainder of ERH system operation.

Temperatures in the deep depth interval improved to some extent, but on average remained lower than temperatures in overlying soil. A graph of average subsurface temperature at specific depths over time is shown in Figure 5-3. A graph of monthly average subsurface temperature vs. depth is shown in Figure 5-4.

Although average subsurface temperature peaked at 80.1°C, many TMPs recorded sustained temperatures in excess of 73°C, the boiling point of TCE in contact with water. The maximum subsurface temperature recorded at the site was 111°C, recorded at a depth of 17 ft bgs at TMP-12 on 12 August (Day 98). Following the installation of electrodes GE-1 and GE-2 (the redesigned electrodes), temperature was monitored in MW-9 with a graduated measuring tape and thermocouple setup. Whereas MW-9 exhibited only moderate temperature increase before the installation of the new electrodes, the increase accelerated rapidly after operation of those electrodes, as shown in Figure 5-5 (see Section 5.1 for a description of these electrodes). The location and construction of these electrodes increased ERH effectiveness in the northwest portion of the site. Figure 5-6 shows the maximum recorded temperature at each electrode.

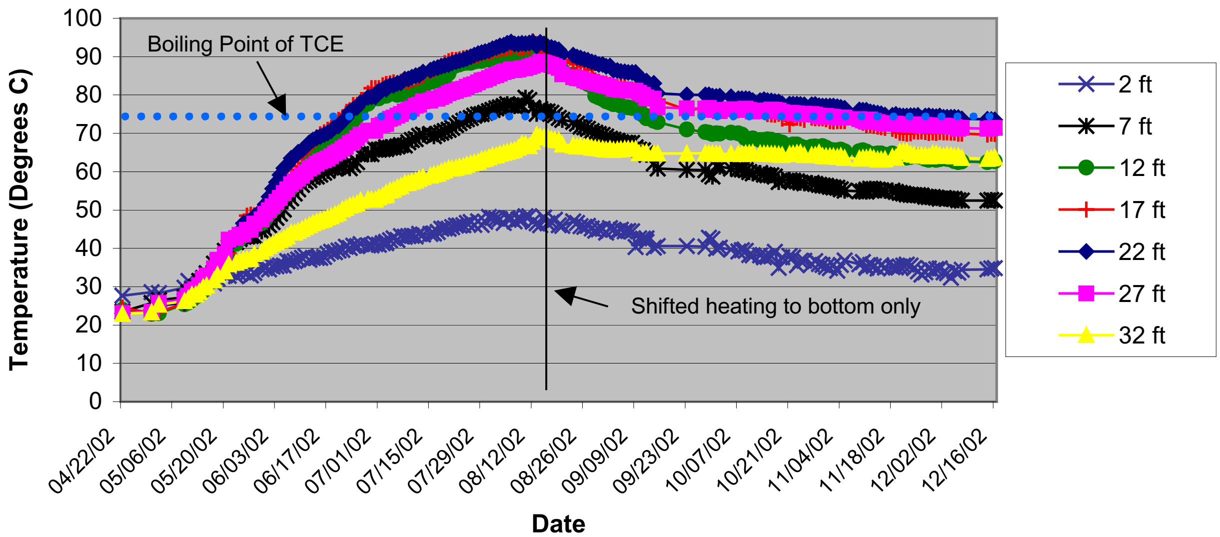


Figure 5-3. Average Temperature by Depth, Over Time

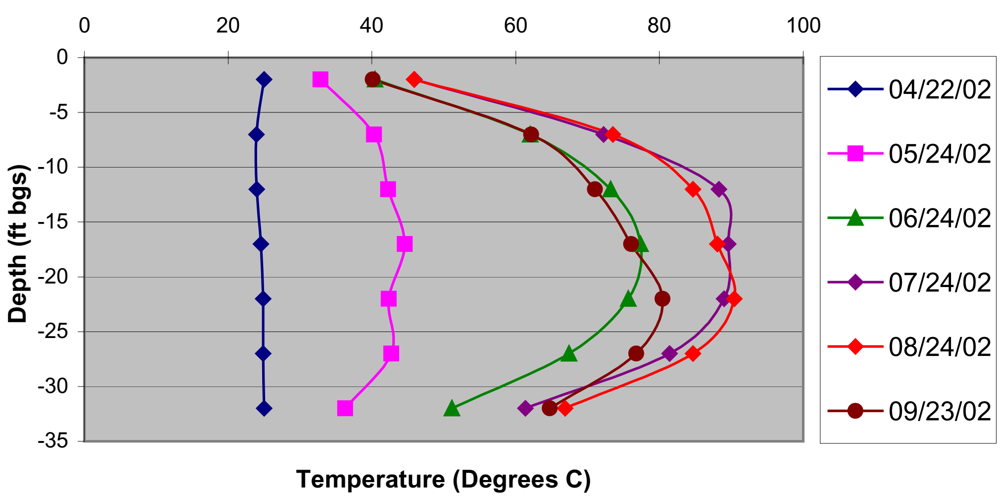


Figure 5-4. Monthly Average Subsurface Temperature vs. Depth

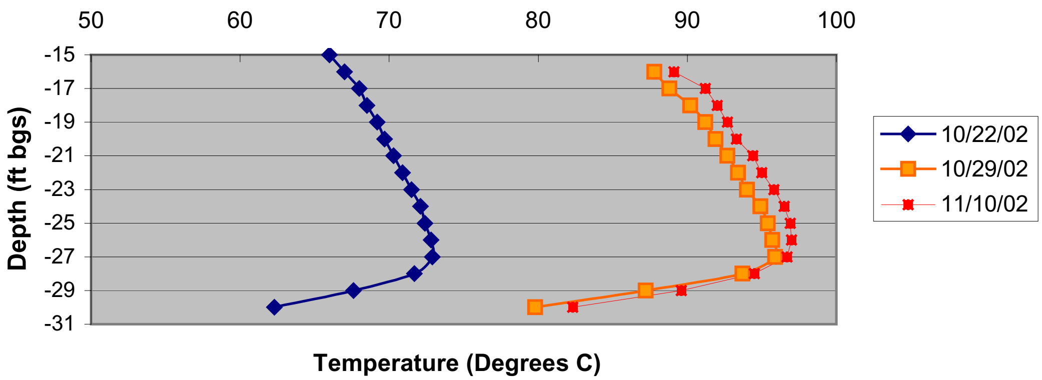


Figure 5-5. Temperature vs. Depth (MW-9) Following Installation of GE-1

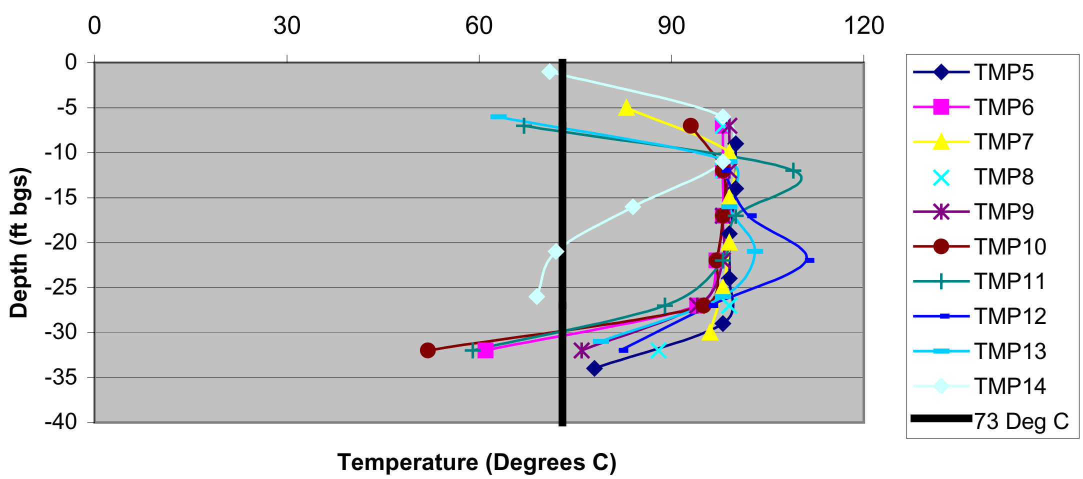


Figure 5-6. Maximum Temperatures Achieved

For clarity, the surficial interval and the older TMPs 1-4 are not shown. The boiling point of TCE in contact with water (73°C) is shown for reference. Section 5.7 will present the effects of these actions on the groundwater concentration of TCE in samples collected from MW-9.

5.3 Vacuum Propagation

Silty clay is the predominant lithology underlying most of the site. Reduced permeability in clay materials results in low transmissivity and typically retards movement of liquids or vapor. Therefore, extraction of soil vapor from this media relies upon preferential pathways such as interconnected layers of sand or gravel, bedding planes, weathered or fractured bedrock, and backfill material around buried pipes or utilities.

Based on data collected from the site TMP network, a vacuum was maintained throughout most of the subsurface for most of the duration of ERH system operation. The rule of thumb criterion that was used to determine successful SVE capture was 0.1 inches of water vacuum or greater.

