In Situ Thermal Treatment of Chlorinated Solvents:
Fundamentals and Field Applications

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Fundamentals and Field Applications

U.S. Environmental Protection Agency
Office of Solid Waste and Emergency Response
Office of Superfund Remediation and Technology Innovation
Washington, DC 20460

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LIST OF ACRONYMS AND ABBREVIATIONS

bgs	Below ground surface		HPO	Hydrous pyrolysis oxidation
BTEX	Benzene, toluene, ethylbenzene, and xylene		ISTD^{TM}	In Situ Thermal Desorption
CA	Chloroethane		MC	Methylene chloride
CAS	Chemical Abstracts Service		MCB	Monochlorobenzene
CF	Chloroform		mg/L	Milligram per liter
CFM	Cubic feet per minute		mm Hg	Millimeters of mercury
CLUIN	EPA's Hazardous Waste Clean-Up INformation system		NAPL	Nonaqueous-phase liquid
			NPL	National Priorities List
CM	Chloromethane		O&M	Operation and maintenance
CT	Carbon tetrachloride		PAH	Polycyclic aromatic hydrocarbon
DCA	Dichloroethane		PCA	Tetrachloroethane
DCB	Dichlorobenzene		PCB	Polychlorinated biphenyl
DCE	Dichloroethene		PCE	Tetrachloroethene
DNAPL	Dense nonaqueous-phase liquid		psi	Pounds per square inch
DUS	Dynamic underground stripping		PVC	Polyvinyl chloride
			SEE	Steam enhanced extraction
EPA	U.S. Environmental Protection Agency		SVOC	Semivolatile organic compound
ERH	Electrical resistive heating		TCA	Trichloroethane
ERT	Electrical resistance tomography		TCE	Trichloroethene
			VC	Vinyl chloride
ft	Foot/feet		VOC	Volatile organic compound

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1.0 INTRODUCTION

1.1   PURPOSE AND SCOPE OF REPORT

This report contains information about the use of *in situ* thermal treatment technologies to treat chlorinated solvents in source zones containing free-phase contamination or high concentrations of contaminants that are either sorbed to soil or dissolved in groundwater in the saturated or unsaturated zone. Chlorinated solvent source zones have a high frequency of occurrence at hazardous waste sites. *In situ* thermal treatment technologies have proven to be effective in remediating source zones contaminated with chlorinated solvents, and are increasingly being used for that purpose.

The information in this report may be helpful to site managers, site owners, treatment technology vendors, regulators, consulting firms, and the public who may be involved in the cleanup of sites contaminated with chlorinated solvents. The information presented in this report assumes that the reader is familiar with the technical aspects of site remediation and soil and groundwater treatment technologies, although not necessarily with *in situ* thermal treatment.

This report includes the following information:

> Principles and science behind the *in situ* thermal treatment of chlorinated solvents, such as the effects of increased temperature on the fate and transport properties of chlorinated solvents.

> Applicability and general engineering considerations associated with *in situ* thermal treatment for chlorinated solvents, such as the observation that energy costs for *in situ* thermal treatment are typically less than 30 percent of the total project costs, and that these technologies are not generally affected by variations in soil permeability.

> Application of *in situ* thermal treatment to chlorinated solvent remediation through site-specific examples; included as detailed case studies for some projects and brief summaries for other projects.

Readers should note that specific projects discussed in this report, including those provided as case studies, took place over a ten-year period. It is to be expected that later applications will incorporate lessons learned from earlier applications.

This report is intended to be used as an information source about the application of *in situ* thermal treatment technologies for chlorinated solvent remediation. As a technology overview document, the information can serve as a starting point for identifying options for chlorinated solvent remediation. However, decisions about the use of a particular technology will depend on site-specific factors and may require treatability studies.

1.2   SPECIFIC TECHNOLOGIES ADDRESSED

Information is provided about the following *in situ* thermal treatment technologies:

> **Steam Enhanced Extraction (SEE)** - *In situ* thermal treatment in which steam is injected into the source zone to volatilize, mobilize, or degrade contaminants.

> **Electrical Resistive Heating (ERH)** - *In situ* thermal treatment in which electrical current is passed through the contaminated zone, increasing the subsurface temperature based on the electrical resistance of the soil and groundwater to volatilize, mobilize, or degrade contaminants.

> **Thermal Conductive Heating** - *In situ* thermal treatment in which surface or subsurface conductive heating elements are used to create a high-temperature zone to volatilize, mobilize, or degrade contaminants.

These *in situ* thermal treatment technologies have been used to treat a variety of contaminants, including chlorinated solvents, nonchlorinated volatile organic compounds (VOCs), petroleum hydrocarbons, and semivolatile organic compounds (SVOCs). For example, SEE was used to remediate a creosote- and pentachlorophenol-contaminated source zone at the Visalia Pole Yard Superfund site; ERH was used to address contamination with diesel-range organics (DRO) at a site in Atlanta, Georgia; and thermal conductive heating has been used to remediate polychlorinated biphenyls (PCBs) and diesel range organics (DRO) at other sites.

Additional variations of *in situ* thermal treatment, such as hot water injection and radio frequency heating, have also been applied to site remediation. However, these technologies have typically been used to remediate less volatile petroleum contamination rather than chlorinated solvents, and are not discussed further in this report.

1.3   SOURCES OF INFORMATION

The U.S. Environmental Protection Agency (EPA) has compiled a database of projects that use *in situ* thermal treatment. The database is available on-line at http://cluin.org/products/thermal/ (see Figure 1-1). A review of that database and additional information provided by project managers, technology vendors, and researchers in the field of *in situ* thermal treatment identified a total of 41 projects where *in situ* thermal technologies were used to treat soil and groundwater contaminated with chlorinated solvents, as of February 2004. These projects included 24 full-scale and 17 pilot-scale projects (technology applications) located throughout the U.S. and in one foreign country (Germany). Table 1-1 lists the 41 technology applications, along with information on their locations, scales, and operational status.

Figure 1-1: *In Situ* Thermal Treatment Profiles

As of February 2004, the EPA *In Situ* Thermal Treatment Web Site, available at http://cluin.org/products/thermal/, included profile information about more than 70 *in situ* thermal treatment applications. Of the technology applications, 41 were used to treat chlorinated solvents. Each profile has a varying level of detail, depending on the data and information that were available. The profiles contain available information from each technology application, including the following:

- Project information
  - o   Site background and setting
  - o   Contaminant(s) and media treated
  - o   Area of contamination and quantity treated
- Technology design and operation
- Cost and performance information
- Point(s) of contact
- References

This database and website are updated as additional information is made available.

Table 1-1: *In Situ* Thermal Treatment Technology Applications Used to Treat Chlorinated Solvents

Site Name	Site Location	Scale	Status
STEAM ENHANCED EXTRACTION			
A.G. Communications [a]	Northlake, IL	Full	Completed (2002)
Plating Facility	Danbury, CT	Full	Completed
Jennison Wright Corporation, Inc.	Granite City, IL	Full	Ongoing
Young-Rainey STAR (Former Pinellas Site), Area A (SEE plus ERH)	Largo, FL	Full	Completed (2003)
Young-Rainey STAR (Former Pinellas Site), Area B (SEE plus ERH)	Largo, FL	Full	Pending (Contract awarded)
Edwards Air Force Base, Site 61	CA	Pilot	Completed (2003)
Former Hazardous Waste Disposal Site	Muehlacker, Germany	Pilot	Completed (2001)
Loring AFB	Caribou, ME	Pilot	Completed (2003)
McClellan AFB	Sacramento, CA	Pilot	Completed
North Island NAS	San Diego, CA	Pilot	Completed (2000)
Portsmouth DOE	Portsmouth, OH	Pilot	Completed (1999)
Savannah River Site, Building 321 [a]	Aiken, SC	Pilot	Completed (2001)
Site 5, Alameda Point	Alameda, CA	Pilot	Completed (1999)
Launch Complex 34 (Steam Injection)	Cape Canaveral, FL	Pilot	Completed (2002)

Table 1-1 (continued): *In Situ* Thermal Treatment Technology Applications Used to Treat Chlorinated Solvents

Site Name	Site Location	Scale	Status
ELECTRICAL RESISTIVE HEATING			
Air Force Plant 4	Fort Worth, TX	Full	Completed (2002)
Avery Dennison Site[a]	Waukegan, IL	Full	Completed (2000)
Charleston Naval Complex	Charleston, SC	Full	Completed (2002)
Electronics Manufacturing Facility	Chicago, IL	Full	Completed (1997)
Fargo Dry Cleaner	Fargo, ND	Full	Pending (contract award expected shortly)
Former Drycleaner	Seattle, WA	Full	Completed (1999)
Former Electronics Manufacturing Facility [a]	Skokie, IL	Full	Completed (1999)
Former Pharmaceutical Manufacturer/ICN [a]	Portland, OR	Full	Completed (2000)
Ft. Lewis	WA	Full	Ongoing
Honeywell	FL	Full	Pending (contract awarded)
Lockformer	Lisle, IL	Full	Ongoing
Naval Air Station Alameda (Project 1)	Alameda, CA	Full	Ongoing
Naval Air Station Alameda (Project 2)	Alameda, CA	Full	Ongoing
Operating Dry Cleaner	Chicago, IL	Full	Completed (2003)
Paducah Gaseous Diffusion Plant	Paducah, KY	Full	Pending (following successful pilot – pilot completed 2003)
Dover AFB	Dover, DE	Pilot	Completed (1997)
Launch Complex 34 (3-phase)	Cape Canaveral, FL	Pilot	Completed (2000)
Lowry Landfill	Aurora, CO	Pilot	Completed (2002)
Poleline Road Disposal Area (PRDA), Operable Unit B [a]	Fort Richardson, AK	Pilot	Completed (1999)
Savannah River Site, Area M	Aiken, SC	Pilot	Completed (1993)
Silresim	MA	Pilot	Completed
USAFB Fire Training Pit	Niagara Falls, NY	Pilot	Completed (1996)
Former Agricultural Products Facility, Pesticide Remediation	Newark, CA	Pilot	Ongoing
THERMAL CONDUCTIVE HEATING			
Confidential Chemical Manufacturing Facility [a]	Portland, IN	Full	Completed (1997)
Delavan Municipal Well No. 4	Delavan, WI	Full	Completed (2001)
Confidential Chlorinated Solvent Site, Ohio	OH	Full	Ongoing
Confidential Chlorinated Solvent Site, California	CA	Full	Ongoing

Notes**:**

*	Includes ERH component
a	A case study for this project is included in Appendix A

Source: EPA Thermal Treatment Profiles 2002

Table 1-2 provides general information about seven selected *in situ* thermal treatment projects that are discussed further in Section 3.0 and in case studies provided in Appendix A. These projects cover the range of technologies discussed in this report.

Table 1-2: Selected *In Situ* Thermal Treatment Technology Applications

Application	Contaminants Treated	Media Addressed	Description of Hydrogeology
STEAM ENHANCED EXTRACTION			
A.G. Communications Systems (full-scale)	TCE, cis-1,2-DCE, and BTEX	Soil and groundwater	Alternating clay and sandy till layers; groundwater at 38 to 40 ft bgs
Savannah River Site 321-M, Solvent Storage Tank Area (pilot-scale)	PCE and TCE	Soil and groundwater	Interbedded sand and clay over a clay aquitard; groundwater at 143 ft bgs
ELECTRICAL RESISTIVE HEATING			
Former Manufacturing Facility – Skokie (full-scale)	PCE, TCE, and degradation products	Soil and groundwater	Heterogeneous sand, silt, and clay; groundwater at 7 ft bgs
Poleline Road Disposal Area, Area 3 (pilot-scale)	1,1,2,2-PCA, PCE, and TCE	Soil and groundwater	Sand and gravel; perched groundwater and water table at 12 ft bgs
ICN Pharmaceutical Site (full-scale)	TCE, cis-1,2-DCE, VC, and other VOCs	Soil and groundwater	Silt and sand; groundwater at 8 ft bgs
Avery Dennison Site (full-scale)	MC and industrial solvent	Soil and groundwater	Glacial till with silty clay; groundwater at 6 to 30 ft bgs
THERMAL CONDUCTIVE HEATING			
Confidential Chemical Manufacturing Facility – Portland (full-scale)	PCE, TCE, 1,1-DCE	Soil and groundwater	Heterogeneous layers of clay, sand, and gravel; groundwater at 22 to 25 ft bgs

Notes:

TCE	Trichloroethene
DCE	Dichloroethene
BTEX	Benzene, toluene, ethylbenzene, and xylene
ft	Feet
bgs	Below ground surface
PCE	Tetrachloroethene
PCA	Tetrachloroethane
VC	Vinyl chloride

1.4   STRUCTURE AND CONTENTS OF THE REPORT

The remainder of this report is organized as follows:

Section 2.0 – Background – Describes the properties and fate and transport of chlorinated solvents and provides general information about *in situ* thermal treatment technologies.

Section 3.0 – *In Situ* Thermal Treatment Technologies – Describes the principles, applicability considerations, and engineering considerations related to *in situ* thermal treatment technologies, as well as information about field experience with each technology.

Section 4.0 – Summary – Includes a discussion of overall applicability and engineering considerations for *in situ* thermal treatment.

Section 5.0 – Information Sources – Includes a list of cited references, as well as additional sources of information that are relevant to *in situ* thermal treatment.

Appendix A contains detailed case studies about seven *in situ* thermal treatment projects. Appendix B contains brief snapshots of additional *in situ* thermal projects, and Appendix C contains a list of *in situ* thermal treatment technology vendors.

2.0 BACKGROUND

2.1 PROPERTIES OF CHLORINATED SOLVENTS

Chlorinated solvents are artificial organic compounds, including tetrachloroethene (PCE); trichloroethene (TCE); 1,1,1-trichloroethane (TCA), carbon tetrachloride (CT); chloroform (CF); methylene chloride (MC); vinyl chloride (VC); and other chlorinated methanes, ethanes, ethenes, and benzenes. Chlorinated solvents are typically manufactured from naturally occurring hydrocarbon constituents (methane, ethane, and ethene) and chlorine through various processes that substitute one or more chlorine atoms for hydrogen atoms, or selectively dechlorinate chlorinated compounds to a less chlorinated state. Chlorinated solvents have historically been used in a wide variety of applications, including uses as solvents and degreasers and in the manufacturing of other chemicals. As a result of this widespread historic use, three of the 12 most common contaminants at Superfund sites are specific chlorinated solvents (VC, 1,1,1-TCA, and TCE) (EPA 2001). Table 2-1 lists the chlorinated solvents most commonly identified as environmental contaminants, their abbreviations, and their common names. Figure 2-1 presents the molecular structures of some of the more common chlorinated solvents.

The physical and chemical properties of chlorinated solvents govern their fate and transport in the subsurface environment, as well as their susceptibility to various remediation technologies. The number of substituted chlorine atoms on the chlorinated solvents directly affects their physical and chemical behavior. As the number of substituted chlorine atoms increases, molecular weight and density generally increase, and vapor pressure and aqueous solubility generally decrease. Table 2-2 lists pertinent physical and chemical data for the chlorinated solvents commonly identified as subsurface contaminants.