The baseline vacuum pressure in the subsurface was zero in most cases (with the extraction system turned off). Of the 42 individual vapor probes, nine exhibit zero or positive pressure near the beginning of heat application. As heating continued (and site temperature increased), some vapor probes eventually read zero, then positive pressure. Others remained at zero. Apparently, the pressure induced by steam generation in the subsurface overwhelmed the capacity of the SVE to remove steam in some cases. However, there is a strong possibility that the probes that remained at zero pressure were plugged. Likewise, some of the extraction wells exhibited zero flow and may have been "smeared over" with clay during SVE well installation. In some locations where there was zero pressure measured in the TMP, nearby wells were freely flowing.

The relationship between the 92 wells is complex and, in some locations, zero pressure that was observed in the TMP vacuum probes may be a result of overlapping zones of influence. Attempts to overcome the positive pressure on the west side of the array were unsuccessful. Extraction wells along the west side were opened fully to allow more flow from this area; while this was effective in some of the vapor extraction wells, many continued to exhibit zero flow. These remaining wells were then subjected to cycling (repeatedly turning the valve from fully closed to fully open in an attempt to obtain airflow). Additionally, attempts were made to "develop" these wells with positive pressure (from a portable pump), alternating with system vacuum. These wells were subjected to pressures of nearly 100 pounds per square inch (psi), then evacuated to several inches of mercury, but this was also generally unsuccessful. Therefore, the vapor extraction array was re-optimized to maximize steam recovery.

The western portion of the site (in the vicinity of TMPs 11 through 14) consistently exhibited positive pressure as the pressure generated by steam overcame the system vacuum. Valves located throughout the SVE network were manually adjusted in numerous attempts to optimize vacuum conditions in this area, but these efforts were generally not effective. While in most areas the SVE vacuum was sufficient to overcome this positive pressure, it is possible that in isolated zones, positive pressure conditions would undoubtedly prevail.

5.4 TCE Mass Removed

A calculated total of 1,413 lbs of TCE were removed from the subsurface in Building 181 via the steam extraction system. The total TCE mass removed from the subsurface is the sum of the mass that was removed via vapor and via steam (condensate). The mass removed via vapor was calculated on the basis of the vapor flow rate (see Section 4.2.4) and the vapor phase concentration (see Section 4.2.5). The mass removed via condensate was calculated on the basis of the water phase concentration and the condensate discharge rate. Figures 5-7 and 5-8 show the cumulative mass removed and the instantaneous removal rate (respectively). Of the 1,417 lbs that were documented removed from the subsurface, only about half of one pound was removed via condensate. It should be noted that these results do not account for any reduction in mass due to biodegradation effects.

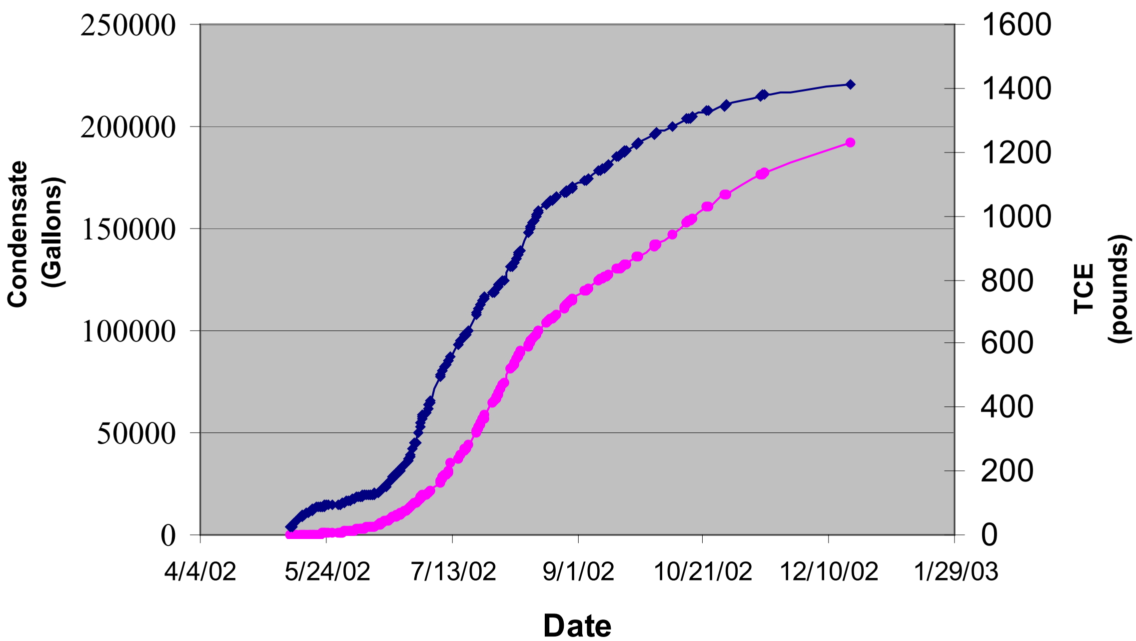


Figure 5-7. Cumulative Steam (Red) and TCE (Blue) Recovery

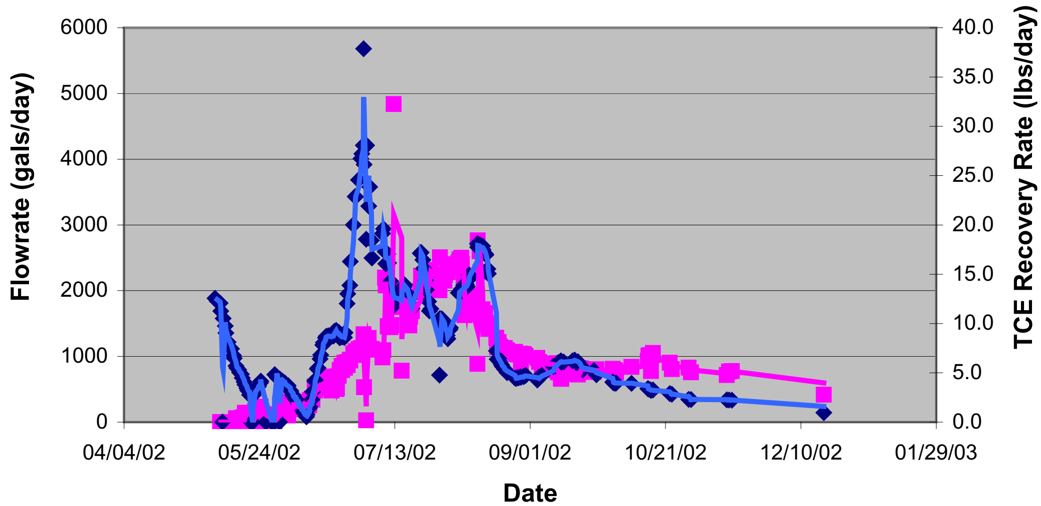


Figure 5-8. Steam (Red) and TCE (Blue) Recovery Rates vs. Time

5.5 Soil Vapor Results

Roughly 150 soil vapor samples were collected both before and after heating to evaluate the ERH remediation effects on TCE soil vapor concentration. Samples were collected from various types of wells, including SVE wells and vapor monitoring wells. The wells were purged for 3 to 5 minutes with a portable pump prior to sample collection and analysis with a PID. The results indicate that both the concentration and extent of the vapor plume decreased. Specific observations include:

- The mean TCE concentration was reduced by 93% (1,049 to 73.4 ppmv);
- There was a marked reduction in the area of vapor plume greater than 100 ppmv; and,
- The maximum result decreased from > 5,200 to 1,358 ppmv.

Figure 5-9 shows the before and after TCE soil vapor plumes. The data collected for the pre-ERH application soil vapor survey was collected during March 2002. The data for the post-application survey was collected in early February 2003.