Table 2-1: Chlorinated Solvents Commonly Identified as Environmental Contaminants

Name	Common Name(s)	Abbreviation[1]
CHLORINATED ETHENES		
Tetrachloroethene (-ethylene)	*Perchloroethene*	PCE
Trichloroethene(-ethylene)	None	TCE
cis-1,2-Dichloroethene(-ethylene)	Acetylene dichloride	cis-DCE
trans-1,2-Dichloroethene (-ethylene)	Acetylene dichloride	trans-DCE
1,1-Dichloroethene(-ethylene)	Vinylidene chloride	1,1-DCE
Chloroethene (-ethylene)	*Vinyl chloride*	VC
CHLORINATED ETHANES		
1,1,2,2-Tetrachloroethane	*1,1,2,2-Perchloroethane*	1,1,2,2-PCA
1,1,1-Trichloroethane	Methyl chloroform	1,1,1-TCA
1,1,2-Trichloroethane	Vinyl trichloride	1,1,2-TCA
1,2-Dichloroethane	Ethylene chloride	1,2-DCA
1,1-Dichloroethane	Ethylidene chloride	1,1-DCA
Chloroethane	Chloroethane	CA

**Table 2-1 (continued): Chlorinated Solvents Commonly Identified
as Environmental Contaminants**

Name	Common Name(s)	Abbreviation[1]
CHLORINATED METHANES		
Tetrachloromethane	***Carbon tetrachloride***	CT
Trichloromethane	***Chloroform***, methane trichloride	CF
Dichloromethane	***Methylene chloride***, methylene dichloride	MC
Chloromethane	Methyl chloride, monochloromethane	CM
CHLORINATED BENZENES		
Monochlorobenzene	Chlorobenzene	MCB
Dichlorobenzene (3 isomers)	1,2- (ortho-), 1,3- (meta-), and 1,4- (para-) dichlorobenzene	DCB

Notes:
[1] Abbreviations are based on the names in bold italic type.
Sources: Sawyer and others 1994, Merck 1989

Figure 2-1: Molecular Structures of Common Chlorinated Solvents
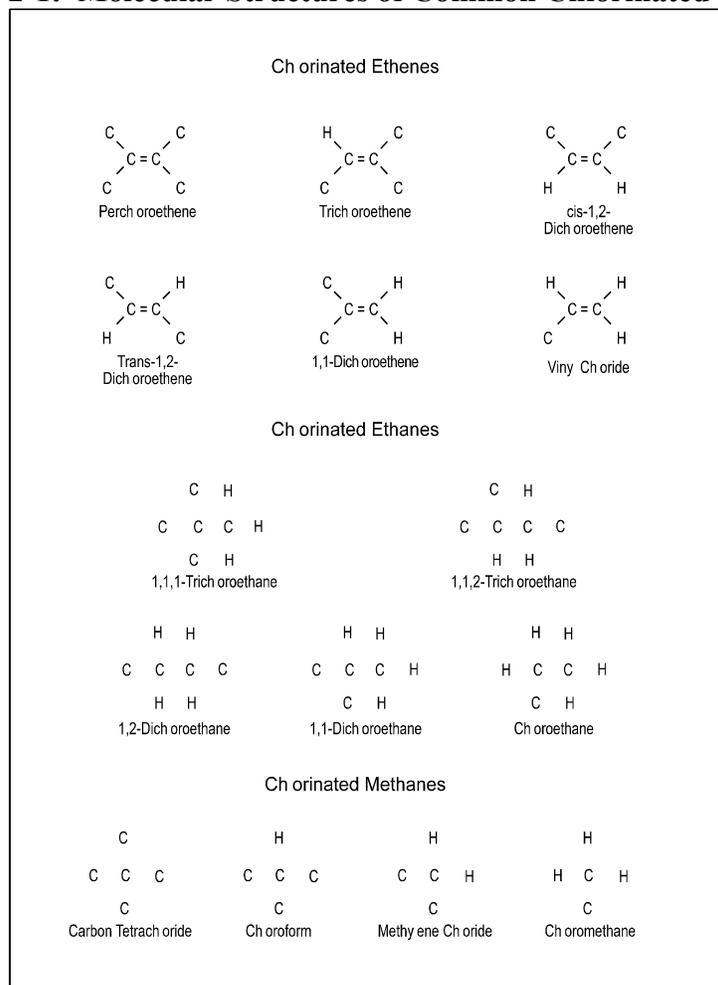
Source: Modified from Sawyer and others 1994

Table 2-2: Chemical and Physical Properties of Chlorinated Solvents

Chlorinated Solvent (CAS Number)	Boiling Point (EC)	Liquid Density (g/mL at 20EC)	Liquid Viscosity (cP @ 25EC)	Octanol-Water Partition Coefficient (@ 25^{E}C)	Aqueous Solubility (mg/L @ 25^{E}C)	Vapor Pressure (mm Hg @ 25^{E}C)	Henry's Law Constant (atm-m^3/mol @ 25^{E}C)
CHLORINATED ETHENES							
PCE (127-18-4)	121	1.62	0.844	3.40	200	19	0.0184
TCE (79-01-6)	87	1.46	0.545	2.42	1,472	73	0.0103
cis-1,2-DCE (156-59-2)	60	1.28	0.445	1.86	3,500	203	0.0041
trans-1,2-DCE (156-60-5)	49	1.26	0.317	2.09	6,300	333	0.0094
1,1-DCE (75-35-4)	32	1.21	0.464	2.13	2,250	600	0.0261
VC (75-01-4)	-13	gas	gas	1.36	8,800	2,982	0.0270
CHLORINATED ETHANES							
1,1,2,2-PCA (79-34-5)	130	1.50	1.6	3.00	11,000	12	0.0024
1,1,1-TCA (71-55-6)	74	1.34	0.793	2.49	1,334	124	0.0172
1,1,2-TCA (79-00-5)	114	1.44	NA	2.05	4,420	23	0.0009
1,2-DCA (107-06-2)	84	1.24	0.779	1.48	8,524[1]	79	0.0010
1,1-DCA (75-34-3)	57	1.18	NA	1.79	5,057	227	0.0056
CA (75-00-3)	12	gas	gas	1.43	5,678[1]	1,008[1]	0.0088
CHLORINATED METHANES							
CT (56-23-5)	77	1.59	0.908	2.83	793	115	0.0304
CF (67-66-3)	61	1.48	0.537	1.97	7,920	197	0.0037
MC (75-09-2)	40	1.33	0.413	1.25	13,030	433	0.0022
CM (74-87-3)	-24	gas	gas	0.91	5,325	4,300	0.0088
CHLORINATED BENZENES							
MCB (108-90-7)	132	1.10	0.8	2.80	470	12	0.0037
DCB (3 isomers)	173-180	1.20-1.30	1.3	3.40-3.60	79-160	1-2	0.0019-0.0031

Notes:

|			
[1]	Reference temperature is 20EC for the properties of these compounds	g/mL	Grams per milliliter
NA	Liquid viscosity of 1,1,2-TCA and 1,1-DCA not available	cP	Centipoises
gas	VC, CA, and CM are pure gases under standard temperature and pressure	mg/L	Milligrams per liter
		mm/Hg	Millimeters of mercury
atm	Atmosphere	m^3/mol	Cubic meter per mole
CAS	Chemical Abstracts Service		

Sources: Superfund Chemical Data Matrix (EPA 1996), Davis 1997, Perry and others 1984

2.2 FATE AND TRANSPORT OF CHLORINATED SOLVENTS

A chlorinated solvent released to the subsurface as an organic liquid (commonly referred to as a nonaqueous-phase liquid [NAPL] in the subsurface) will result in a source zone containing free-phase contamination or high concentrations of contaminants that are either sorbed to soil or are dissolved in groundwater in the saturated or unsaturated zone in the area of the release. Most of the chlorinated solvent NAPLs, such as PCE, TCE, and TCA, are denser than water (referred to as dense nonaqeous-phase liquids [DNAPLs]). Chlorinated solvents that do not form DNAPL include VC, chloroethane (CA), and chloromethane (CM). These compounds are gaseous in their pure phases under standard conditions. DNAPLs tend to sink through both unsaturated and saturated soils until they reach the lowest point on the top of a confining layer. DNAPLs may also penetrate some distance into the confining layer, depending on its geotechnical characteristics and the amount of DNAPL present. In addition, capillary forces can trap NAPLs in porous media above or below the water table (EPA 2000).

Chlorinated solvents released to the environment will seek phase equilibrium (a condition in which all acting influences are canceled by others, resulting in a stable, balanced, or unchanging system). The chlorinated solvent will remain as a NAPL, adsorb to soil, dissolve in groundwater, or volatilize into soil gas to the extent defined by the physical and chemical properties of the individual chlorinated solvent and the subsurface environment. Partition coefficients, which are related to the hydrophobicity and aqueous solubility of a chlorinated solvent, define the extent to which a chlorinated solvent will partition between NAPL, adsorb to soil, and dissolve in groundwater. The vapor pressure of a chlorinated solvent defines the extent to which it will partition between NAPL and soil gas or soil and soil gas. Chlorinated solvents dissolved in groundwater will also partition themselves between the dissolved phase and the vapor phase, as defined by their Henry's Law constants. Figure 2-2 shows the mechanisms by which chlorinated solvents transfer phases to reach equilibrium conditions, along with the related physical and chemical properties of the chlorinated solvents (EPA 2000).

Figure 2-2: Phase Equilibrium Mechanisms and Properties of Chlorinated Solvents
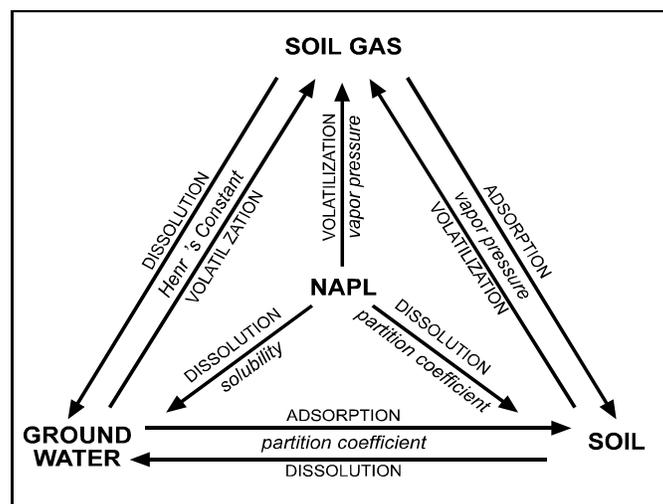
Source: Modified from Huling, S.G., and J.W. Weaver 1991

Chlorinated solvents can migrate in the subsurface in their nonaqueous, aqueous, and vapor phases through various processes. Through advection and dispersion, chlorinated solvents can migrate along with the flow of the groundwater or soil gas to which they are partitioned. In addition, diffusion in the vapor and aqueous phases driven by concentration gradients causes the chlorinated solvent to seek phase and concentration equilibrium with its surrounding environment. The extent of subsurface migration is a function of the volume of chlorinated solvent released, the area over which the release occurs, the duration of the release, and the chemical and physical properties of both the chlorinated solvent and the subsurface environment (EPA 2000).

Releases of chlorinated solvents can result in the formation of a source zone containing NAPL, either as a separate phase or adsorbed to soil. If this source zone is in contact with groundwater or is in the pathway of recharge to groundwater, it will result in the formation of a groundwater plume. In soil, chlorinated solvents typically are transported by the flow of DNAPL or diffusion in soil-gas vapor. In groundwater, advective transport (the movement of contaminants by flowing groundwater) is the most important process that affects the fate of dissolved chlorinated solvents. In general, the more soluble the compound, the more readily it can be transported with groundwater flow. For example, based on solubility data provided in Table 2-2, MC and CF would be transported more readily in groundwater than PCE and CT. Figure 2-3 presents an example of typical DNAPL subsurface transport processes. In addition, DNAPL can move independent of, and in different directions, than groundwater flow. For example, Figure 2-3 shows DNAPL moving in a direction opposite to groundwater flow (EPA 2000).

Figure 2-3: Example Chlorinated Solvent Subsurface Transport Processes
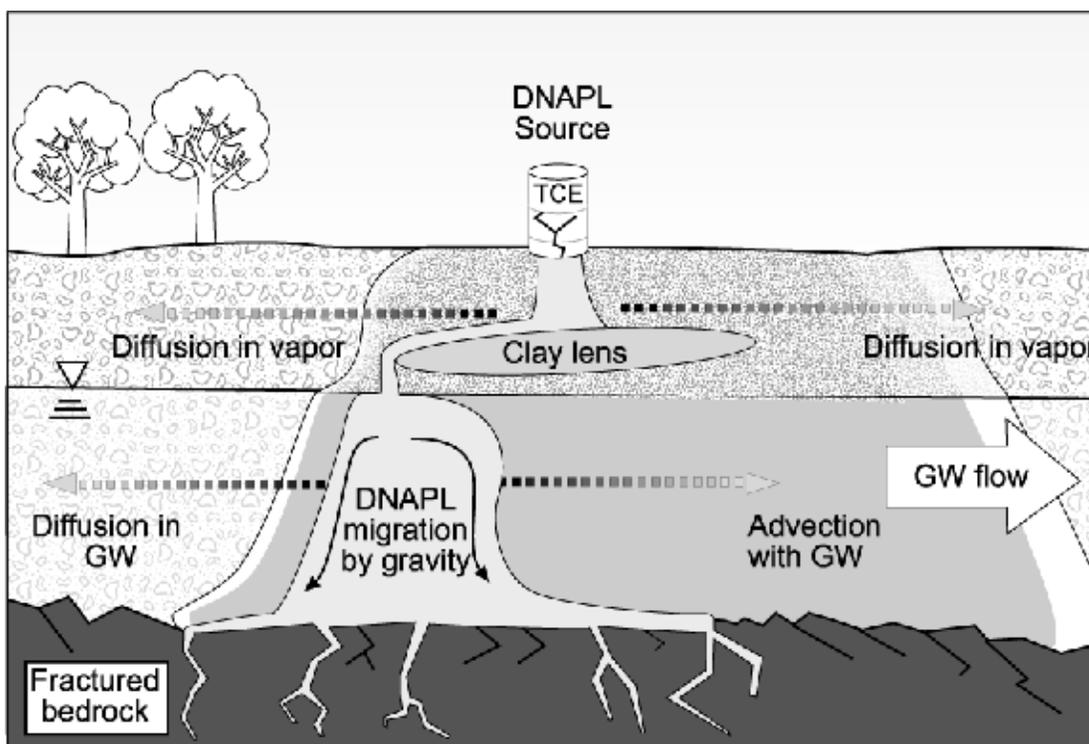
Source: Modified from Sims and others 1992

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In addition to the physical transport processes described above, chlorinated solvents can also be biologically degraded through natural mechanisms (intrinsic bioremediation). Some chlorinated solvents (for example, 1,1,1-TCA and CT) can also degrade naturally through abiotic (nonbiological) mechanisms. In most systems under ambient conditions, biological degradation tends to dominate, depending on the type of contaminant and the groundwater chemistry (EPA 2000).

Recent work suggests that in appropriate subsurface conditions, abiotic processes may also contribute. Abiotic processes are affected by items such as mineralogy (e.g., ferrous iron), reactivity, organic content, and soil surface area. Thermal enhancement of such processes is a subject of active investigation. (Benson, 2003)

While the above discussion addresses the fate and transport of chlorinated solvents under naturally occurring conditions, these properties and mechanisms can be modified through engineered systems, such as those employed during *in situ* thermal treatment. The modifications employed during *in situ* thermal treatment, and how they can enhance remediation, are discussed later in this section.

2.3   CONVENTIONAL AND INNOVATIVE TREATMENT OF CHLORINATED SOLVENTS

Use and management of wastes containing chlorinated solvents has resulted in contamination of soil and groundwater, with chlorinated solvents present at many contaminated groundwater sites in the U.S. Chlorinated solvents and their degradation products, including DCA, DCE, and VC, may persist in the subsurface because of their chemical properties and fate and transport tendencies, discussed above.

Many sites contaminated with chlorinated solvents have used pump-and-treat systems to clean up and/or contain groundwater plumes. These systems likely will need to be operated for extended time frames, with the potential for relatively high operation and maintenance (O&M) costs. Pump-and-treat involves extracting contaminated groundwater through recovery wells or trenches and treating the groundwater by *ex situ* (aboveground) processes, such as air stripping, carbon adsorption, biological reactors, or chemical precipitation. Variables in the design of a typical pump-and-treat system include the number, depth, and pumping rate of groundwater extraction points, and the *ex situ* treatment processes employed (EPA 2001b).

Use of innovative source zone treatment technologies is being considered for many sites contaminated with chlorinated solvents, including sites that currently are using pump-and-treat or other conventional treatment approaches. Directly addressing the source zone can result in a more time- and cost-effective remedial approach than addressing the contaminated plume alone; even considering energy costs, which are typically less than 30 percent of total project cost for *in situ* thermal treatment, with ERH typically less than 15-20 percent. Innovative source zone remediation technologies have included *in situ* thermal treatment, as well as *in situ* chemical oxidation, and surfactant/co-solvent flushing (ITRC 2002).

Challenges in using conventional approaches such as pump-and-treat to remediate sites contaminated with chlorinated solvents present as DNAPL or dissolved in groundwater, especially to stringent clean up levels such as maximum contaminant levels (MCLs), include:

> The relatively low aqueous solubility of chlorinated solvents does not allow for significant mass removal through dissolution in groundwater (even at concentrations approaching saturation).

> The relatively high octanol-water partition coefficient for chlorinated solvents results in the preferential partitioning of solvents to organic matter in the subsurface, rather than to groundwater, making contaminants more difficult to extract.

In situ thermal treatment technologies increase the temperature of the source zone to increase the mobility of the chlorinated solvents in the subsurface. This enhanced mobility facilitates the removal of chlorinated solvents, and, in some cases, can also result in *in situ* destruction of contaminants (Davis 1997).

2.4 GENERAL PRINCIPLES OF *IN SITU* THERMAL TREATMENT

The key physical and chemical properties that govern the fate and transport of chlorinated solvents, including viscosity, solubility, vapor pressure, octanol-water partition coefficient, and Henry's Law constant, are temperature dependent. The chlorinated solvent properties summarized in Table 2-2 are generally based on a "standard" temperature of 25°C. At the higher temperatures employed during *in situ* thermal treatment, these properties change, typically in a way that enhances the treatability of the chlorinated solvents. The primary thermal effects applicable to chlorinated solvents present in the free phase, sorbed phase and the dissolved phase are summarized below and in Table 2-3. More detailed information is available in the document titled *How Heat Can Enhance In-situ Soil and Aquifer Remediation: Important Chemical Properties and Guidance on Choosing Appropriate Technique* (Davis 1997).

Table 2-3. Thermal Effects on Chlorinated Solvent Properties

Fate and Transport Property	Effect as Temperature Increases
Liquid density	Decreases moderately (less than 100 percent)
Vapor pressure	Increases significantly (10 to 20 fold)
Liquid viscosity	Decreases significantly until boiling point and drops markedly upon conversion from liquid to vapor
Vapor viscosity	Increases slightly as vapor temperature increases
Diffusivity	Increases
Solubility	Increases as temperature increases
Henry's constant	Increases (more likely to volatilize from water)
Partition coefficient	Decreases (less likely to partition to organic matter in soil)
Biological degradation	Increases (may decrease at higher temperatures)
Abiotic degradation	Increases

Source: Derived from Davis 1997

The common chlorinated solvents present as free-phase liquids under ambient temperatures boil and convert to a gas at temperatures ranging from 40 to 180°C. However, mixtures of chlorinated solvents (both free-phase and dissolved-phase) with water exhibit heterogeneous azeotropic properties; that is, the mixture boils at a constant temperature without a corresponding change in composition. Typically, the boiling points of aqueous chlorinated solvent mixtures are less than the pure-phase boiling points of both the chlorinated solvent and water. For example, an azeotropic mixture of PCE and water will boil at 88°C, more than 30°C less than the 121°C boiling point for pure PCE and significantly less than the boiling point of water. Table 2-4 shows the heterogeneous azeotropes of several common chlorinated solvents (Gmehling and Onken 1977).

Table 2-4. Heterogeneous Azeotropes of Common Chlorinated Solvents

Chlorinated Solvent	Pure Substance Boiling Point (°C)	Heterogeneous Azeotrope with Water	
		Boiling Point (°C)	Molar Concentration of Chlorinated Solvent in Liquid/Vapor (%)
PCE	121	88	83
TCE	87	73	94
1,1,2-TCA	114	86	84
CT	77	67	96
CF	61	56	97
MC	40	39	99

Source: Gmehling and Onken 1977

Even at temperatures less than their boiling points, free-phase chlorinated solvents tend to partition to the gas phase because their vapor pressures increase as the temperature increases. Typically, chlorinated solvents that boil at less than 100 °C will have a 5 to 7 times greater vapor pressure at 50 °C than at 10 °C (Fares and others 1995). In addition, the liquid viscosity of a given chlorinated solvent generally decreases by 1 percent per °C of increased temperature up to its boiling point, enhancing its mobility in the subsurface. In the gas phase, a mass of chlorinated solvent occupies a larger volume than it does as a liquid, resulting in expansion and advective flow. For example, a mass of water occupies 1,600 times more volume as a gas than it does as a liquid (Davis, 1997). As chlorinated solvents expand, the mass of a chlorinated solvent can be captured and removed from the subsurface. In addition, the viscosity and diffusivity rates (in air) allow for more efficient flow of chlorinated solvents as a gas than as a liquid. The viscosity of a chlorinated solvent as a gas is generally 2 orders of magnitude less than that of a liquid. Increasing the temperature from 10 to 100 °C will increase the diffusion in the vapor phase by approximately 50 percent (Davis 1997).

Thermal effects also enhance the removal of chlorinated solvents dissolved in source zone groundwater or pore water. Physical and chemical properties, such as solubility, Henry's Law constant, octanol-water partition coefficient, and aqueous diffusivity rate, change in ways beneficial to remediation. For solubility, concentrations increase by a factor or two or more as an area is heated. The Henry's Law constant for chlorinated solvents generally increases and the partitioning from the aqueous phase to soil (based on the octanol-water partition coefficient) generally decreases with elevated temperature. For example, the Henry's Law constant for TCE

increases by 1 order of magnitude, and its adsorption from the aqueous phase onto soils can be expected to decrease by a factor of approximately 2.2 when the temperature is increased from 20 to 90°C (Heron and others 1996). The aqueous diffusion rate will increase by approximately 30 percent when the temperature is increased from 10 to 90°C (Treybal 1980).

The elevated temperatures achieved during *in situ* thermal treatment can also enhance abiotic and biotic degradation or destruction of chlorinated solvents. Abiotic degradation pathways, such as hydrolysis, where the hydrogen ions in water replace the chlorine ions in the chlorinated solvent molecule, and hydrous pyrolysis oxidation (HPO), where chlorinated solvents under oxidizing and aqueous conditions may be oxidized (eventually to carbon dioxide), have been shown to increase substantially at elevated temperatures. For example, the hydrolysis rates for chlorinated methanes and ethanes have been shown to result in relatively short half-lives for these contaminants at elevated temperatures (Jeffers and others 1989). In addition, rates of HPO of chlorinated solvents have been shown to increase (up to a maximum rate) with temperature (Baker and Kuhlman 2002).

Biological degradation pathways may also be enhanced at elevated temperatures. One commonly used rule of thumb, (based on the Van't Hoff-Arrhenius relationship) states that, for every 10°C increase in temperature, there is roughly a two-fold increase in biological activity resulting in an increase in degradation rate constants (EPA 1997). Extremely high temperatures may sterilize soils of some microbes. However, significant levels of thermophiles (microbes that thrive under high temperature conditions) are present in many soils, and nearly all microbes benefit from elevated temperatures in the more moderately heated soil regions at the fringe of the treatment area. The overall effect of the elevated temperatures achieved during *in situ* thermal treatment on biological degradation pathways has not been fully determined, and is dependent on site-specific conditions. The following references provide additional information about research on this subject as related to petroleum contamination:

> Newmark, R.L. and R.D. Aines. Summary of the LLNL gasoline spill demonstration-Dynamic Underground Stripping Project, Lawrence Livermore National Laboratory, Berkeley Environmental Restoration Center. UCRL-ID-120416. April 3, 1995.

> Udell, K.S., M. Itamura, L. Alvarez-Cohen, and M. Hernandez. NAS Lemoore JP-5 cleanup demonstration. Berkeley Environmental Restoration Center, University of California, Berkeley. 1994.

> Richardson, R.E.; C.A. James; V.K. Bhupathiraju; L. Alverez-Cohen. "Microbial activity in soils following steam treatment". *Biodegradation.* 13, 285-295, 2002

Each of the three technologies discussed in this report (SEE, ERH, and thermal conductive heating) employs a different method to increase the temperature within the saturated or unsaturated contaminated zone. This temperature increase results in conditions under which chlorinated solvents can be more easily volatilized, mobilized, and then extracted from the subsurface using a vapor (and in some cases liquid extraction) system. In addition, each technology may also degrade contaminants directly in the subsurface through HPO or hydrolysis at lower temperatures, oxidation or pyrolysis at higher temperatures, or by stimulating the growth of microbes that biodegrade contaminants.

3.0 *IN SITU* THERMAL REMEDIATION TECHNOLOGIES

In situ thermal heating methods were first developed by the petroleum industry for enhanced oil recovery. These methods were adapted to the treatment of soil and groundwater. Initial variations included hot water injection, steam injection, hot air injection, and ERH. In the late 1980s and early 1990s, thermal conductive heating was developed.

Currently, steam injection (SEE), ERH, and thermal conductive heating are used for remediation of soil and groundwater in source zones contaminated with chlorinated solvents. These *in situ* thermal treatment technologies have also been used for treating other volatile and semivolatile organic contaminants, such as PCBs; polycyclic aromatic hydrocarbons (PAHs); pesticides; and various fuels, oils, and lubricants that are less amenable to other treatment methods. For example, hot water injection has been used to enhance the recovery of low volatility and low solubility oils. RF-heating, a variety of ERH that uses radio-frequency energy, has been applied to remediation of various contaminants in the unsaturated zone, but its applicability in the saturated zone has been limited. Hot air injection has seen limited application as a stand-alone remediation technology because of the relatively low heat capacity of air (1 kilojoule per kilogram-°C) compared to that of steam (4 kilojoules per kilogram-°C). In addition, steam provides additional heating capacity based on the heat of condensation of water (2,300 kilojoules per kilogram). As such, higher airflow rates would be needed as compared to steam flow rates to provide the same heating effect. Air injection also can lead to formation of soil fractures when performed at very high pressures. However, hot air injection has sometimes been applied during steam injection to maintain the excess concentrations of oxygen necessary to promote HPO (Davis 1997).

3.1   STEAM ENHANCED EXTRACTION

TECHNOLOGY DESCRIPTION AND PRINCIPLES

SEE was initially used by the petroleum industry for the enhanced recovery of oil during production operations by lowering the viscosity of heavy oils and increasing the volatility of light oils, facilitating the production from deep formations. SEE takes advantage of the relatively large heating capacity of steam, which provides a greater heat input to the subsurface than injecting hot air. In remedial applications, as shown in Figure 3-1, SEE typically involves the injection of steam into the subsurface to dissolve, vaporize, and mobilize contaminants that are then recovered. Mobilized contaminants are extracted from the subsurface using vapor and liquid extraction equipment. Extracted vapors and liquids are treated using conventional aboveground treatment technologies, such as condensation, air stripping, carbon adsorption, and thermal oxidation.

Figure 3-1: SEE System Schematic
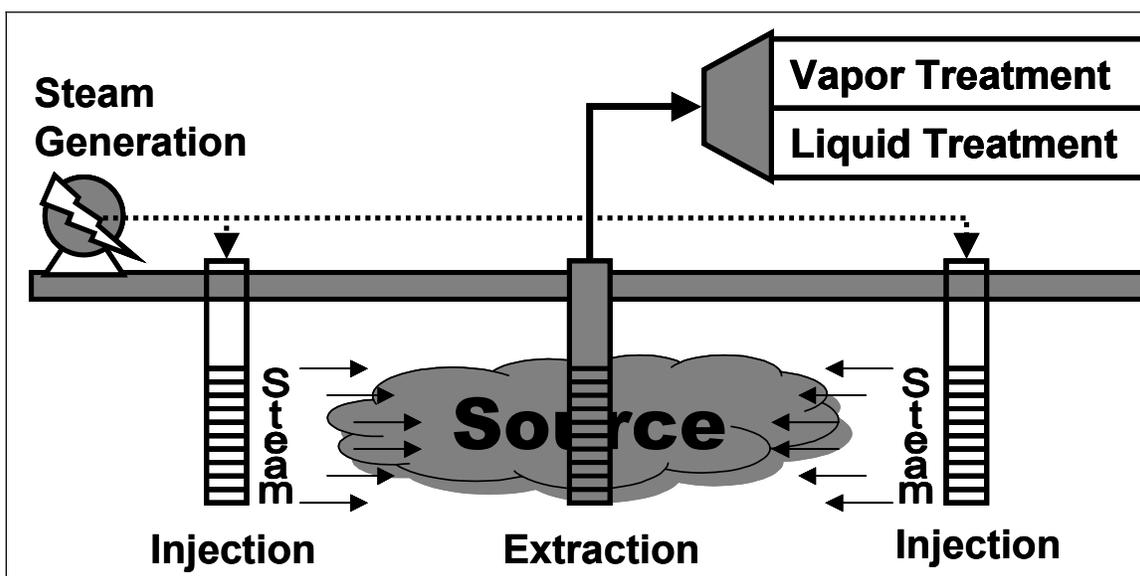
Source: Derived from Davis 1998

During the initial stages of SEE, injected steam condenses and raises the temperature of the soil and pore fluids. When the soil surrounding the injection wells becomes heated to the boiling point of water, a steam front begins to form in the subsurface, and liquids and vapors are mobilized towards recovery wells. The steam front is characterized by high contaminant concentrations in the vapor phase (behind the steam front) and the aqueous phase (ahead of the steam front). At this stage, three distinct zones develop: a steam temperature zone, a variable temperature zone, and an ambient temperature zone. Within the steam zone, the main contaminant removal mechanisms are steam distillation and displacement. In the variable zone, physical forces (such as viscous, expansion, and inertial) play the largest role in contaminant transport. In the ambient zone, direct displacement is the main contaminant removal mechanism (Wu 1977). Pressure cycling has been used to increase the removal efficiency of SEE after the target volume has been heated to near boiling temperatures and steam is breaking through to the extraction wells (Udell and others 1991).

At some sites, such as Young-Rainey STAR, Northeast Area A (see summary in Appendix B), SEE and ERH were used in a combined treatment system. ERH is incorporated in the steam injection wells to mobilize contaminants within less permeable zones (Newmark and others 1998). This combination is sometimes referred to as dynamic underground stripping (DUS).

An enhancement of SEE, HPO, uses injected air in addition to steam. The oxygen in the injected air, coupled with the high temperatures, has been shown to promote the *in situ* oxidation of some contaminants. Air and steam are both typically injected into the subsurface using the same injection wells, often in alternating cycles (Udell and others 1994).

Steam injection has been applied at two fractured bedrock sites (Loring AFB and Edwards AFB). During 2002, a research/pilot project was carried out using steam at the former Quarry site at Loring Air Force Base, located in Limestone, Maine. Drums containing waste solvents had been

disposed in various locations in the quarry. Limited groundwater characterization efforts located an area in the fractured limestone bedrock where PCE concentrations indicated the possible presence of DNAPL. The objectives of the research project included determining the feasibility of using steam to remediate VOCs from fractured limestone, and reducing the mass of contaminants in the subsurface to reduce the timeframe for natural attenuation. Extensive characterization of the fracture framework and contaminant distribution was carried out as the steam injection system was installed. Characterization activities included logging of bedrock cores, conventional borehole geophysics, extracting and analyzing rock chip samples, transmissivity testing on discrete intervals, groundwater sampling from discrete intervals, and interconnectivity testing. Based on the information gathered during these characterization efforts, the steam injection and extraction system was designed to inject steam into the less-contaminated boreholes while extracting contaminants from the more contaminated boreholes. The characterization activities had revealed that the fracture spacing was larger than expected, and thus the transmissivity was lower. This limited the steam injection rates that could be achieved. However, even with only limited heating of the subsurface, significant increases in the extraction rate of contaminants was achieved during this limited-duration project. The data from this project indicates that different mechanisms than are normally found in unconsolidated media are likely contributing to the enhanced extraction rates found here. Laboratory experiments are planned to help elucidate the mechanisms for contaminant recovery that are important in fractured limestone (Davis, 2004).

Edwards AFB Site 61 was also a pilot effort, conducted in fractured granite (quartz monzonite). The pilot encompassed a vapor capture radius of approximately 80 ft and heated to a depth of approximately 45 ft. Heating was initially at depth with vapor recovery in shallow zones. Although steam distribution was uneven, the site was partially heated and mass removal was accelerated. Approximately 700 pounds of VOCs were recovered, some from zones not thought to contain NAPL. Air co-injection was included as part of the pilot. Data suggests that the air injection may have had a beneficial effect of opening fractures to steam flow. Electrical Resistance Tomography (ERT) proved useful as a process monitoring tool as heated zones showed significant increases in electrical resistivity (Davis, 2004).

APPLICABILITY CONSIDERATIONS

SEE is most effective when the steam is able to enter the pore space of the soils and best suited for zones of moderate to high permeability. In low permeability soil, steam cannot penetrate the pore space as rapidly, resulting in higher heat losses and, in some cases, the inability to completely heat the area. In addition, smaller pore diameters create higher capillary pressures and, as a result, lower the rate of evaporation of contaminants. It may be possible to heat lower permeability zones with steam if the zones are sufficiently thin that they can be conductively heated from above or below. Alternatively, it may be possible to combine SEE with other technologies, such as ERH during DUS, to address lower permeability zones. Heterogeneities in subsurface geology can also affect the flow of injected steam in the subsurface because preferential flow through higher permeable zones can result in channeling. However, channeling effects for steam may be minimized because heat losses from more permeable zones are typically higher. This effect results in a slowed steam front in these zones and, overall, a more uniform steam front expansion. Lower permeable lenses typically will heat more slowly in inter-bedded

soils. If the scale of the bedding is small (less than about 9 feet thick), this effect may not be significant. As described above, if the low permeable zone thickness is large, other *in situ* thermal treatment technologies alone or in combination with SEE may be more appropriate.

ENGINEERING CONSIDERATIONS

The major components of SEE systems are steam generating equipment, a steam distribution system, and vapor, groundwater, and free product extraction systems. At chlorinated solvent sites, most contaminants will be recovered in the vapor phase. Steam for the SEE system may be supplied by existing equipment used for other purposes at the site (such as at the Savannah River site described in Appendix A) or by using a mobile steam plant. Such plants can be powered with natural gas, propane, or other fuel sources. The sizes and numbers of generators necessary will depend on the required steam mass injection rate. The fuel source will depend on the availability of fuel at the location of the site. In most cases, steam-generating equipment may require feed water pretreatment to avoid scale buildup and fouling in areas where water supplies are of low quality (Schumacher 1980). The steam distribution typically includes a manifold that allows for the control of steam flows to individual wells or groups of wells.

Important operational parameters for SEE equipment include steam pressure, steam quality (level of saturation), and the ability to inject continuously until breakthrough at the extraction wells occurs in the more permeable zones. Steam pressures must be sufficient to penetrate the soils and displace groundwater while not exceeding the fracturing pressure. Fracturing during injection can cause channeling, leading to the potential for bypassing contaminated areas and steam breakthrough at the soil surface. Under certain conditions, injection pressures as high as 2.4 pounds per square inch (psi) per meter below ground surface (bgs) have been used without causing fracturing (Earth Tech and SteamTech 2003). As a rule of thumb, achievable injection pressure increases by about 1.5 psi per meter (0.5 psi per foot) of overburden (Davis 1998).

High quality (100 percent vapor) steam is typically preferred for *in situ* thermal treatment application. Supersaturated or higher temperature steam does not appear to offer an additional advantage because the heating potential of the steam is relatively independent of temperature. In addition, increased steam temperature can result in greater radiant and conductive heat losses to areas outside of the treatment area. Continuous injection until the steam zone extends from the injection wells to the extraction wells is typically employed to provide adequate heating rates and reduce heat losses.

A SEE system typically consists of a series of injection wells and extraction wells. For small applications, a ring of injection wells typically surround a central extraction well located near the middle of the DNAPL area. In this configuration, the injection wells are placed in clean areas around the source zone, if possible, to minimize the risk of contaminant spreading. In some cases, but less frequently, an inside-out configuration has been used, where the steam is injected centrally, and extraction wells on the perimeter provide hydraulic and pneumatic control, reducing the potential for contaminant spreading outward. For larger areas, multiple arrays of injection and extraction wells typically are used to heat the area and capture mobilized contaminants in the treatment area. The patterns and spacing of the injection/extraction wells depend on the geologic conditions (including whether the application is in unsaturated or

saturated media), the permeability, and the depth of application. Typical spacing for SEE wells ranges from several to more than 10 meters (Davis 1998).

Thermocouples or electrical resistance tomography are used to monitor subsurface temperatures. Once the desired subsurface temperature within the treatment zone has been achieved, cyclic steam injection is sometimes used. When steam injection is cycled off but vapor extraction is continued, the subsurface is depressurized, resulting in the vaporization of residual water and contaminants present within pore spaces. This approach has been shown to reduce the amount of steam required to meet a given cleanup level, and possibly to reduce overall cleanup time (Itamura and Udell 1993).