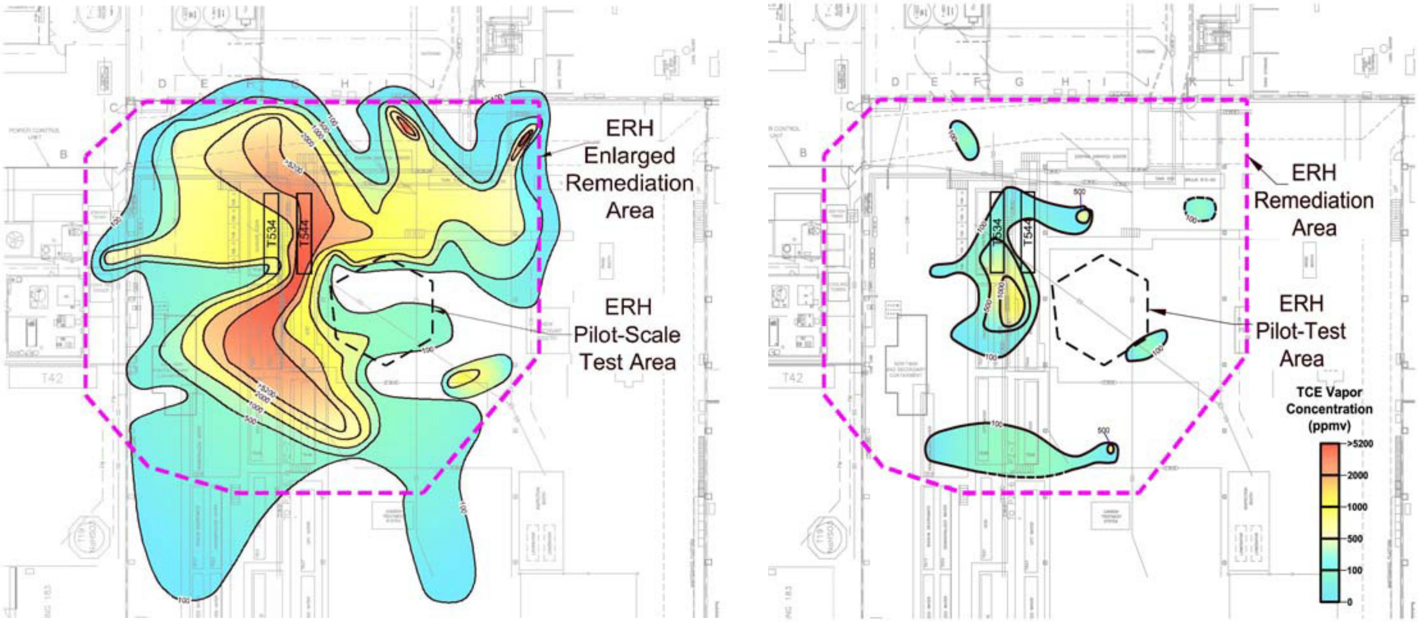


Figure 5-9. Pre- and Post-ERH Application Soil Vapor Concentrations (ppmv TCE)

5.6 Soil Results

To assess soil remediation throughout the site at the conclusion of ERH system operation, confirmation soil samples were collected from the same locations and depth intervals as select samples that were collected during system construction. These locations, shown in Figure 5-10, include TMP-5, -6, -8, -10, -12, -14, and SB-1 through -4. Samples were obtained using HSA drilling as outlined in Section 4.2.7. A comparison of pre- and post-ERH application soil TCE concentrations is presented in Table 5-1. Overall, soil sample results reveal that:

- The highest recorded TCE concentration was reduced by 99% (19.8 to 0.22 mg/kg);
- The mean TCE concentration was reduced by 90% (1.76 to 0.184 mg/kg);
- The 95% UCL TCE concentration reduced by 97% (8.4 to 0.29 mg/kg); and,
- All post-ERH results were below RAO of 11.5 mg/kg TCE.