The wells used for injection, extraction, or monitoring, and the steam distribution system need to be designed to handle the expected temperatures and changes in temperatures that are inherent to SEE. Steel is typically the preferred casing and screen material, because conventional polyvinyl chloride (PVC) or fiberglass wells can degrade or deform under high temperature conditions. Well casing joints and grout must also be selected to handle pressures and thermal expansion. In some cases, grouts can be amended with quartz silica or silica flour for temperature stability and with sodium chloride for greater expansion capability. Temperature considerations are also relevant to the selection of groundwater extraction and monitoring wells and equipment, because some *in situ* groundwater extraction pumps do not function reliably under high temperature conditions. Often, water extraction pumps with the drive systems at the surface are used, including pneumatic air lift pumps, positive displacement pumps, liquid ring pumps (limited to shallower depth applications of less than 30 feet bgs) (Davis, 1998), and progressive cavity pumps (often employed to minimize emulsification of extracted contaminants). SEE has been employed under structures with no reported adverse effects. Geotechnical considerations are an integral part of the remedial design process when treating contamination through structures.

TECHNOLOGY FIELD EXPERIENCE

This report includes information on the following two full-scale technology applications employing SEE to treat chlorinated solvents:

> SEE at A.G. Communication Systems - *Northlake, Illinois*
> DUS/HPO at Savannah River Site 321-M Solvent Storage Tank Area - *Aiken, South Carolina*

Full-text case studies for these projects are included in Appendix A. The case studies include information about observed performance and cost of SEE. Table 3-1 summarizes the cost data that was available for these two SEE applications.

Table 3-1: Cost Data Reported for Selected SEE Applications

Application	Total Cost	Total Cost Components	Unit Costs
A.G. Communication Systems, *Northlake, IL*	$4,900,000	Pilot testing, design, installation, O&M, negotiation support	$15 per cubic yard treated $140 per pound of contaminant removed
Savannah River Site 321-M Solvent Storage Tank Area (field demonstration), *Aiken, SC*	Not provided	Not provided	$29 per cubic yard treated (not including steam generation and aboveground treatment, provided by SRS)

3.2 ELECTRICAL RESISTIVE HEATING

TECHNOLOGY DESCRIPTION AND PRINCIPLES

ERH involves the application of electrical current through the subsurface, resulting in the generation of heat. ERH uses the natural electrical resistance within the subsurface where energy is dissipated through ohmic, or resistive, losses. This manner of *in situ* heating allows energy to be focused into a specific source zone. When the subsurface temperature is increased to the boiling point of the pore water or the saturated media in the treatment zone, steam is generated. The steam strips contaminants from the soils and enables them to be extracted from the subsurface. In addition, contaminants are directly volatilized from unsaturated soil.

The necessary power input to the subsurface is inversely proportional to the soil resistivity and directly proportional to the square of the applied voltage, based on the following equation derived from Ohm's Law.

$$Power = (Voltage)^2/Resistance$$

The resistance of a subsurface matrix is largely determined by its water content, concentration of dissolved salts or ionic content in the water, and ion exchange capacity of the soil itself (Kendall and Wolf 1999). The organic carbon content of soils also affects resistivity, but has a greater effect on the required treatment time as a result of the stronger partitioning of organic contaminants, such as chlorinated solvents, to the soils. In addition, the resistivity is a function of temperature, and as the water reaches its boiling point, the resistivity decreases with increased ion mobility. Soil resistance can be measured in the field or estimated from characterization data for soils and groundwater. The total resistance of an ERH system is determined based on the resistivity of the soil and the geometry of the electrode system. For matrices with a total resistance of 10 to a few hundred ohms, and applied voltages range from 100 to 1,500 volts, required power inputs will be on the order of tens or hundreds of kilowatts.

APPLICABILITY CONSIDERATIONS

ERH is particularly suited to the treatment of lower permeability strata and to DNAPLs that have become consolidated within lower permeability zones with higher organic content. In some cases, ERH can be combined with SEE (as in DUS) in aquifers interbedded with low permeable lenses or in situations where a lower aquitard has been impregnated with DNAPLs. ERH is used to treat the lower permeability zones, which the steam vapors cannot penetrate rapidly (Beyke 1998).

ENGINEERING CONSIDERATIONS

An ERH system consists of subsurface electrodes to direct current through the subsurface, and a vapor extraction system to capture the volatilized water and contaminants. In some cases, groundwater extraction is also used to lower the water table within the treatment zone during initial stages of treatment (prior to temperatures exceeding the boiling point of subsurface water) or to provide hydraulic control. To improve the uniformity of heating and reduce local current densities at the electrodes, most configurations employ multiple phased arrays of electrodes with a central ground electrode that typically doubles as a vapor extraction well. This method increases the available current pathways as electrodes are phased so that current can flow from one electrode to any other electrode or to the neutral ground. Larger areas are remediated by installing adjacent arrays so that the heated zones overlap (Beyke 1998). Figure 3-2 shows a general schematic of an ERH system using six electrodes surrounding a combination ground electrode/vapor extraction well.

Electrodes can be installed using several different drilling or direct-push techniques, including angled or horizontal methods. The installation method generally depends on space constraints at the surface or on the geology. Because the current density is highest at the electrodes, the applied voltage is dependent on the contact resistance. In vadose zone applications or once full steaming conditions are achieved in aquifer applications, water is typically injected to maintain good electrical contact and prevent excessive drying or voltage breakdown at the electrodes. This injection may be augmented with low concentrations of salt added to the water and/or the use of highly conductive packing (for example, carbon/graphite or steel shot) around the electrodes. Additional equipment is required for water (or brine) injection at the electrodes.

Figure 3-2: Typical ERH System Configuration
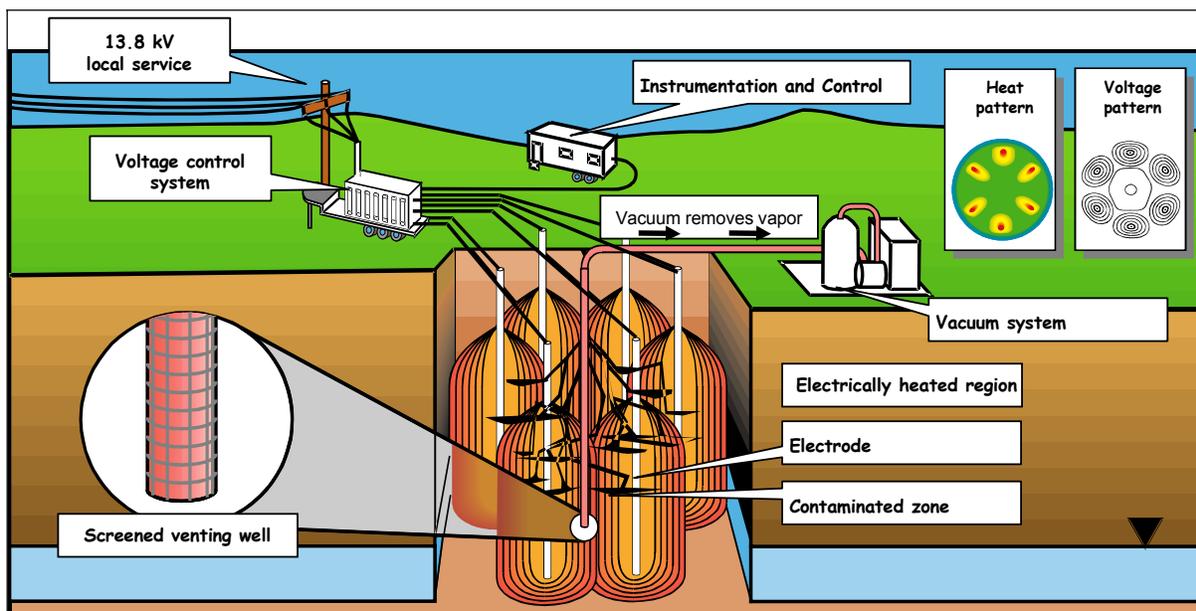
Source: Pope and Nienkerk 2002

Surface equipment varies depending on the specific method, site, and scale. Typically, utility (60 Hertz) electrical power is used with power conversion equipment to regulate voltage or to convert the phase characteristics of the power. Depending on soil properties, single arrays up to 100 feet in diameter (typical arrays are 30 to 40 feet in diameter) can be operated. Multi-phase heating requires additional space for a transformer (typically mounted on a standard tractor trailer), which can also be designed to include voltage controls (Beyke 1998).

Vapor extraction systems are typically used to remove volatilized water and contaminants from the subsurface. The vapor extraction and aboveground treatment equipment is similar to that used with SEE, as described in Section 3.1. Higher temperature conditions should be considered when designing extraction and monitoring wells and associated equipment for the treatment area. Existing equipment may require modifications or replacement to accommodate these elevated temperature conditions. Furthermore, due to safety concerns with regard to high voltage potentials in surface work areas and/or the potential for buried conductors to carry high voltage potentials out of the immediate remediation area, care must be taken in applying the technology in heavily developed or industrial areas. Typically, all conductive (metallic) equipment, such as well components, process piping, monitoring ports, and electric equipment, are bonded together with a copper conductor, which is connected to an earth ground.

ERH practitioners use Power Control Units (PCUs) for electrical power delivery from the municipal power line to the subsurface electrodes installed in the remediation area. These PCUs include isolation transformers that prevent electrical current from traveling outside of the remediation area and offsite to above ground structures. Common electrical grounding techniques developed and used by the electrical utility industry are used on ERH projects to further enhance and ensure safe working conditions during ERH operations. The standard for safe working electrical voltages adopted by the Occupational Safety and Health Administration

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(OSHA) is less than 50 volts at the surface of a working site. Most ERH practitioners have adopted safety policies that provide a significant safety margin by ensuring that less than 15 volts are present at the surface during the operations of ERH remediation systems. This is accomplished by implementing a combination of engineering controls and standard grounding techniques. In addition, standard practice during the operation of ERH systems involves ongoing monitoring of surface voltages.

TECHNOLOGY FIELD EXPERIENCE

This report includes information on the following four full-scale technology applications employing ERH to treat chlorinated solvents:

ERH at Former Manufacturing Facility - *Skokie, Illinois*
ERH at Poleline Road Disposal Area, Area 3 - *Fort Richardson, Alaska*
ERH at ICN Pharmaceutical Site - *Portland, Oregon*
ERH at Avery Dennison Site - *Waukegan-Gurnee Industrial Park, Illinois*

Full-text case studies for these projects are included in Appendix A. The case studies include information about observed performance and cost of ERH. Table 3-2 summarizes the cost data that was available for these four ERH applications.

Table 3-2: Cost Data Reported for Selected ERH Technology Applications

Application	Total Cost	Total Cost Components	Unit Costs
Former Manufacturing Facility, *Skokie, IL*	Not provided	ERH power and electrodes; soil vapor extraction and condensate treatment; project permitting; preparation of work plans; electrical use; waste disposal; interim sampling; progress reporting (electrical usage cost was 20% of total cost	$32 per cubic yard treated (air emission controls not required or included in cost; estimated to add approximately $9 per cubic yard)
Poleline Road Disposal Area, Area 3 (field demonstration), *Fort Richardson, AK*	$968,000	Total cost includes on-site power generation	$189 - $288 per cubic yard treated
ICN Pharmaceutical Site, *Portland, OR*	$2,206,000	Capital ($1,291,000) and O&M ($915,000)	$73 per cubic yard treated

3.3 THERMAL CONDUCTIVE HEATING

TECHNOLOGY DESCRIPTION AND PRINCIPLES

Thermal conductive heating involves simultaneous application of heat and vacuum to subsurface soils with an array of vertical heater/vacuum wells or, much less commonly, with surface blanket heaters and a vacuum insulated shroud. In both of these configurations, heat originates from a

heating element and is transferred to the subsurface largely via thermal conduction and radiant heat transport, which dominates near the heat sources (Stegemeier 1998). There is also a contribution through convective heat transfer that occurs during the formation of steam from pore water. Because this technology can achieve elevated soil temperatures (in excess of 500°C), a significant portion (reported up to 99 percent at some sites) of organic contaminants either oxidize (if sufficient air is present) or pyrolize once high soil temperatures are achieved. Therefore, this technology is also considered to be an *in situ* destruction method (Baker and Kuhlman 2002).

Because soil is not an efficient conductor of heat (as compared to other substances like metals), high temperatures heat sources are required to effectively conduct energy into soils where contaminants and water can be destroyed or vaporized *in situ* and extracted and treated at the surface (Vinegar 1998). Soil heat conductivities are all fairly similar in magnitude, and the movement of heat away from the heaters, whether vertically or radially outward, is uniform. However, because the driving force for heat migration is the temperature gradient, soils initially are not heated to the same temperature within the treatment area resulting in a temperature profile that decreases radially from the source. Over time, superposition of heat from adjacent heaters tends to even out these differences. Other factors, including advective heat transport, the anisotropic nature (variable thermal conductivity depending on flow direction) of the thermal conductivity of soils, or heat loss through groundwater flow, can also affect the uniformity of subsurface heating.

Soil thermal conductivities are affected by moisture content, with conductivities diminishing as water content decreases. Therefore, once soils become dry, higher temperature gradients are needed to transfer the required energy. Other soil properties, such as permeability, carbon content, grain size, and mineralogy can vary between soils and these properties may, to a lesser extent, affect the well spacing and temperature needed for effective treatment. At high temperatures, soils can shrink and crack and become permeable, enhancing contaminant transport.

APPLICABILITY CONSIDERATIONS

Thermal conductive heating is suited to treating DNAPL source zones in most hydrogeologic conditions. Thermal conductive heating differs from other heating methods (SEE and ERH) in that it does not rely solely on steam as a heat source or water as a conductive path. It can heat soils to temperatures in excess of 500°C, making it particularly applicable to semivolatile organic contaminants (SVOCs) such as PCBs, PAHs, pesticides, and herbicides (Vinegar 1998). However, these higher boiling point compounds typically require high temperatures (for example 325°C that typically can only be achieved in the unsaturated zone. Lower boiling compounds such as chlorinated solvents can be treated with thermal conductive heating through achievement of steam distillation temperatures in the bulk of the interwell regions. Locations close to heaters may achieve temperatures well above the boiling point of water. However, boiling off of all of the soil water is not necessary. Removal rates in excess of 99 percent have been measured for thermal conductive heating of chlorinated solvents (Vinegar and others 1999).

Thermal conductive heating has been employed under structures. As noted previously, geotechnical features are considered in designing thermal conductive heating applications.

ENGINEERING CONSIDERATIONS

A thermal conductive heating system generally consists of subsurface heaters (electrical elements within a solid casing) used to generate heat and a vapor extraction system used to capture the volatilized water and contaminants. Heater-vacuum wells that combine the vapor extraction well with a heating element situated inside a non-perforated pipe running down the length of the well casing are typically used. In some cases, groundwater extraction or diversion is also used to dewater the treatment zone during initial stages of treatment (prior to temperatures exceeding the boiling point of subsurface water). Figure 3-3 shows a general cross-section of both a subsurface heater (as well as the less frequently used thermal blanket) configuration for a thermal conductive heating system, referred to as *In Situ* Thermal Desorption (ISTD™) (Baker and Kuhlman 2002).

Figure 3-3: Typical Thermal Conductive Heating System Configuration
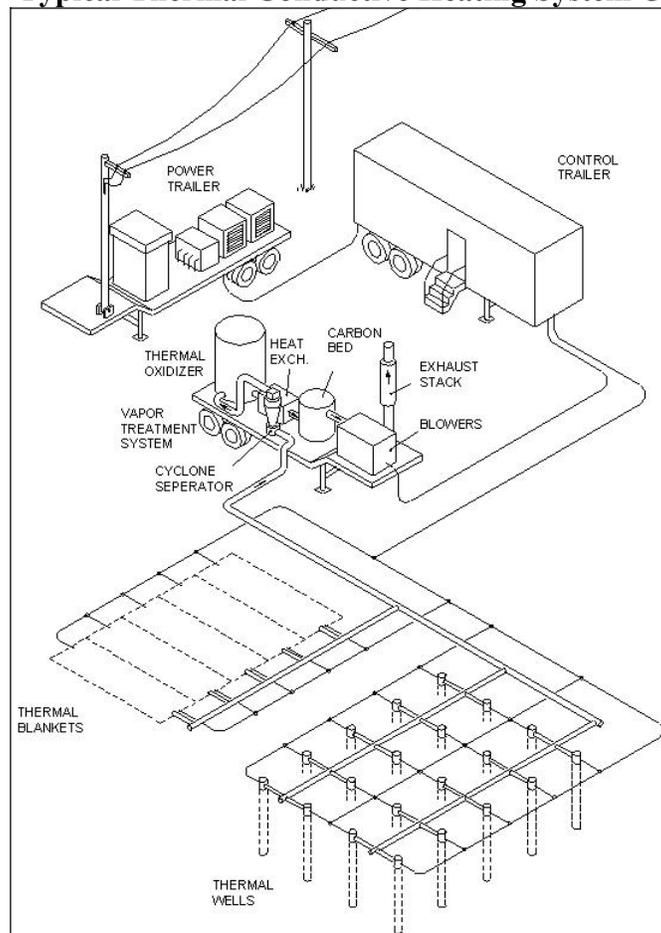
Source: Stegemeier and Vinegar 2001

The spacing of subsurface heaters depends on several factors, including the contaminant type and depth, the soil type and moisture content, the power output, the desired minimum temperature between heaters, and the time desired to achieve that temperature. A triangular pattern is generally used; this results in a hexagonal pattern for large arrays in which the centrally located subsurface heater also serves as a vacuum extraction well. If high temperatures are required, such as for treating SVOCs, spacing between heaters is typically 5 to 7 feet (Vinegar and Stegmeier 1998). If lower temperatures are required, such as for chlorinated solvents, spacing between heaters is typically 12 to 20 feet. Thermal heaters can be installed with any conventional drilling or direct-push technique. The treatment area is usually covered with an impermeable and insulating surface seal that prevents infiltration of precipitation into the treatment area, minimizes surface heat losses, and minimizes short-circuiting of the vapor extraction system.

Surface equipment includes a power transformer and a control room trailer. The control room uses data from thermocouples placed within the treatment area to adjust power outputs. Because of the high temperatures achieved in the subsurface, the surface vapor treatment and handling equipment may need to be designed to handle corrosive vapors (containing hydrochloric acid). Acid generation during thermal conductive heating is more prevalent during the treatment of highly chlorinated contaminants, such as PCBs and pesticides. However, systems designed to treat chlorinated solvents may need to be constructed or lined with corrosive resistant materials. Because the temperatures and chemical properties of the off-gas vapors may damage vacuum blowers, they are typically placed near the exhaust end of the treatment process, after the exhaust has been cooled and treated to remove corrosives. In some cases, treatment may also include a cyclone separator to handle entrained particulate produced in the subsurface (Vinegar 1998).

TECHNOLOGY FIELD EXPERIENCE

This report includes information on the following technology application employing thermal conductive heating to treat chlorinated solvents:

> Confidential Chemical Manufacturing Facility - *Portland, Indiana*

A full-text case study for this project is included in Appendix A. This case study summarizes information about observed performance of thermal conductive heating. No information about the cost of thermal conductive heating at this site was provided.

4.0 OVERALL APPLICABILITY AND ENGINEERING CONSIDERATIONS

SEE, ERH, and thermal conductive heating have been used to treat chlorinated solvent source zones after conventional remediation technologies, such as SVE or pump-and-treat, have been ineffective. For example, *in situ* thermal treatment was used at the Poleline Road Disposal Area, where a soil vapor extraction/air sparging system was ineffective, and at the Avery Dennison Site, where a similar system was ineffective, in treating the chlorinated solvent source zone. This section summarizes information on the overall applicability and engineering considerations associated with *in situ* thermal treatment. This information was derived from the treatment profiles (available at http://cluin.org/products/thermal/), as well as other information sources listed at the end of this report. This report focuses on the treatment of chlorinated solvents. The technology applications selected for inclusion in Appendices A and B treated PCA, PCE, TCA, TCE, DCE, VC, and MC, as well non-halogenated VOCs, such as benzene, toluene, ethylbenzene, and xylene (BTEX) constituents.

4.1   APPLICABILITY OF SEE, ERH, AND THERMAL CONDUCTIVE HEATING

CONTAMINANT TYPE AND EXTENT OF CONTAMINATION

The scientific basis for *in situ* thermal treatment technologies suggests that these technologies can be used to treat any contaminant that can be volatilized. *In situ* thermal treatment technologies have proven to be effective in remediating chlorinated solvents, as well as other VOCs and SVOCs within a source zone under a wide range of site conditions. Contaminants may include VOCs, such as chlorinated solvents; SVOCs, such as fuels, oils, PCBs, and pesticides; and even volatile metals (using thermal conductive heating), such as mercury (Davis 1997).

In situ thermal treatment typically is used to target the source zone (or hot spots) within the saturated or unsaturated zones rather than to address larger, less contaminated areas of soil or groundwater plumes. The technology applications identified in this report have treated quantities of soil and groundwater ranging from 5,000 to 300,000 cubic yards.

In situ thermal treatment can address contaminated source zones in the following areas:

> Beneath structures or active areas
> Beneath the water table
> Too deep to be excavated

The maximum depth of *in situ* thermal treatment is only limited by the ability to deliver a heat source (steam, electricity, or conductive heater) to a desired depth. The depths of the technology applications included in this report ranged from 11 to 160 feet bgs.

SITE HYDROGEOLOGY

In situ thermal treatment has been used to treat contamination in a wide range of hydrogeologic conditions. Applications included in this report have been performed in site hydrogeologies such as high permeability sand formations, low permeability silty-clay layers, and heterogeneous matrices. As discussed below, certain methods of *in situ* thermal treatment are more suited to high versus low permeability or saturated versus unsaturated conditions.

4.2   ENGINEERING CONSIDERATIONS FOR SEE, ERH, AND THERMAL CONDUCTIVE HEATING

Several physical and chemical soil properties, such as heat capacity, soil type, and degree of saturation, affect energy requirements. For saturated soils (unconsolidated sands and silts), about 200 kilowatt hours per cubic meter is usually required. The largest contribution to the energy requirement (approximately two-thirds of the energy for saturated soils) is the heat capacity (latent heat of vaporization) of water. Because of their azeotropic characteristics, DNAPL-water mixtures can boil at temperatures below $100^{o}C$. Heat losses to soil outside of the treatment area, through the surface, or with the extracted vapors also contribute to the overall energy requirement. Groundwater flowing into the treatment zone can also significantly affect the energy requirements because of its "heat sink" effect.

In situ thermal heating technologies enhance contaminant transport. Design of thermal treatment systems are based on the horizontal and vertical extent of contamination, as well as the types of soil and lithology. *In situ* thermal treatment can extract contaminants from throughout a heterogeneous subsurface.

When applied to a highly concentrated plume or source area, *in situ* thermal heating typically employs a subsurface layout configuration involving placement of multiple arrays of "heat sources" (steam injectors, electrodes, or conductors). Where appropriate, systems have been designed with heat sources located below the contaminated zone that induce the rising of heated (and thus lower density) contaminants in the vapor phase through the contaminated zone (referred to as the "hot floor" effect). In addition, some system configurations may incorporate the injection of a noncondensable gas, such as air, to aid in the upward mobilization of contaminants. Vapor extraction is accomplished with wells within and/or above the contaminated area. In some cases, the extraction wells have been placed both within and around the target treatment area to minimize migration out of the treatment zone area.

Aboveground water and vapor treatment systems associated with *in situ* thermal treatment systems generally are constructed to withstand the elevated temperatures and extraction rates associated with these processes. Most *in situ* thermal treatment applications for chlorinated solvents rely on vapor extraction as the primary contaminant removal mechanism, coupled with liquid extraction to remove condensate and maintain hydraulic control. In some cases, additional condensation potential is added to the aboveground treatment process to accommodate extracted steam. The condenser module sometimes requires an organic/water separator to handle NAPL condensed from the extracted vapor stream. Off-gas treatment systems are sized to treat higher and often highly varying concentrations and the vacuum extraction pump(s) are sized to handle

the higher vapor flow. Consideration is given to induced fluid movement during thermal applications (for example, rising hot vapors, thermal convection in groundwater, etc.) and this movement may need to be taken into account when deciding where to locate extraction wells and screens (Webb 1994).

The U.S. Army Corps of Engineers is in the process of preparing a design manual about the use of *in situ* thermal treatment.

5.0   INFORMATION SOURCES

Baker, R.S., and Bierschenk, J.M. "In Situ Thermal Destruction Makes Stringent Soil and Sediment Cleanup Goals Attainable." *Proceedings of the Fourth Tri-Service Environmental Technology Symposium.* San Diego, CA, 18-20. June 2001.

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

Benson, L.A. The Determining Role of Abiotic CAH Fate Processes: Possible Impacts on Your Remedy Plans and Implementation Efforts. Presentation at 2003 AFCEE Technology Transfer Workshop. February 26, 2003.

Beyke, G. 6-Phase Electrical Heating. Paper presented at the In Situ Thermal Treatment Conference, U.S. EPA TIO. Atlanta, Georgia. December 1998.

Davis, E.L. *How Heat Can Enhance In Situ Soil and Aquifer Remediation: Important Chemical Properties and Guidance On Choosing The Appropriate Technique*. EPA/540/S-97/502. April 1997.

Davis, E.L. *Steam Injection For Soil and Aquifer Remediation*. EPA/540/S-97/505. January 1998.

Davis, E.L. Comments on *In Situ* Thermal Treatment Document. E-mail to James Cummings, EPA. March 5, 2004

Earth Tech and SteamTech. *Site 61 Treatability Study Report: Steam Injection, Northwest Main Base OU 8, Edwards Air Force Base, California*. Draft report prepared for US Air Force and AFCEE. March 2003.

EPA. *Superfund Chemical Data Matrix*. EPA 540/R-96/028. June 1996

EPA. *Analysis of Selected Enhancements for Soil Vapor Extraction*. EPA/542/R-97/007. September 1997.

EPA. *Engineered Approaches to In Situ Bioremediation of Chlorinated Solvents: Fundamentals and Field Applications*. EPA 542-R-00-008. July 2000.

EPA. *Treatment Technologies for Site Cleanup: Annual Status Report (Tenth Edition)*. EPA 542-R-01-004. 2001a.

EPA. *Groundwater Pump and Treat Systems: Summary of Selected Cost and Performance Information at Superfund-financed Sites*. EPA 542-F-01-025. December 2001b.

EPA. *Thermal Treatment Profiles*. 2004. http://cluin.org/products/thermal/

Fan, Y.H. and Udell, K.S. An Analysis of the Vaporization of Volatile Organic Contaminants from Porous Media by Conductive Heating. Proceedings of the ASME Heat Transfer and Fluids Engineering Divisions, HTD-32, 715-721. 1995.

Fares, A., B. Kindt, R. Lapuma, and G. P. Perram. Desorption kinetics of trichloroethylene from powdered soils. *Environ. Sci. Technol.* 29(6):1564-1568. 1995.

Finsterle, Stefan. "Demonstration of Optimization Techniques for Groundwater Plume Remediation" LBNL-46746. September 2000.

Gmehling and Onken. *Vapor-Liquid Equilibrium Data Collection.* DECHEMA Chemistry Data Series, Colume 1 (Parts 1-10). Frankfort. 1977.

Hansen, K.S., D.M. Conley, H.J. Vinegar, J.M. Coles, J.L. Menotti, and G.L. Stegemeier. "In Situ Thermal Desorption of Coal Tar." *Proceedings of the Institute of Gas Technology/Gas Research Institute International Symposium on Environmental Biotechnologies and Site Remediation Technologies*. Orlando, FL, December 7-9, 1998.

Heine, Kevin S., Steckler, David. *Augmenting In-Situ Remediation by Soil Vapor Extraction with Six-Phase Soil Heating*. 1999.

Heron, G.; Christensen, T.H.; Enfield, C.G. "Henry's Law Constant for Trichloroethylene between 10 and 95 C". *Environmental Science and Technology*. 32 (10), 1433-1437. 1998a.

Heron, G.; Van Zutphen, M.; Christensen, T.H.; Enfield, C.G. "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. 1998b.

Heron, G., T. H. Christensen, and C. G. Enfield. Temperature effects on the distribution of organics in soils and groundwater and implications for thermally enhanced in-situ remediation. Submitted for publication in *Environ. Sci. Technol.* December 1996.

Huling, S.G. and J.W. Weaver. *Groundwater Issue: Dense Nonaqueous Phase Liquids*. EPA Office of Solid Waste and Emergency Response, Office of Research and Development. Washington, D.C. EPA/540/4-91-002. March 1991.

ITRC. *Dense Non-Aqueous Phase Liquids (DNAPLs): Review of Emerging Characterization and Remediation Technologies.* June 2000.

Itamura, M.T., and K.S. Udell. Experimental clean-up of a dense Nonaqueous phase liquid in the unsaturated zone of a porous medium using steam injection. *Multiphase Transport in Porous Media*. HTD-265, 57-62. 1993.

Jeffers, P.M., L.M. Ward, L.M. Woytowitch, and N.L. Wolfe. Homogeneous hydrolysis rate constant for selected chlorinated methanes, ethanes, ethenes, and propanes, *Environ. Sci. Technol. 23*, 965-969. 1989.

Kaslusky, S.F., and K.S. Udell. "A Theoretical Model of Air and Steam Co-Injection to Prevent The Downward Migration of DNAPLs During Steam-Enhanced Extraction." *J. Contaminant Hydrol.*, 55, 213-232. 2002.

Kendall, S. and J. Wolf. *Six-Phase Heating: The New Power Tool.* 1999.

Looney, B.B. and R.W. Falta, Eds. Vadose Zone Science and Technology Solution, Volume II. Battelle Press. Columbus, Ohio. 2000.

Merck & Co., Inc. *The Merck Index, An Encyclopedia of Chemicals, Drugs, and Biologicals, Eleventh Edition*. Merck & Co., Inc. Rahway, New Jersey. 1999.

Naval Facilities Engineering Service Center *Cost and Performance Report: In-Situ Thermal Desorption at The Former Mare Island Naval Shipyard.* November 1999.

Newmark, R.L. and R.D. Aines. Summary of the LLNL Gasoline Spill Demonstration-Dynamic Underground Stripping Project, Lawrence Livermore National Laboratory, Berkeley Environmental Restoration Center. UCRL-ID-120416. April 3, 1995.

Newmark, R.L., R.D. Aines, R. Leif, and K. Knauss. Thermal Treatment: Dynamic Underground Stripping and Hydrous Pyrolysis Oxidation. Paper presented at the In Situ Thermal Treatment Conference, U.S. EPA TIO. Atlanta, Georgia. December 1998.

Perry, R.H., Green, D.W., and Maloney, J.O. *Perry's Chemical Engineers' Handbook, Sixth Edition*. McGraw-Hill. 1984.

Pope, J.L, and M.M. Nienkerk. *In Situ Remediation of Methylene Chloride in Low-Permeability Soils Using Electrical Resistive Heating.* Clayton Group. 2002.

Richardson, R.E.; James, C.A.; Bhupathiraju, V. K.; Alvarez-Cohen, L. "Microbial activity in soils following steam treatment". *Biodegradation*. 13, 285-295. 2002.

Sawyer, C.N. and others. *Chemistry for Environmental Engineering, Fourth Edition*. McGraw-Hill, Inc. New York. 1994.

Schmidt, R., J. Gudbjerg, T.O. Sonnenborg, and K.H. Jensen. "Removal of NAPLs From The Unsaturated Zone Using Steam: Prevention of Downward Migration By Injecting Mixtures of Steam and Air." *J. Contaminant Hydrol.*, 55, 233-260: 2002.

Schumacker, M.M. *Enhanced Recovery of Residual and Heavy Oils, Second Edition.* Noyes Data Corporation, Park Ridge, New Jersey. 1980.

Sims, J.L. and others. *Groundwater Issue: In-Situ Bioremediation of Contaminated Ground Water*. EPA Office of Solid Waste and Emergency Response, Office of Research and Development. Washington, D.C. EPA/540/S-92/003. February 1992.

Stegemeier, G.L. *Design Equations for In Situ Thermal Desorption.* January 19, 1998.

Stegemeier, G.L. and H.J. Vinegar. "Thermal Conduction Heating For In Situ Thermal Desorption of Soils." *Hazardous & Radioactive Waste Treatment Technologies Handbook.* Boca Raton, FL: CRC Press. 2001.

Stegemeier, G.L., and H. J. Vinegar. "Soil Remediation By Surface Heating and Vacuum Extraction." *Proceedings, 1995 SPE/EPA Exploration & Production Environmental Conference*. Houston, Texas. March 27-29, 1995.

Technical Resources. *Thermal Conduction Process Destroys PAHs in Soil.* Volume 17, Issue 7. November/December 1999.

Technical Resources. *Treating Chlorinated Solvents in Soil and Groundwater using Natural Attenuation Volume 18, Issue 2. 2000.*

TerraTherm, Inc. Website. 2003. http://www.terratherm.com/

Treybal, R. E. *Mass-Transfer Operations, 3rd. ed*. McGraw-Hill. New York. 1980.

Udell, K.S., M. Itamura, L. Alvarez-Cohen, and M. Hernandez. NAS Lemoore JP-5 cleanup demonstration. Berkeley Environmental Restoration Center, University of California, Berkeley. 1994.

Udell, K.S.; Sitar, N.; Hunt, J.R.; Stewart, L.D. *Process for In Situ Decontamination of Subsurface Soil and Groundwater*. United States Patent # 5,018,576. 1991.

U.S. Army Corps of Engineers. "Technical Guidance for the Hazardous and Toxic Waste Treatment and Cleanup Activities." *U.S. Army Corps of Engineers Engineer Manual EM 1110-1-5-230*. Washington, DC: U.S. Army Corps of Engineers. April 1994.

Vinegar, H. and Stegemeier, G. In Situ Thermal Desorption. Paper presented at the In Situ Thermal Treatment Conference, U.S. EPA TIO. Atlanta, Georgia. December 1998.

Vinegar, H.J., G.L. Stegemeier, F.G. Carl, J.D. Stevenson, and R.J. Dudley. "In Situ Thermal Desorption of Soils Impacted with Chlorinated Solvents." *Proceedings of the Annual Meetings of the Air and Waste Management Association*, Paper No. 99-450. 1999

Webb, S.W. TOUGH2 Simulations of the TEVES Project Including the Behavior of a Single-Component NAPL; SAND94-1639/UC-2010. Sandia National Laboratories, Albuquerque, NM, prepared for the U.S. Dept. of Energy, under Contract DE-AC04-94AL85000. 1994.

Wu, C.H. A critical review of steamflood mechanisms. *Society of Petroleum Engineers Paper SPE 6550.* 1977.