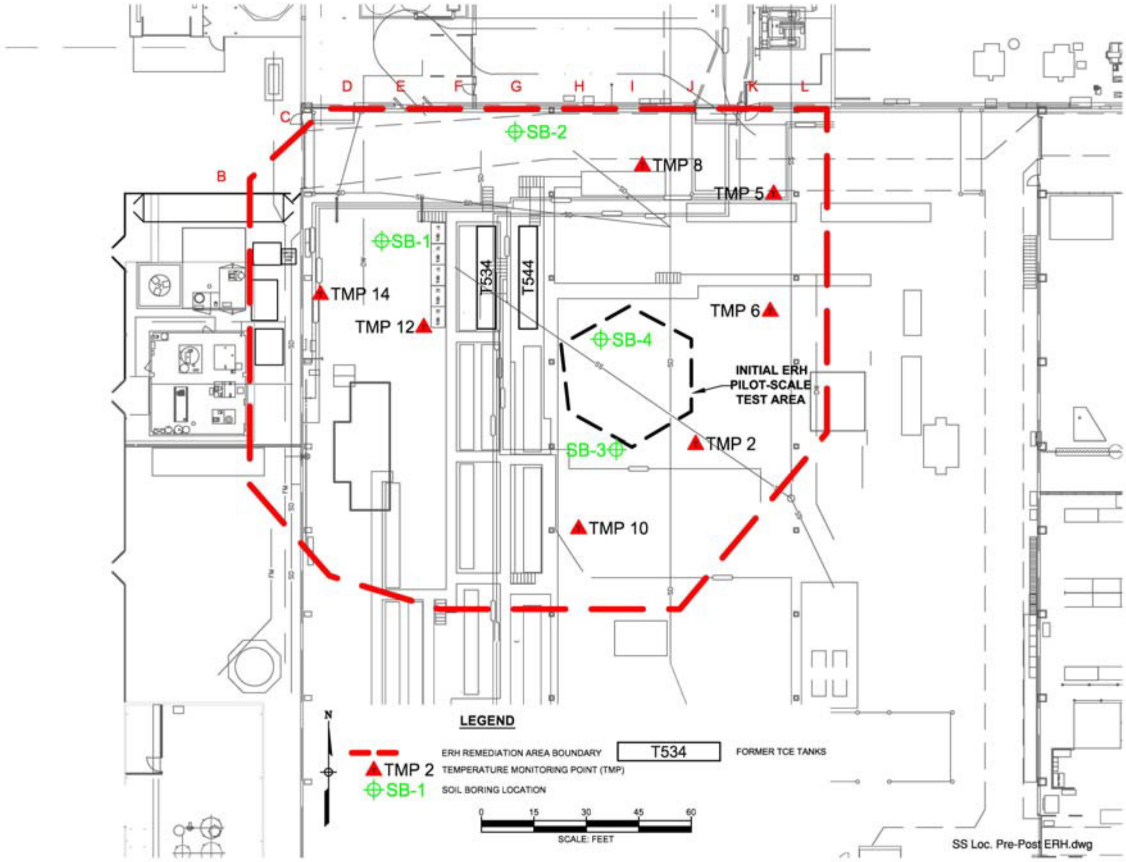


Figure 5-10. Soil Sampling Locations Used To Compare Pre-ERH With Post-ERH TCE Concentrations

Table 5-1. Comparison of Pre- and Post-ERH Soil TCE Concentrations

Sample Location	Depth Interval (ft bgs)	Pre-ERH TCE Concentration (mg/kg)	Post-ERH TCE Concentration (mg/kg)
SB-1	4-5	5.68	0.228 JL
	7-8	1.73	<0.000590
	21-22	12.5	0.0286
	23-24	5.84 J	1.20 JL
	27.5-28	1.22	0.729 JL
SB-2	6-7	1.07	<0.000512
	21-22	0.0663	<0.000484
	23-24	1.38	0.134
	25.5-26	19.8	0.220
	27-28	6.66	0.363 JL

Table 5-1. Comparison of Pre- and Post-ERH Soil TCE Concentrations (Continued)

Sample Location	Depth Interval (ft bgs)	Pre-ERH TCE Concentration (mg/kg)	Post-ERH TCE Concentration (mg/kg)
SB-3	0.5-2	0.0617	<0.000596
	6-7	<0.00188	0.620 JL
	18.5-20	0.0750	<0.000530
	23-24	0.0720	<0.000575
	27-28	0.0873	0.0819
SB-4	6-7	0.0826	<0.000528
	14-15	0.134	<0.000522
	18-19	0.0552	<0.000552
	20-21	0.355 J	<0.000572
	26-27	1.20	0.011
TMP-5	24-25	<0.00182	<0.000567
	26-27	0.0166	<0.000547
	28-29	0.0235	0.0122
	30-31	0.0241	0.0202
TMP-6	4-6	0.0762	0.486 JL
	10-11	0.0217	<0.000548
	14-15	0.0118	<0.000580
	19-20	<0.00184	<0.000594
	25-26	0.0151	<0.000530
	30-31	0.167	0.466 JL
TMP-8	8-9	<0.00178	0.0569
TMP-10	4-6	19.1	2.27
	9-11	<0.00168	<0.000682
	14-16	<0.00169	<0.000610
	19-21	0.141	<0.000575
	25-26	0.0394	<0.000539
	30-31	<0.00177	0.0377
TMP-12	5.5-6	0.145	0.0186
	8-9	1.43	0.0303
	11-12	1.05	<0.000583
	23-24	1.62	0.762 JL
	27.5-28	0.0767	0.0921
TMP-14	6-8	0.818	0.0197
	8.5-9.5	1.52	0.0316
	22.5-23.5	6.48	0.225
	24-25	0.0617	0.447 JL
	28-29	<0.00164	0.0443

J – Estimated L – Biased low

5.7 Groundwater Results

Groundwater samples were collected from the 12 ERH monitoring wells before, during, and after heating. During the target heating of groundwater and then the northwest portion of the site, wells MW-9 and MW-10 were sampled separately to gauge the performance of the ERH system in that area. Overall, results for groundwater reveal that:

- The mean TCE concentration was reduced by 87% (33.2 to 4.3 mg/L);
- The 95% UCL TCE concentration reduced by 85% (47.2 to 7.3 mg/L);
- The post-application mean and 95% UCL TCE concentration in groundwater were less than the 10 mg/L RAO; and,
- A 353% increase in average chloride concentrations was noted and may indicate enhanced biodegradation of TCE (average of 30 mg/L increasing to 106 mg/L).

Groundwater concentrations over time for each monitoring well are shown in Figure 5-11. The progress of the groundwater remediation was hampered by the power delivery rate and the factors previously outlined. In response to this, targeted heating of the lower electrode intervals began in Week 14. Average temperatures in the lower portions of the TMPs were not raised significantly, as shown in Figures 5-3 and 5-4. Targeted heating of the northwest portions of the site were begun to address TCE concentrations in MW-9 and MW-10. GE-1 and GE-2 were then brought on line, and the following was noted:

- Four "in-plume" wells exhibited decreases in concentration of TCE (MW-9 dropped significantly);
- Four in-plume wells exhibited slight increases in concentration of TCE;
- Two side/down gradient wells exhibited slight decreases;
- One side/down gradient well exhibited a moderate increase; and,
- Except for the decrease in MW-9, the overall remediation progress remained relatively stable.