APPENDIX A

IN SITU THERMAL TREATMENT SUMMARIES

Dynamic Underground Stripping-Hydrous Pyrolysis Oxidation at the Savannah River Site 321-M Solvent Storage Tank Area, Aiken, South Carolina

Steam Enhanced Extraction at the A.G. Communication Systems Site, Northlake, Illinois

Electrical Resistive Heating at the Former Manufacturing Facility, Skokie, Illinois

Electrical Resistive Heating at the Poleline Road Disposal Area, Arrays 4, 5, and 6, Fort Richardson, Alaska

Electrical Resistive Heating at the ICN Pharmaceutical Site, Portland, Oregon

Electrical Resistive Heating at the Avery Dennison Site, Waukegan, Illinois

In Situ Conductive Heating at the Confidential Chemical Manufacturing Facility, Portland, Indiana

APPENDIX A

IN SITU THERMAL TREATMENT SUMMARIES

Table A-1. Information from the Seven *In Situ* Thermal Treatment Summaries

Application	Application Dates	Quantity Treated	Injection/Extraction Wells	Temperature	Aboveground Treatment
STEAM ENHANCED EXTRACTION APPLICATIONS					
Savannah River Site 321-M Solvent Storage Tank Area (field demonstration), *Aiken, SC*	June 2000 to Sept. 2001	52,000 cy soil/ groundwater (200 ft^2 by 160 ft deep)	9 injection wells (three clusters) 3 vapor extraction wells on perimeter 1 combination groundwater/vapor extraction well in center	87EC (target)	Condenser, phase separation, air stripper, vapor treatment
A.G. Communication Systems, *Northlake, IL*	Sept. 1994 to Dec. 2001	330,000 cy soil/ groundwater (180,000 ft^2 by 50 ft deep)	65 injection wells (two depth zones) 186 vapor extraction wells 2 groundwater extraction wells 80 dual-phase extraction wells	29-60EC (soil) 20-74EC (groundwater)	Condenser, phase separation, air stripper, carbon adsorption
ELECTRICAL RESISTIVE HEATING APPLICATIONS					
Former Manufacturing Facility, *Skokie, IL*	June 1998 to Nov. 1998 and Dec. 1998 to April 1999	23,000 cy soil initially (26,000 ft^2 by 24 ft deep); 11,500 cy soil additional	107 electrodes initially (78 additional electrodes added) 37 SVE wells (5 ft bgs)	1,250 kW 100EC	Condenser, phase separation, air stripper
Poleline Road Disposal Area, Area 3 (field demonstration), *Fort Richardson, AK*	July 1999 to Oct. 1999	13,000 tons (16,800 cy) soil (5,500 ft^2 by 35 ft deep)	21 electrodes in 3 arrays (38 ft bgs) 9 SVE wells	700-800 kW 44-100EC	Information not available
ICN Pharmaceutical Site, *Portland, OR*	May 2000 to Dec. 2001	30,000 cy (39,000 tons) soil (18,400 ft^2 from 20 to 60 ft deep)	60 electrodes in 3 zones initially (80 additional electrodes added) 53 SVE wells (25 to 35 ft bgs)	950 kW	Condenser, phase separation, carbon adsorption, oxidation (KPO$_4$)
Avery Dennison Site, *Waukegan, IL*	Dec. 1999 to Nov. 2000	16,000 cy soil (to 24 ft bgs)	95 electrodes 34 SVE wells	342 kW 65-80EC	Information not available
THERMAL CONDUCTIVE HEATING APPLICATIONS					
Confidential Chemical Manufacturing Facility, *Portland, IN*	July 1997 to Dec. 1997	5,200 cy soil in 2 areas (7,500 ft^2 by 18 ft deep and 600 ft^2 by 11 ft deep)	148 heater vacuum wells	1 - 1.5 MW 760 - 870EC (heater) 100 - 260EF (soil)	Thermal oxidation, carbon adsorption

COST AND PERFORMANCE REPORT

Dynamic Underground Stripping-Hydrous Pyrolysis Oxidation
at the Savannah River Site 321-M Solvent Storage Tank Area
Aiken, South Carolina

June 2003

IDENTIFYING INFORMATION

Site Name: Savannah River Site 321-M Solvent Storage Tank Area
Location: Aiken, SC
Regulatory Context: RCRA
Technology: Dynamic Underground Stripping-Hydrous Pyrolysis Oxidation (DUS/HPO)
Scale: Field demonstration

TECHNOLOGY APPLICATION

Period of Operation: September 9, 2000 to September 28, 2001

Type/Quantity of Material Treated during Application: Source zone - Total volume of 52,000 cubic yards based on a surface area of 100 ft by 100 ft and a depth of 160 ft

BACKGROUND [1,2,3]

The M-Area Settling Basin Hazardous Waste Management Facility (HWMF) includes the M-Area Settling Basin and associated areas of the U.S. DOE Savannah River Site (SRS), in Aiken, S.C. The HWMF received effluent from various processes at SRS containing high concentrations of tetrachloroethene (PCE), trichloroethene (TCE), and other volatile organic compounds (VOCs). VOC contamination occurred as a result of breaks in the former process sewer line and disposal practices associated with the settling basin. An estimated 3.5 million pounds of residual solvents were released to the sewer leading to the M-Area settling basin and associated outfall. An initial site characterization, conducted in the early 1990's, identified high levels of chlorinated solvents (0.2-0.3% by weight) indicating the presence of DNAPL contamination. Additional site characterization using surface geophysics was performed to further delineate DNAPL contamination and determine chemical composition. Results estimated the composition of the DNAPL as 90% PCE and 10% TCE. Prior to treatment, the total contaminant mass was estimated at 26,800 lbs (total contaminants, not only DNAPLs).

The Solvent Storage Tank Area (SSTA) is located west of Building 321M in the M-Area of SRS. Building 321M operated as a target fabrication facility, primarily housing metallurgical and mechanical processes such as casting, extrusion, hot-die-sizing and welding. Cleaning solvents and caustic solutions were used to prepare the materials for fabrication. The SSTA consisted of a 17,000 gallon storage tank with associated piping and equipment. The tank, located adjacent to a railroad car transfer facility, was used to store chlorinated solvents including PCE and TCE, beginning in 1957. Numerous undocumented spills and leaks were suspected to have occurred in this area. One reported spill released an estimated 1,200 gallons of PCE to the ground. The tanks, part of the railroad track and associated above-ground equipment were removed in the fall of 1997. The concrete pad and two sumps were left in place. The SSTA contains three M-Area SVE wells and the groundwater is maintained under hydraulic control by two M-Area recovery wells.

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MATRIX DESCRIPTION

MATRIX AND CONTAMINANT IDENTIFICATION

Type of Media Treated with Technology System: Source zone (saturated and unsaturated)

Primary Contaminant Groups: Chlorinated Solvents (PCE and TCE)

SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [1,2]

The surficial geology of the SRS consists of Atlantic Coastal Deposits, which is primarily composed of both unconsolidated and consolidated strata, ranging from Late Cretaceous to Miocene in age. Coastal Plain Sediments are comprised of interbedded sand, muddy sand, and mud (clay and silt).

The hydrogeology of the area includes three aquifers of the Floridian-Midville aquifer system which includes in ascending order the McQueen Branch aquifer, the Crouch Branch aquifer, and the Steed Pond aquifer. The Crouch Pond aquifer is the principle water producing aquifer. The vadose zone beneath the

M-Area contains several clay layers interspersed with more transmissive, sandier intervals. A "Green Clay" horizon is located at approximately 160 - 165 ft bgs.

The high concentrations of contaminants suggested the presence of DNAPL in silts and clays in the vadose zone above the water table at depths ranging from 20 to 35 feet bgs, and below the water table in the form of disconnected ganglia (rather than a large, solvent saturated layer).

Table 1 lists the matrix characteristics affecting treatment cost or performance for this application.

Table 1. Matrix Characteristics [1,2]

Parameter	Value
Soil Classification	Interbedded sands and clays overlying a clayey aquitard
Depth to Groundwater	143 ft
Porosity	0.3
Presence of NAPLs	Contaminant concentrations suggested the presence of DNAPL
Hydraulic Conductivity	0.4 ft/min - average value from pump tests conducted on 5/4/2000

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY

Dynamic Underground Stripping and Hydrous Pyrolysis Oxidation (DUS/HPO)

TREATMENT SYSTEM DESCRIPTION AND OPERATION [1,2,3]

Figure 1 shows a plan view of the DUS/HPO system used at the SSTA. Three steam-injection well clusters were installed around the perimeter of the 100 ft by 100 ft treatment area (at the northwest corner, northeast corner, and southern boundary). Each well cluster consisted of three injection wells with screen intervals at 50-70 ft bgs, 110-130 ft bgs , and 150-160 ft bgs. One dual-phase groundwater and vapor extraction well (DUS-10) was installed in the center of the target zone with a screen interval from 20-160 ft and used to extract both groundwater and vapor from the subsurface. Groundwater was extracted from the well using a high-temperature electric-submersible pump, located 25 to 35 ft below the static groundwater elevation (143 ft bgs). The extracted groundwater was collected in a tank, with final discharge through an air stripper.

Vapor extraction was performed using DUS-10 and three existing vadose zone soil vapor extraction wells (MVE-1, -2, and -3), located along the perimeter of the target zone. The steam for the system was supplied from other industrial operations at SRS. Steam pressure was reduced to 100 psi prior to entering the DUS/HPO system.

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Figure 1. Plan View of DUS/HPO System [1]

SOLVENT STORAGE TANK AREA PLAN VIEW
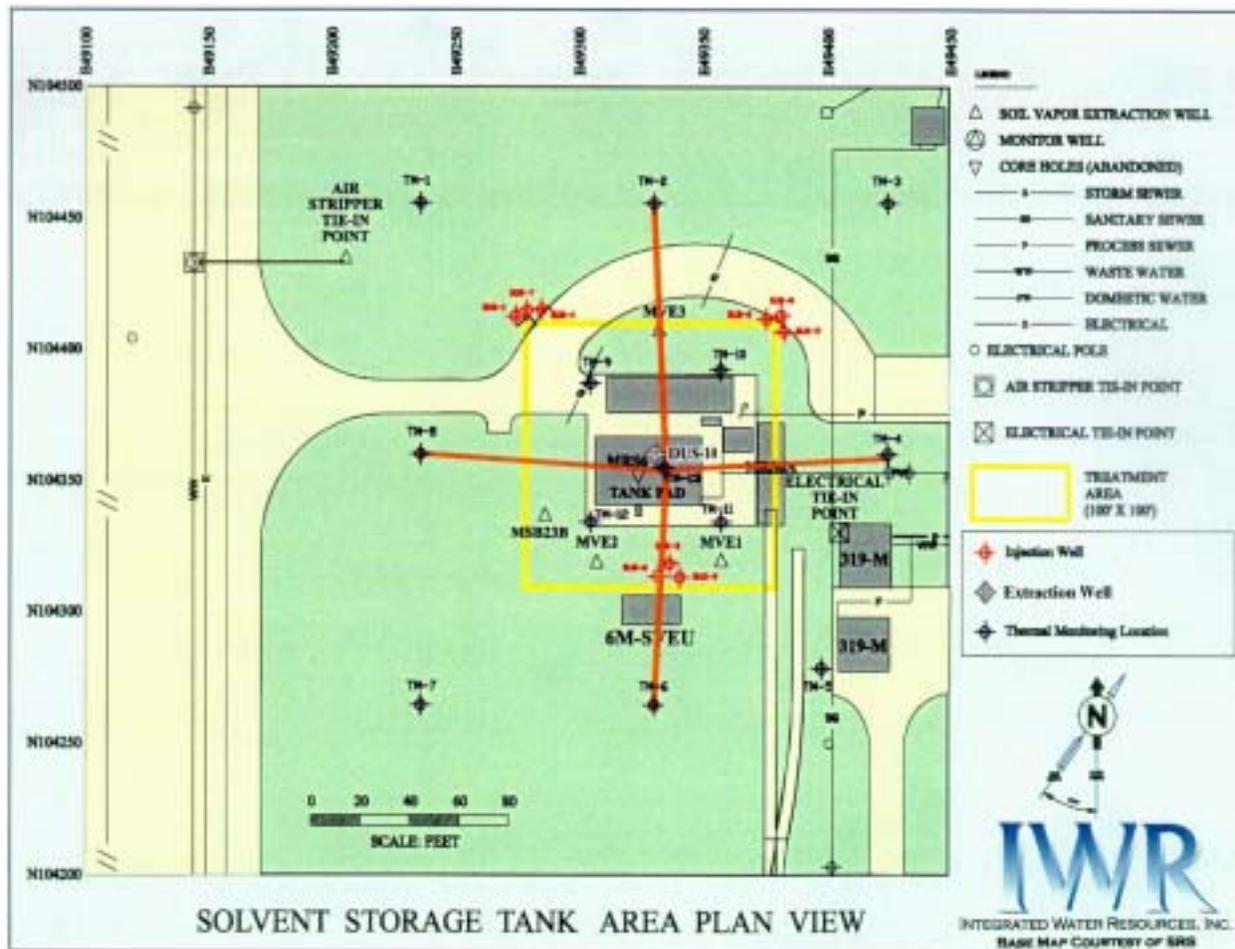
SRS's 6M Soil Vapor Extraction Unit (6M-SVEU) was used to extract vapors from wells DUS-10 and MVE-1, 2, and 3. The vapor flow input of the unit was about 500 scfm. The hot extracted vapors were cooled through a heat exchanger, and condensed liquids were separated from vapors in a knockout tank. The condensate was routed through a DNAPL-water separator (DWS), which separated DNAPL droplets for collection and removal. Figure 2 shows a process flow diagram of the DUS/HPO system, with vapor and wastewater treatment. The 6M-SVEU was operated to keep levels of contaminants in the vapor discharge was below air emissions limits.

Beginning in December of 2000, air was injected into the deep saturated zone injection wells to enhance the HPO process. Air injection was implemented over one 10-hour period at a rate of approximately 5 scfm. According to the vendor, air injection occurred whenever deep injection of steam occurred. During the later stages of the effort, this injection into the deep wells was implemented intermittently during periods of steam injection into the shallow wells.

Initial steam injection to the deep vadose zone was at a maximum design pressure of 60 psig and a temperature of 152°C; and 40 psig and 143°C for the intermediate vadose zone. In addition, initial heating was performed in the saturated area to set up a "hot plate" at the base of the treatment area, and followed by steam injection heating in the vadose zone. According to the vendor, this approach helped to drive contaminants towards the recovery system while limiting potential for dispersal in the subsurface. Approximately 50% - 90% dilution air was used prior to contaminant entry into the SVE unit (6M) so that vapor emissions remained within permitted discharge limits.

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Figure 2. Simplified Process Flow Diagram [1]
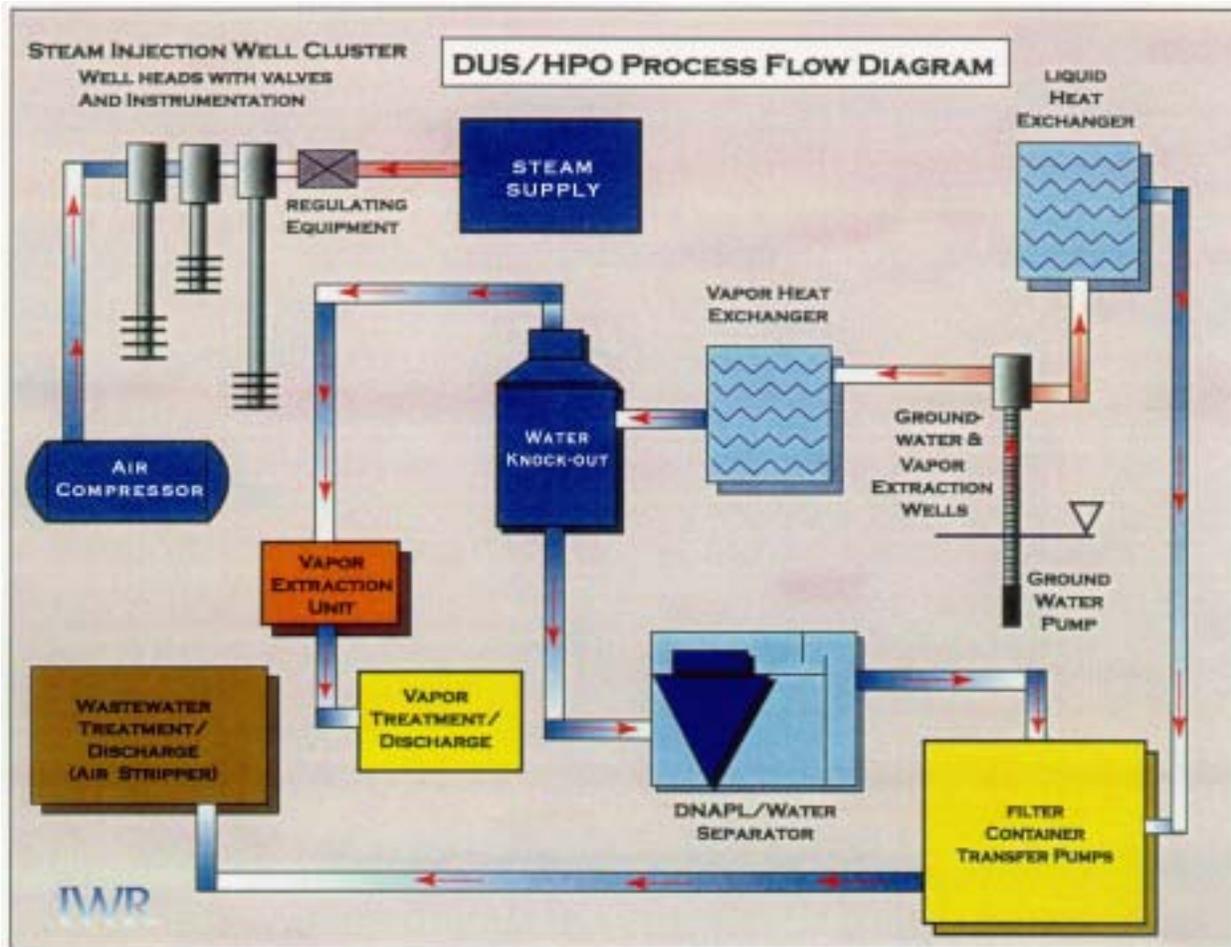
Thermal monitoring of the subsurface conditions included temperature profiles from 14 downhole thermocouple arrays and electrical resistance tomography (ERT) images which displayed changes in subsurface resistance caused by differences in temperature. For ERT monitoring, 6 electrode strands were placed through narrow boreholes: 4 on the perimeter of the treatment zone, one in the middle, and one in an abandoned groundwater monitoring well. Each borehole with an electrode also housed a thermocouple string. Eight additional thermocouple strings were installed: four outside and four inside the target area. In addition, one thermocouple was installed at the base of each steam injection well and at the base of the main vapor extraction well.   Thermocouples ranged in depth from 3 ft bgs to 163 ft bgs, and were vertically spaced 6 ft apart on each thermocouple strand.