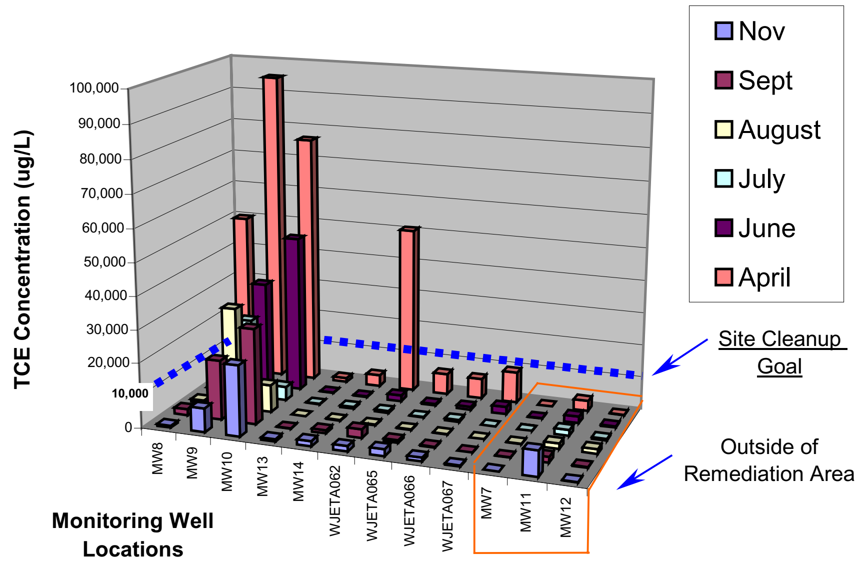


Figure 5-11. Groundwater TCE Concentrations Over Time

The TCE concentrations over time for MW-9 and MW-10 are shown in Figure 5-12. The targeted heating (via electrodes GE-1 and GE-2 in late October) in the vicinity of MW-9 resulted

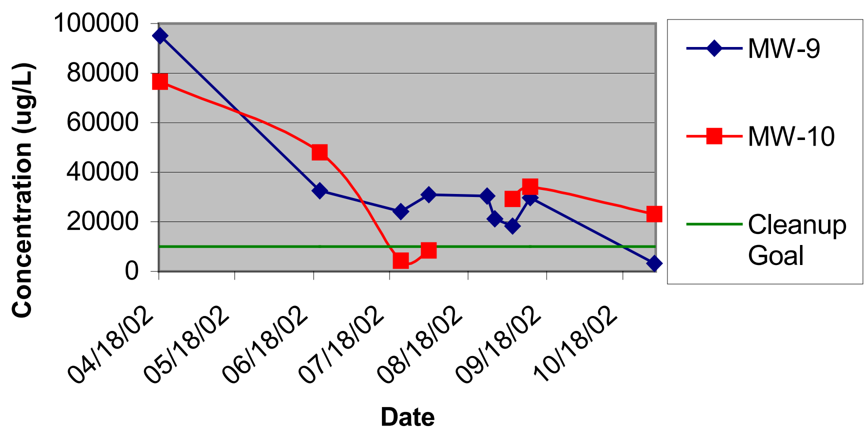


Figure 5-12. Concentration of TCE in MW-9 and MW-10 Over Time

in a sharp drop in TCE concentration in that well. Despite all attempts, targeted heating was not successful in the vicinity of MW-10. It is unclear why TCE concentration dropped so significantly in MW-10 in late July and increased significantly in August. It is possible that the variations in concentration in the less contaminated wells were due to minor fluctuations caused by the effects of the steam extraction process, by pore pressure increases due to heating, and by water addition to keep the electrodes moist and conductive. These forces could have caused minor contaminant movement within the ERH array.

The increase in chloride concentration is most likely due to reductive dehalogenation of chlorinated hydrocarbons, mainly TCE. This biologically mediated reaction is greatly accelerated by the temperature rise caused by ERH. Assuming that no other significant source of chloride exists in the soil volume affected by ERH, an average chloride increase of 76 mg/L corresponds to an average degradation of 94 mg/L of TCE. This suggests that biological degradation of TCE, enhanced by heating, is a significant contributor to the overall TCE reduction at this site.

Total organic compounds (TOCs) are important because they represent a reservoir of electron donor compounds to support continued reductive dehalogenation of chlorinated hydrocarbons. The final TOC levels should be adequate to support the reduction of the residual TCE in the groundwater.

6.0 COST SUMMARY

As shown in Table 6-1, the total estimated cost for the enlarged ERH application was $2,500,000 including costs incurred by URS, LM Aero, and Shaw/IT Corporation. Since some of the existing Building 181 SVE system was used for vapor phase extraction and control, the costs incurred do not account for capital costs associated with purchasing some of the infrastructure (i.e., vacuum blowers, air stripping equipment, and some piping). However, a large portion of the Building 181 ERH steam extraction and treatment system was accounted for under this program. This includes the heat exchanger, most of the piping, the cooling tower, and carbon adsorption.

The following line items included in the cost estimate are consistent with ***Guidance to Documenting and Managing Cost and Performance Information for Remediation Projects*** (EPA 542-B-98-007, October 1998) reporting format:

Capital Costs

- Mobilization, setup, and demobilization;
- Equipment construction and installation; and
- Engineering Submittal Package (i.e., design), Work Plan, Quality Assurance / Quality Control (QA/QC) Plan, Field Sampling Plan, and Health and Safety Plan preparation.

Operation and Maintenance (O&M) Costs

- Operational labor;
- Electricity costs;
- Equipment rental;
- Groundwater, soil, and soil vapor sample analyses; and
- Other testing (indoor air monitoring).

Other Technology-Specific Costs

- Toxic characteristic leaching procedure (TCLP) testing of drill cuttings, and VOC testing of air stripper effluent discharged to the POTW; and
- Disposal of drill cuttings.

Other Project Costs

- Proposal preparation.