For the pilot demonstration, data collected included: steam flow; steam injection at each well-head; vapor extraction information from the SVE unit, including concentration data; extracted vapor temperature and pressure collected at the wellhead; cooling system data; and wastewater stream data (total flow and temperature). In addition, regular vapor (Tedlar bag) and water samples were collected to track system performance. Groundwater was heated to a temperature of approximately 100 $^{\circ}$C, while the source zone reached a temperature of approximately 87°C. Table 2 provides a summary of operational data for the DUS/HPO pilot demonstration.

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Table 2. Operational Data from SRS DUS/HPO Pilot Demonstration [1,2]

Parameter	Value
Source zone temperature	87 °C
Operating pressure/vacuum	5.1 in of Hg
Weight of injected steam	45,400,000 lbs
Heat content of injected steam	4.5×10^{10} BTUs
Total time for steam injection	3,226 hours (134 days)
Total time for effluent treatment system operation	7,020 hours (293 days)
No. of pore volumes extracted	420
Total volume of extracted air	176,000,000 ft^3
Volumetric equivalent flow rate of extracted steam	698 scfm
Average non-condensible extraction rate	300 scfm

TIMELINE [1,2]

- September 9, 2000   Demonstration system operations began
- December 2000   Air injection for enhancing HPO began
- March 8, 2001   Performance objective met; operational period extended to meet revised mass removal goals
- September 28, 2001   System shutdown; began cold standby
- October 2001   Began demobilization

TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [1,2]

The following performance objectives were identified for the pilot demonstration:

- Contaminants must be extracted from the target source zone
- The target source zone must be heated to the applied boiling point
- Air to support HPO must be injected into the treatment area

In addition, discharge limits were established for vapor emissions and water discharge, however specific values were not provided.

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TREATMENT PERFORMANCE [1,2]

Concentrations of PCE an TCE were provided for the four vapor extraction wells (DUS-10, MVE-1, MVE-2, and MVE-3) from August 2000 to February 2001, and for the 6M-SVEU from March 2001 to July 2002. During the first six months of operation, concentrations of PCE and TCE from the dual-phase extraction well (DUS-10), located in the target zone, increased to 4,200 ppmv and 230 ppmv, respectively, while concentrations in wells MVE 1, 2, and 3 varied. From March 2001 to July 2002, vapor contaminant concentrations for 6M-SVEU ranged from 963 to 5,733 ppmv for PCE and 25 to 99 ppmv for TCE.

Table 3. Contaminant Concentrations in Extracted Vapors August 2000 to July 2002 [1]

Date	6M-SVEU			DUS-10		MVE-1		MVE-2		MVE-3	
	PCE	TCE	Flow (scfm)	PCE	TCE	PCE	TCE	PCE	TCE	PCE	TCE
8/22/00	NR	NR	NR	160	42	NR	NR	3.6	1.1	NR	NR
9/14/00	NR	NR	474	120	19	9.5	1.9	10	7.4	160	49
10/11/00	NR	NR	468	190	48	86	15	2.3	0.76	3.5	4.3
11/15/00	NR	NR	645	160	34	57	17	3.9	1.2	22	2.1
12/13/00	NR	NR	578	570	73	17	4.1	25	3.1	120	4.4
1/30/01	NR	NR	545	1,500	120	47	36	2.2	0.52	5.6	0.93
2/14/01	NR	NR	554	4,200	230	12	3.4	310	8.7	NR	NR
3/19/01	5,733	66.3	500	NR	NR	NR	NR	NR	NR	NR	NR
4/3/01	5,320	99.1	306	NR	NR	NR	NR	NR	NR	NR	NR
5/7/01	963.1	25.2	301	NR	NR	NR	NR	NR	NR	NR	NR
6/11/01	3,471	38.7	272	NR	NR	NR	NR	NR	NR	NR	NR
7/9/02	1,256	35.9	288	NR	NR	NR	NR	NR	NR	NR	NR

NR - not reported

Figure 4 shows the cumulative removal of PCE and TCE from September 2000 through September 2001. During this time, a total of 30,000 kg of PCE and 1,000 kg of TCE were removed for a total of 31,000 kg of mass of contaminant removed.

By March 2001, over 62% of TCE mass had been removed compared to 26% of PCE mass, attributed to the lower boiling point of TCE. According to the vendor, after March 2001, concentrations and daily removal rates decreased more rapidly for TCE than for PCE, likely due to removing the majority of TCE during initial heating and the relatively higher rate of destruction of TCE by HPO.

Performance objectives were met on March 8, 2001, however system operation was continued until September 26, 2001 for additional contaminant mass removal. Once the treatment area had reached the target temperatures in March, only intermittent steam injection was needed to maintain steam temperatures. After March, the majority of steam injection was targeted at maintaining temperature in the shallow sections which tended to cool more rapidly. Contaminant removal patterns also indicated that much of the contaminant mass was being removed from the shallowest portion of the treatment area.

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Figure 3. Average Concentrations in Extracted Vapors for PCE and TCE [1]
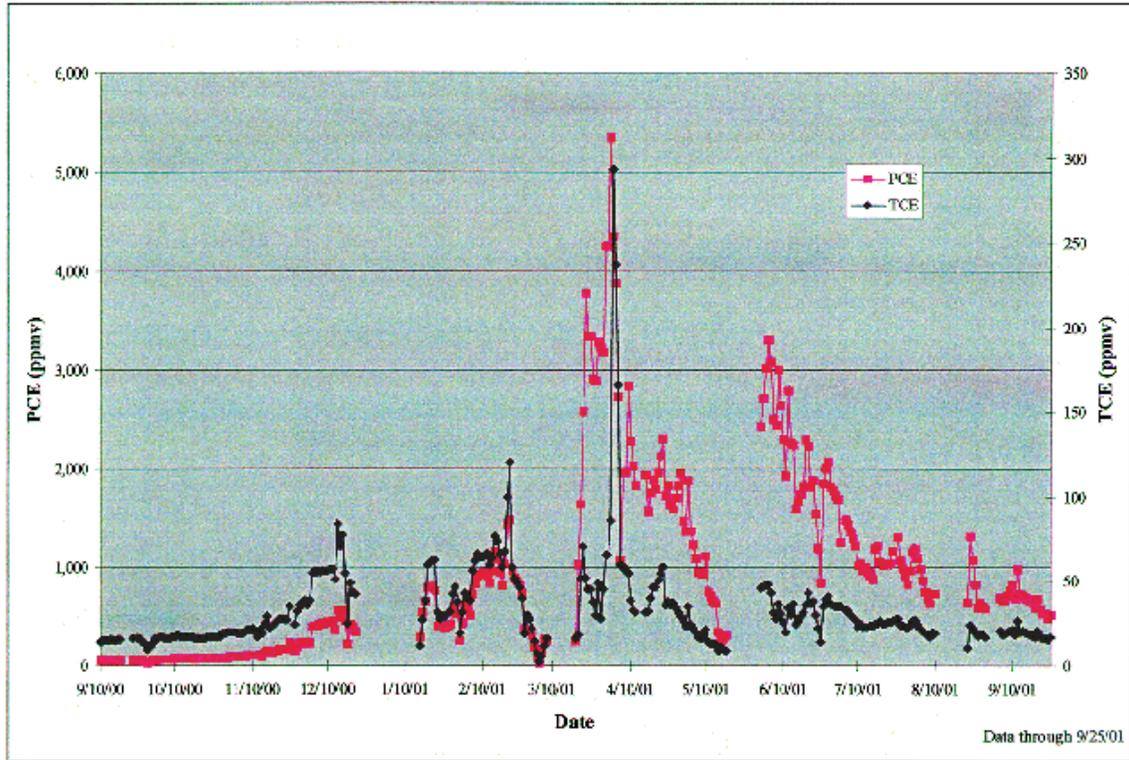
Figure 4. Cumulative Mass Removal Rates for PCE and TCE [1]

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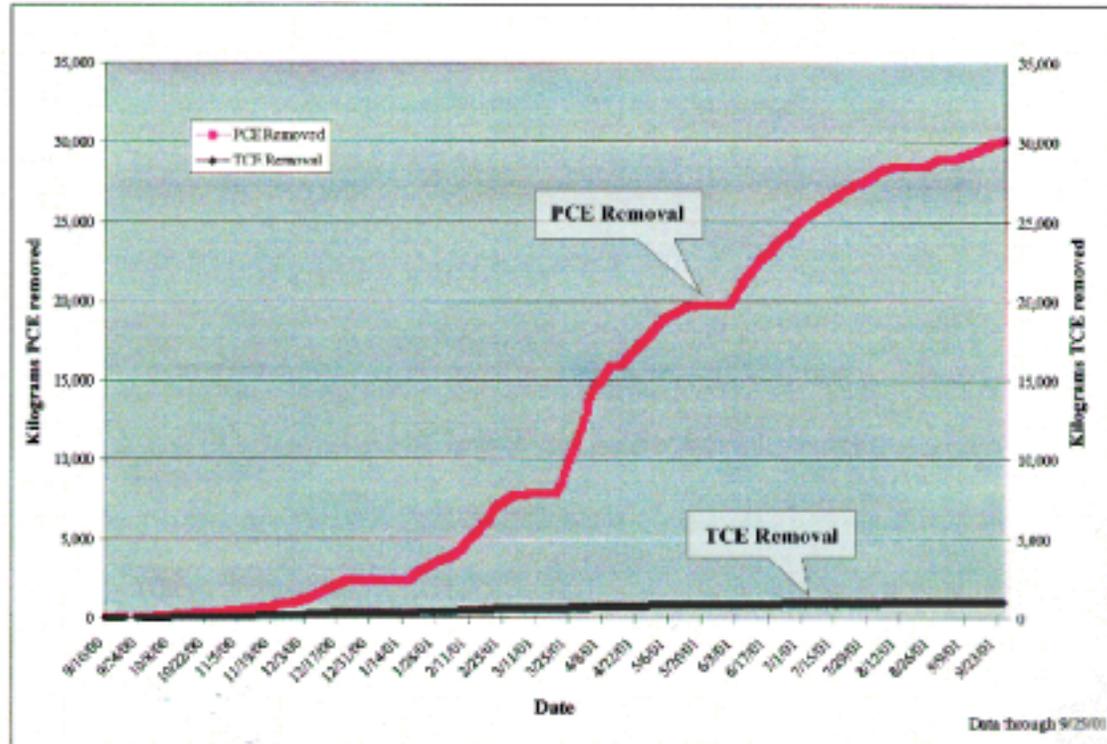
From May to September 2001, vapor extraction data indicated that the majority of the contaminant mass removal was coming from within the periphery of the target zone (DUS-010 consistently recorded the highest concentrations of vapor). The vendor indicated that the residual contaminant removal pattern may have resulted from the volatilization of PCE and TCE bound in clay horizons above 20 ft bgs (above the DUS/HPO remedial target zone). The vendor also indicated that the data from the last two months of operation suggested that the source of this contaminant had not been heated much, supporting the interpretation that it was volatilized from horizons above the target zone.

The mass of contaminants destroyed in the subsurface by HPO was not quantified. However, based on estimates from other projects and experimental work at Lawrence Livermore National Laboratory, the vendor indicated that the amount of dissolved phase contaminants expected to be destroyed by HPO would be at least 10% (6,800 lbs) and could be as high as 30% (20,000 lbs) of the contaminant removed by DUS. Information was not provided about any potential indicators for the amount of contaminant removed by HPO.

The following information about wastewater stream totals, steam injection rates/pressure, vapor extraction temperatures, and subsurface thermal monitoring were provided by the vendor.

Wastewater Stream Totals:
At the beginning of the pilot demonstration, groundwater accounted for the majority of the wastewater collected. Following steam breakthrough in the saturated zone, condensate increased and at times exceeded the groundwater production rates. In comparison to the vapor stream, the wastewater stream produced a very small amount of contaminant. This was because PCE has a solubility limit of 150 ppm, which would only be sustained in condensate when the vapor stream was saturated with PCE. Low wastewater production rates combined with a low solubility contaminant like PCE yielded a modest amount of contaminant removed via groundwater extraction (about 75 lbs PCE and 10 lbs TCE).

Steam Injection Rates/Pressures:
Steam injection rates regularly increased from startup to a maximum rate of 20,000 lb/hr in February 2001 and continued at that level through March 2001 and most of May 2001. Injection pressures never reached the design injection pressures (design injection pressures were 60, 40, and 26 psig), particularly in the deep and intermediate wells (DUS-004 through DUS-009). Injection pressures remained constant over the life of the project, indicating a lack of blockage in the wells that might require well maintenance.

Vapor Extraction Temperatures:
Vapor extraction temperaturescan be found in Figure The vendor reported that maintenance of very high vapor temperatures in the extracted vapor stream (+93°F) would have required almost continuous steam injection. The reduced steam injection rates used in June to September 2001 caused only minor decreases in vapor extraction temperatures, indicating that considerable latent heat remained in the subsurface.

Subsurface Thermal Monitoring Data:
ERT images identified several lithologic layers, particularly a zone at approximately 100 ft bgs that was slower to heat than surrounding layers. Boring logs indicated that those layers are fine-grained clay horizons and were slow to show changes in electrical resistance and heat up or cool down. For example, during a shutdown period, more permeable horizons cooled slightly but the finer grained layers showed increasing temperatures caused by.

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COST OF THE TECHNOLOGY SYSTEM

COST DATA [2]

For this pilot demonstration, the Interstate Technology Regulatory Council (ITRC) reported a project cost of $29/cu yd, but did not indicate what was included in the cost or how it was calculated. The ITRC stated that cost for steam generation and treatment of vapor and dissolved phase contaminants were not included in this cost, because these services were provided by SRS.

Information was not provided about the projected cost for using this technology on a full-scale basis at SRS.

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED [1,2,3]

A one-year pilot demonstration of steam injection lead to the removal of 31,000 kg (68,000 lbs) of PCE and TCE. The target treatment area was heated to near 90 ^{o}C and air was injected to support HPO, leading to an additional, unquantified amount of contaminant destroyed in situ by HPO.

The following lessons learned were provided by the vendor:

- During the DUS/HPO process, steam was injected through wells that were specially designed to withstand elevated pressures and temperatures. It was important that existing and new monitoring wells be similarly designed or removed prior to steam injection. If non-high temperature wells are left in place, then DNAPL likely would have condensed and collected within the target region.

- During the later stages of system startup and testing, the jet pump designed for groundwater extraction was not performing well. Using steam as the motive fluid combined with the depth to groundwater was not sufficient for pumping. Other fluids such as air or water were determined not to be cost effective. To address these concerns, a 15 gpm high-temperature electric submersible pump was installed in November of 2000.

- During the span of system operations, there was little loss of injection capability, which would have resulted in increasing pressures for constant injection rates. High injection rates with low injection pressures indicated that the formation had the ability to receive large volumes of steam. Consequently, the steam injection rate was limited only by the amount of steam that could be delivered.

- The most difficult region of the target zone to heat was the shallow portions at the center of the treatment area. The most likely reason for this was the circulation of air from the surface to the shallow zone. Restricting vapor extraction and continuous long-term steam injection sufficiently heated this portion after five months of steam injection.

- Removal rates could have been considerably higher had there been the capability for contaminant destruction in the vapor stream. However, the SRS SVE unit was not configured for contaminant destruction.

- During system operations, both thermocouple and ERT systems experienced shutdowns due to lightning ground strikes in the immediate vicinity of the project area. The ERT experienced fewer but more prolonged shutdowns from the lightning strikes due to its complexity.

- On November 26, 2000, the knockout tank was reported to be physically rocking on its base and the SVE unit was shut down. It was determined that the concrete pad supporting the knockout tank was not level and the support used to stabilize the tank was no longer in place. The restarting of the SVE system disturbed water in the tank causing the water to slosh and the tank to rock. The support was relocated to the base of the unit and checked daily; there was no recurrence of the problem over the remainder of the project.

REFERENCES

1. Integrated Water Resources. "Deployment of a Dynamic Underground Stripping-Hydrous Pyrolysis/Oxidation System at the Savannah River Site 321-M Solvent Storage Tank Area, Final Report. September 2002.

2. ITRC DNAPL Team Case Study Report: 321 M Solvent Storage Tank Area, Savannah River Site, Aiken, South Carolina. September 2002.

3. Project Descriptions, Integrated Water Resources. Savannah River Site- 321-M Solvent Storage Tank Facility. Savannah River, South Carolina.