Table 6-1. AFP4 ERH Application Cost Summary

Cost Category/Element		Cost (Year 2002 $)	Cost for Calculating Unit Cost
1.	**Capital Cost for Technology**		
a	Technology mobilization, setup, and demobilization	$41,889	
b	Planning and preparation	$94,348	
c	Site work	$4,396	
d	Equipment and appurtenances/construction – Structures - Process Equipment and -appurtenances/construction - Other	$573,765	
e	Startup and testing	$25,896	
f	Other	$0	
	Total capital costs		$740,294
2.	**O&M for Technology**		
a	Labor	$421,528	
b	Materials	$0	
c	Utilities and fuel	$85,455	
d	Equipment ownership, rental, or lease	$906,293	
e	Performance testing and analysis	$98,130	
f	Other (Indoor air monitoring)	$79,698	
g	Total operation and maintenance costs		$1,591,103
3.	**Other Technology-Specific Costs**		
a	Compliance testing and analysis	$0	
b	Soil, sludge, and debris excavation, collection, and control	$0	
c	Disposal of residues	$9,998	
4.	**Other Project Costs**	**$28,238**	
Total cost (in 2002)		**$2,369,633**	
Total cost for calculating unit cost			**$2,331,397**
Pounds of TCE Removed			**1,413**
Calculated unit cost ($/lb)			**$1,650**
Volume of Treated Media (yd^3)			**20,167**
Calculated unit cost ($/$yd^3$)			**$116**
Basis for quantity treated			**½ acre by 25 ft deep**

The EPA cost guidance was used to establish which line items belonged in the unit cost calculations. For the cost per pound of contaminant removed, only the mass of contaminants physically stripped from the subsurface was used in the calculation. Estimates of mass removed by reductive dechlorination were not included in the cost per pound value reported. The cost per cubic yard calculation used a volume basis of ½ acre treated over an interval of 25 ft.

Approximately one third of the total project cost was identified as capital costs, with the largest expenditures associated with the drilling and installation of electrodes and piping. The remaining two thirds of the total project cost were incurred as O&M costs. The largest O&M line item was the ERH vendor subcontract, which includes the equipment rental and some of the operational labor. The utility (electrical) costs represented only 4% of the overall project cost.

The calculated unit cost should provide a good comparison with other remedial technologies that have been applied at full-scale. The enlarged ERH application project costs may have been higher than normal due to the following:

- The ERH installation was indoors in the middle of an active aircraft manufacturing area. Angle drilling and shifted work hours were necessary to avoid interrupting or interfering with LM Aero's operations.
- The operation of the system was modified and amended to attempt to reduce the concentrations in a few "hot spots".
- Because the ERH application was operated inside a building with LM Aero, URS, and other personnel present, additional indoor air monitoring equipment and monitoring was required.

The calculated unit costs for the enlarged ERH application were nearly identical to those calculated for the ***Six-Phase Heating™ Pilot-Scale Test in the Technology Performance Report*** (URS, 2001).

7.0 CONCLUSIONS AND RECOMMENDATIONS

The ERH application proved successful in heating the subsurface and removing TCE contaminants from the soil and groundwater at the site. The RAOs for soil and groundwater were met, and soil vapor TCE concentrations were reduced significantly. Although the desired temperature was observed through most of the array, it did not appear to be adequate in the vicinity of MW-10. The following subsections give specific conclusions and recommendations.

7.1 Conclusions

- The ERH system delivered approximately 1,899 MW hour of energy to the approximately one-half acre source area in Building 181.

- The application of power raised the subsurface temperature above the boiling point of TCE (73°C) in 70 of 98 thermocouple locations. Excluding the uppermost intervals that may have been affected by surface cooling, 69 of 84 thermocouple locations were above 73°C.

- The increase in temperature resulted in the production of steam that was recovered by the steam extraction network. Approximately 191,900 gallons of condensate were produced and the calculated recovery of TCE was 1,413 lbs. Combined with calculated TCE recovery from the preceding pilot-scale test, a total of 1,743 lbs of TCE were recovered. Most of this recovered TCE was in the vapor phase, with about one pound being removed in the water phase.

- The removal of TCE resulted in a reduction of soil vapor, soil, and groundwater TCE concentrations in the subsurface. On the basis of the work plan statistical evaluation criteria involving both 95% UCL and means comparisons, ERH was effective at remediating the soil and groundwater to the ROD-required TCE concentrations.

- The results indicate that both the concentration and extent of the vapor plume decreased. The mean TCE concentration was reduced by 93% (1,049 to 73.4 ppmv); the maximum result decreased from > 5,200 to 1,358 ppmv.

- The soil mean concentrations fell from 1.76 to 0.184 mg/kg, yielding a 90% reduction. The 95% UCL concentration was reduced from 8.4 to 0.29 mg/kg, yielding a 97% reduction. All post-test soil results were below the 11.5 mg/kg RAO.

- ERH reduced TCE concentrations in the groundwater to below the 10 mg/L RAO. Mean concentrations fell from 33.2 to 4.1 mg/L, yielding an 88% reduction. The 95% UCL concentrations were reduced from 47.2 to 7.3 mg/L, yielding an 85% reduction. Only one well was not reduced to below the threshold limit.

- The chloride measurements in groundwater indicate that biodegradation of TCE was enhanced by the heating resulting from ERH. This biodegradation probably consisted of reductive dehalogenation or halorespiration and contributed significantly to the reduction of TCE concentrations.

- Continuous monitoring of air quality within the building showed no measurable deterioration as a result of the remediation, indicating successful vapor capture by the SVE system.

- After an initial decrease in concentration, downgradient well MW-11 demonstrated a slight increase in TCE concentration near the end of the application of heat. The concentration roughly doubled to 7.7 mg/L. While this may simply be a normal fluctuation, it is important to note.

- The cost of remediating the subsurface with ERH is approximately $1,650/lb TCE removed, or $116/cubic yard.

7.2 Lessons Learned

During the course of ERH operation for the remediation of the Building 181 source area, several attempts were made to improve or optimize the treatment process as described in Section 4. These included optimization of the power input network, optimization of the steam extraction network, and targeted operation. The following lessons learned are based largely on review of these optimization efforts.

Electrical Input

Generally, some of the downhole cables within the electrodes ultimately limited the power delivery, as they were of insufficient size to handle the required current. The design power input rate was calculated on the basis of the pilot system performance. Although the subsurface in the area of the pilot system is lithologically similar to the rest of the expanded area, it is unclear if the soil in that area is naturally more or less conductive. It is more likely that the inherent design of the newer electrodes was more efficient at transmitting energy to the subsurface than those installed for the pilot test. While the below-grade cabling was permanently installed, the above-grade cables were meant to be removed after the application.

The above-grade cables were manipulated in conjunction with the voltage setting to balance the current distribution, but without exceeding the amperage capacity of any portion of the system.

Temperature

Since the amperage limitation was generally the downhole cable, the application took longer than originally anticipated. However, less power than anticipated was required to heat the majority of the site to the desired temperature, possibly due to the electrodes being more efficient overall in delivering power. The temperature objective was not consistently met in the lower portion of the groundwater column (as measured in MW-10 later in the program), which may account for the groundwater concentration in that well to remain above the target 10 mg/L.

MW-9 exhibited the same problem; however, the two electrodes later installed in the northwestern area were effective at raising the groundwater temperature. MW-10 was in a less accessible area than MW-9; new electrodes could not be installed in that area. Additionally, one electrode in the vicinity of MW-10 “burned out” during operation. Grounding rods were installed in its place (these could be installed with portable equipment), but the rods were only effective for several days. It was surmised that these rods dried out the soil, and thus could no longer effectively conduct, as they were installed and operated without the benefit of the electrode rewetting hoses.

Steam Extraction System

The steam extraction system generally performed well, but in some areas, the positive pressure exerted by steam generation exceeded the vacuum influence. This was witnessed at TMP locations along the west side of the array in the same area where several wells were exhibiting zero flow. As described in Section 4, efforts were made to “develop” these wells with an air pump, alternating with system vacuum. These were unsuccessful, as the wells held pressure until released. The wells in question were generally installed in “tighter” soils, so the subsurface in this area may not have natural flow pathways. Therefore, the positive pressure measured in the TMPs was likely localized.

Although ERH is an excellent technology to treat less permeable material, this same characteristic can hinder full steam (and thus contaminant) capture. In future applications, this should be accounted for by installing the steam extraction wells in larger boreholes, possibly with different drilling technology, and potentially enhanced with hydraulic fracturing.

7.3 Recommendations

The following recommended activities are intended to help support future decision making in light of the TCE source removal (e.g., refine clean-up time estimates for the downgradient dissolved-phase plume).

1. *A rebound assessment for groundwater to determine if contaminant concentrations remain below the regulatory objective.* This could be performed by sampling key monitoring wells, within and downgradient of the ERH source removal area, for VOCs. This activity might require additional monitoring well installations in Building 182 to track the impact of the source removal/reduction over time. These data would be useful for revising estimates of cleanup times for the dissolved-phase portion of the groundwater plume.

2. *A natural attenuation study to determine the further potential for microbial degradation of TCE.* This study could be coupled with the rebound assessment by analyzing the same wells for natural attenuation parameters (includes dissolved oxygen, oxidation/reduction potential, nitrate, iron, sulfate, carbon dioxide, methane, and ethane). The results would support understanding the longer-term effect of ERH source removal on the fate and transport of contaminants beyond Building 181.

8.0 REFERENCES

Baker, B., Duffin, G., Flores, R., and Lynch, T., 1990. **Evaluation of Water Resources in Part of North-Central Texas,** Texas Water Development Board Report 319, 65 p.

Dwyer Instruments, Inc. Flow Sensor Bulletin F-50.

Eckenfelder, Inc., 1998. **DNAPL Tracer Tests, Air Force Plant 4, Fort Worth, Texas,** September, 1998.

Jacobs Engineering, 1998a. ***Draft East Parking Lot/Window Area Technical Report.***

Jacobs Engineering, 1998b. ***Remedial Alternatives Evaluation***.

Nordstrom, P.L., 1982. **Occurrence, Availability, and Chemical Quality of Groundwater in the Cretaceous Aquifers of North-Central Texas,** Texas Department of Water Resources Report 269, 2 vols.

Parsons, 1998. ***Technical Report on the Geology of Air Force Plant 4 and Naval Air Station Fort Worth Joint Reserve Base***.

Radian, September 1999. ***Preliminary (30%) Remedial Design, Dense Non-Aqueous Phase Liquid, Eastern Parking Lot Plume, Air Force Plant 4, Fort Worth, Texas,*** prepared for the Air Force Center for Environmental Excellence (AFCEE) and Aeronautical Systems Center (ASC) under Contract No. F41624-97-D-8020, Delivery Order 0109.

Rust Geotech, 1995. ***Air Force Plant 4 Feasibility Study***. Prepared for U.S. Department of Air Force, Headquarters Aeronautical Systems Center, Wright-Patterson AFB, Ohio.

Rust Geotech, 1996. ***Record of Decision for AFP4.*** Prepared for U.S. Department of Air Force, Headquarters Aeronautical Systems Center, Wright-Patterson AFB, Ohio.

URS and CES, May 2001. ***Six-Phase Heating™ Pilot-Scale Test Technology Demonstration Report.***

URS (formerly Radian) and Beyke, January 2002a. ***Enlarged Electrical Resistance Heating Application Work Plan, Sampling and Analysis Plan, and Engineering Submittal Package, Trichloroethene Source Area, Building 181, Air Force Plant 4, Fort Worth, Texas.***

URS and TRS, January 2002b. ***Enlarged Electrical Resistance Heating Application Health and Safety Plan, Trichloroethene Source Area, Building 181, Air Force Plant 4, Fort Worth, Texas.***

U.S. Environmental Protection Agency, October 1998. ***Guidance to Documenting and Managing Cost and Performance Information for Remediation Projects.*** EPA 542-B-98-007.