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COST AND PERFORMANCE REPORT

Steam Enhanced Extraction at the
A.G. Communications Systems Site
Northlake, Illinois

June 2003

SITE INFORMATION

IDENTIFYING INFORMATION

Site Name: A.G. Communications Systems
Location: Northlake, IL
Regulatory Context: State voluntary cleanup
Technology: Steam Enhanced Extraction (SEE)
Scale: Full-scale

TECHNOLOGY APPLICATION [1,2,3]

Period of Operation: September 1995 to November 1999

Type/Quantity of Material Treated during Application: Source zone (saturated and unsaturated) - Estimated 330,000 cubic yards treated

BACKGROUND [1,2]

The A.G. Communications site, located near Chicago, IL, operated as a telecommunications manufacturing facility from the 1950s through the early 1990s when it was sold to a real estate development company. Trichloroethene (TCE) and mineral spirits used in manufacturing operations were stored in underground storage tanks (UST). During the decommissioning of the manufacturing facility, chlorinated solvents, including TCE and cis-1,1-dichloroethene (DCE) and components of mineral spirits, including xylene and benzene, were found in soil and groundwater at the site. The source of the contamination was identified as an area in the vicinity of the former tank farm and beneath the manufacturing facility. Approximately 63,000 tons of contaminated soil were excavated from the former tank farm area and disposed off site.

The site was remediated under the Illinois Environmental Protection Agency (IEPA) voluntary site remediation program (SRP). A SEE system was pilot-tested at the site from January through July 1994. Full-scale SEE operation was performed from September 1995 to November 1999.

CONTACTS

State Regulator:
Not available

Site Contact:
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Environmental and Safety Specialist
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Northlake, IL 60164

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E-mail: tadams@ensr.com

MATRIX DESCRIPTION

MATRIX AND CONTAMINANT IDENTIFICATION [1,2,6]

Type of Media Treated With Technology System: Source zone (saturated and unsaturated)

Primary Contaminant Groups: Chlorinated solvents (TCE, cis-1,2-DCE), and petroleum hydrocarbons (xylene and benzene)

SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [1,4]

The geologic strata at the site consists of three till layers overlying dolomite bedrock. The Tinley Till (0-35 ft bgs; hydraulic conductivity of $1x10^{-8}$ cm/sec), overlain by clayey silt fill, consists of dense silty clay with thin discontinuous seams of sand and silt. The Valparaiso Till (36-38 ft bgs; hydraulic conductivity of $2.9x10^{-3}$ cm/sec) consists of a fine to medium grained sand layer which is underlain by a dense, overconsolidated, well sorted laminated silt (38-48 ft bgs; hydraulic conductivity of $9x10^{-8}$ cm/sec). The Lemont Drift (48-65 ft bgs) consists of thick coarse-grained sand and gravel layer underlain by a fine grained dolomite sand and silt with some gravel fragments. Weathered Silurian dolomite is present at 65-75 ft bgs, with Silurian dolomite bedrock present at greater than 75 ft bgs. The depth to groundwater is 38-40 ft bgs.

Contamination was present primarily in the Tinley and Valparaiso Till layers. According to the vendor, TCE and DCE were present as DNAPL, as well as in the dissolved phase. Xylene and benzene were present as LNAPL and in the dissolved phase. The only data available for contaminant concentration prior to treatment was a groundwater TCE concentration of greater than 45,000 ug/L in December 1995.

Table 1 lists the matrix characteristics affecting treatment cost or performance for this application and the values measured for each.

Table 1. Matrix Characteristics [1,4]

Parameter	Value
Soil Classification	Alternating clay and sand till, with intermittent sand and silt layers
Clay Content and/or Particle Size Distribution	0-7 ft below ground surface (bgs) clayey silt 30-40 ft bgs dense silty clay
Depth to Groundwater	38-40 ft bgs

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY

Steam enhanced extraction

TREATMENT SYSTEM DESCRIPTION AND OPERATION [1,2,3,4]

SEE was tested on a pilot-scale basis at the site from January through July 1994. While details of the pilot-scale system were not provided, the vendor reported that the pilot-scale system was incorporated into the full-scale system. The full-scale system, shown in Figure 1, was operated from September 1995 to November 1999. The system covered an area of about 250,000 ft^2 to a depth of about 50 ft in the former tank farm area and beneath the existing building. The system included shallow vapor extraction wells, shallow and deep steam injection wells, vacuum-enhanced groundwater/vapor extraction wells, deep groundwater extraction wells, and two vacuum extraction units.

The 65 steam injection wells were installed in shallow and deep permeable zones. The 39 shallow steam injection wells were screened across the sand layer at the base on the Tinley Till at a depth of 35 ft bgs. The 26 deep steam injection wells were screened across the cobble layer at the base of the Valparaiso Till at a depth of 46 ft bgs. Steam was supplied by a 294 kilowatt series HF Scotch-Box boiler at pressures ranging from 3 to 7 psi. Temperature thermocouples were installed around two of the deep steam injection wells and one shallow steam injection well. During system operation, soil temperatures ranged from 84°F to 140°F, and groundwater temperatures ranged from 68°F to 165°F.

Soil vapor extraction was performed using 186 shallow wells screened in the Tinley Till and the 76 combination groundwater/vapor extraction wells screened across the Tinley and Valparaiso Tills. Two vapor extraction units (VES #1 and VES #2) were operated at 150 to 250 scfm at 7 to 15 inches of mercury. Hydrocarbon emissions from the VES #1 and VES #2 were measured continuously using a TECO® 51 flame ionization detector (FID). The type of treatment used for off-gases was not identified.

Groundwater extraction was performed using the 76 combination groundwater/vapor extraction wells screened across the Tinley and Valparaiso Tills, the two deep groundwater extraction wells screened in the Lemont Drift, and one excavation dewatering well. Groundwater was extracted at a rate ranging from 15 to 30 gpm with the groundwater/vapor extraction wells operated at a total flow rate of 4 to 6 gpm and the two deep groundwater extraction wells operated at a flow rate of 10 to 11 gpm per well.

Extracted groundwater was treated using a stainless steel shallow tray air stripper equipped with a 900 cubic meter/minute blower followed by treatment using two 1,000 lb activated carbon vessels, and then discharged under the facility's NPDES permit. Groundwater discharge averaged 500,000 gallons per month.

In addition to SEE, chemical oxidant flushing using chlorine dioxide (ClO_2) was performed in recalcitrant source areas. ClO_2 flushing was used to oxidize soil mineral surfaces and modify pH and redox conditions. According to the vendor, this approach was used to enhance TCE partitioning from soil for removal through the groundwater/vapor extraction wells, and redox levels of -100 to -200 mV were achieved. No additional information about the timing, extent, or effectiveness of the ClO_2 flushing was provided.

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Figure 1. Remediation System Layout [1]

L E G E N D:

o — SHALLOW STEAM INJECTION WELL (39)

■ — DEEP STEAM INJECTION WELL (9 INSIDE, 17 OUTSIDE)

× — TEMPERATURE THERMOCOUPLE STRING (12 INSIDE, 6 OUTSIDE)

· — VACUUM ENHANCED GROUNDWATER RECOVERY/VAPOR
      EXTRACTION WELL

△ — SHALLOW VAPOR EXTRACTION/INDUCTION WELL (186)

⊕ — LEMONT DRIFT GROUNDWATER RECOVERY WELL (2)

⊖ — EXCAVATION DEWATERING WELL (3)

⊕ — EXISTING MONITORING WELL

▲ — EXISTING PIEZOMETER

NORTH

MAP SCALE

40   0   40   80

SCALE IN FEET
1" = 40'-0"

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TIMELINE [1,5]

- April 1992   Excavation and off site disposal of soil from former UST area
- January to July 1994   Pilot test conducted
- Sept 1995 to Nov 1999   Full scale system operation performed
- May 2002   Remedial Action Completion Report submitted to Illinois EPA; under review by IEPA

TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [1,2]

The remediation was conducted under the IEPA Voluntary SRP. The remedial objective was to obtain IEPA approved closure under Tiered Approach to Corrective Action guidelines. The proposed closure strategy was to use site-specific parameters to calculate a first order degradation constant and demonstrate that there are no on-site or off-site receptors at risk from volatile organic hydrocarbons in soil or groundwater.

TREATMENT PERFORMANCE [1,2,3,5]

Treatment performance data are available for contaminant concentrations from September 1995 to September 1997, and total mass removal through November 1999. Treatment progress was monitored in terms of the reduction in TCE and DCE concentrations in groundwater and the total mass of hydrocarbons removed. Hydrocarbon mass removal was calculated based on the FID readings from the air stripper and the two vapor extraction units. The FID readings included the mass of chlorinated solvents (TCE, DCE) and petroleum hydrocarbons (xylenes, benzene).

Concentration Data

Quarterly groundwater sampling was performed for the 76 combination groundwater/vapor extraction wells. Figure 2 shows that the average groundwater concentrations for TCE was reduced from approximately 20,000 µg/L to <1,000 µg/L over the period from September 1995 to September 1997.

Figure 2. Average Groundwater Concentrations of TCE Over Time (Sept 95 - Sept 97) [1]

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In addition, groundwater concentration data were available for TCE and cis-1,2-DCE for 17 wells for the period from December 1995 to October 1997. As shown in Table 2, TCE concentrations were reduced in 16 of the 17 wells between December 1995 and October 1997, with most wells showing a reduction of >90%. As of October 1997, TCE concentrations ranged from 28 µg/L to 10,526 µg/L. During this time, DCE concentrations were reduced in 14 of the 17 wells, with about half the wells showing a reduction of >90%. As of October 1997, DCE concentrations ranged from below detection levels to 122 µ/L.

Table 2. Concentrations of TCE and cis 1,2-DCE in Groundwater (µg/L) [1]

Well Location	TCE			Cis 1,2-DCE		
	Dec-1995	Oct-1997	% Reduction Dec 95 to Oct 97	Dec-1995	Oct-1997	% Reduction Dec 95 to Oct 97
200n230e	94,166	74	>99%	2,311	0	>99%
220n210e	3,007	212	93%	1	17	+1600%
220n250e	337	28	92%	29	0	>99%
240n190e	431,318	2,890	99%	168	101	40%
260n250e	161	33	80%	11	7	36%
276n110e	7,615	342	96%	74	0	>99%
276n230e	1,336,589	4,488	>99%	437	80	82%
276n270e	164,764	140	>99%	478	0	>99%
276n310e	190,527	4,700	98%	467	4	99%
300n270e	46,743	1,941	96%	1	10	+900%
300n290e	189,610	1,466	99%	456	13	97%
320n110e	352,639	39	>99%	47	0	>99%
320n220e	266	599	+125%	22	34	+55%
320n290e	341,207	10,526	97%	259	73	72%
340n270e	75,213	270	>99%	228	0	>99%
360n180e	86	28	67%	33	14	58%
360n240e	954	497	48%	423	122	71%

Mass Removal Data

Table 3 provides a summary of the mass of hydrocarbons (including TCE and DCE) removed from the air stripper and two vapor extraction units during the period from August 1995 to January 1998 (29 months). The table shows that the total hydrocarbon removal was approximately 26,000 lbs (11,700 kg) and that the monthly hydrocarbon removal ranged from about 240 lbs (111 kg) to 1,550 lbs (706 kg). Approximately two-thirds of the contaminant mass was removed as vapor from the two VES units. The vendor reported that as of November 1999, more than 33,000 lbs of hydrocarbons had been removed from soil vapor and groundwater. The mass of TCE and DCE removed during this time was not reported separately from the total mass of hydrocarbons removed.

Table 3. Hydrocarbon Removal Totals [1]

Month	Air Stripper Discharge (kg)	VES #1 (kg)	VES#2 (kg)	Monthly Total (kg)
Aug 95	0.0	0.0	222.39	222.39
Sep 95	147.92	64.28	152.59	364.79
Oct 95	110.36	114.17	198.58	423.10
Nov 95	82.62	319.67	190.22	592.51
Dec 95	113.55	247.21	185.78	546.54
Jan 96	139.62	193.09	228.65	561.36
Feb 96	101.78	107.53	106.65	315.96
Mar 96	131.29	400.42	160.92	692.63
Apr 96	181.89	331.48	133.60	646.97
May 96	262.76	298.28	145.42	706.46
Jun 96	255.22	128.59	109.89	463.69
Jul 96	122.83	243.84	72.92	439.59
Aug 96	118.74	202.34	119.80	440.89
Sep 96	127.49	114.43	90.68	332.61
Oct 96	145.63	107.65	98.21	351.50
Nov 96	97.75	128.64	104.07	330.45
Dec 96	86.75	148.49	93.15	328.39
Jan 97	81.57	131.12	82.77	295.46
Feb 97	72.22	71.41	42.96	186.59
Mar 97	87.19	144.67	105.72	337.58
Apr 97	89.57	161.97	86.36	337.90
May 97	98.59	136.17	68.44	303.20
Jun 97	69.95	60.57	44.58	175.11
Jul 97	50.26	28.41	32.67	111.35
Aug 97	132.18	41.75	204.29	378.23
Sep 97	126.55	40.81	164.82	332.18
Oct 97	94.99	87.66	182.30	364.94
Nov 97	224.39	243.76	35.10	503.25
Dec 97	84.58	213.63	46.02	344.24

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Table 3. Hydrocarbon Removal Totals [1] (continued)

Month	Air Stripper Discharge (kg)	VES #1 (kg)	VES#2 (kg)	Monthly Total (kg)
Jan 98	90.98	121.15	87.67	299.80
TOTALS:	**3,499.23**	**4,633.20**	**3,597.25**	**11,729.68**

As of November 1999, more than 55,000 ft^2 of the remediation area had been approved for closure by IEPA. The Remedial Action Completion Report was submitted to IEPA in May 2002, with a decision on site closure expected in October 2002. According to the vendor, based on the site-specific first order degradation constant, the calculated groundwater concentrations at the point of compliance (property boundary) met Class I remediation objectives. Where the soil concentrations beneath the building exceeded the soil remediation objectives, a theoretical groundwater concentration leached from the soil was calculated and, along with the site specific degradation constant, was shown to meet the Class I remediation objectives at the point of compliance. No analytical data were provided to support these calculated values.

COST OF THE TECHNOLOGY SYSTEM

COST DATA [2]

The vendor reported that the actual cost for the application was $4.9 million and $13 to 15 per cubic yard treated, including the cost of the pilot test, system design and installation, five years of operation and maintenance, and negotiations with IEPA. A further breakdown of costs was not provided.

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED [1,2,4]

The use of steam enhanced extraction removed an estimated 33,000 lbs of hydrocarbons from the soil and groundwater at the site and reduced TCE and DCE concentrations by more than 90%. According to the vendor, this application demonstrated that SEE is effective in a heterogenous clay till.

In August 1997, the vendor performed an experiment to evaluate the cycling of steam injection to improve the rate of hydrocarbon removal (analogous to the oil industry practice of using steam for enhanced oil recovery). Results indicated a dramatic increase in hydrocarbon removal following steam shutdown, and the vendor is currently evaluating appropriate frequencies for the steam cycle.

REFERENCES

1. Adams, Timothy V., Smith, Gregory J. "DNAPL/LNAPL Remediation in Clay Till Using Steam Enhanced Extraction." Battelle Conference Proceedings. Not Dated.

2. ENSR, Case Study: Northlake, IL Site, "DNAPL Remediation in Heterogeneous Clay Till Using Steam-Enhanced Groundwater and Vapor Extraction." Not Dated.

3. ENSR, Statement of Qualifications. "DNAPL Remediation in Clay Till Using Steam-Enhanced Groundwater and Vapor Extraction". Not Dated.

4. ENSR, Power Point Presentation: "DNAPL/LNAPL Remediation in Clay Till Using Steam-Enhanced Groundwater and Vapor Extraction". Not Dated.

5. Tim Adams, ENSR. E-mail correspondence about A.G. Communications, North Lake, IL. September 18, 2002.

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COST AND PERFORMANCE REPORT

Electrical Resistive Heating at the
Former Manufacturing Facility
Skokie, Illinois

June 2003

SITE INFORMATION

IDENTIFYING INFORMATION

Site Name: Former manufacturing facility (confidential commercial client)
Location: Skokie, Illinois (near Chicago, Illinois)
Regulatory Context: State voluntary cleanup
Technology: Electrical Resistive Heating
Scale: Full-scale

TECHNOLOGY APPLICATION

Period of Operation: June 4, 1998 to November 20, 1998 (initial area treated); December 1998 to April 30, 1999 (additional area treated)

Type/Quantity of Material Treated during Application [7,8]: Initial source zone area - approximately 23,100 cubic yards of soil and groundwater, based on a treatment area of 26,000 square feet and a depth of 24 feet below ground surface (bgs). Additional source zone area - 11,500 cubic yards of soil and groundwater

BACKGROUND [2,4,5,7,8,9,13]

The site is a former electronics manufacturing facility located in Skokie, Illinois. Manufacturing at this location began in 1958 and included machining, electroplating, heat treating, silk screening, silicon chip production, and research and development. Trichloroethene (TCE) and 1,1,1-trichloroethane (TCA) were feedstock chemicals associated with various manufacturing processes. By 1988, all processes had been discontinued, and the facility was sold and redeveloped.

Releases occurred from spill containment systems and underground storage tanks that leaked. Figure 1 shows the areas where soil and groundwater at the site were found to be contaminated with pools of dense nonaqueous phase liquids (DNAPL). The site was remediated under Illinois' voluntary Site Remediation Program. From 1991 to 1998, steam injection combined with groundwater and vapor extraction was used to clean up the site. After seven years of operation, the area of contamination had been reduced from about 115,000 square feet to about 23,000 square feet. As of early 1998, the remaining area to be remediated represented four source locations where manmade subsurface features limited the effectiveness of the previously used steam-based remediation system. These locations consisted of a closed-end catch basin acting as a heat sink, a subsurface void, two areas with very dense soil near a building (believed to be limiting vapor extraction), and an additional area adjacent to a wall with a deep foundation (where foundation backfill was believed to be providing a preferential pathway for injected steam).

To complete the remediation, the site owner selected Electrical Resistive Heating (ERH) technology that combines electrically heating the subsurface with electrodes inserted in the ground, and soil vapor extraction. This report focuses on the use of ERH and not the steam injection previously completed at the site.

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Figure 1. Layout of the Skokie Site [7,13]
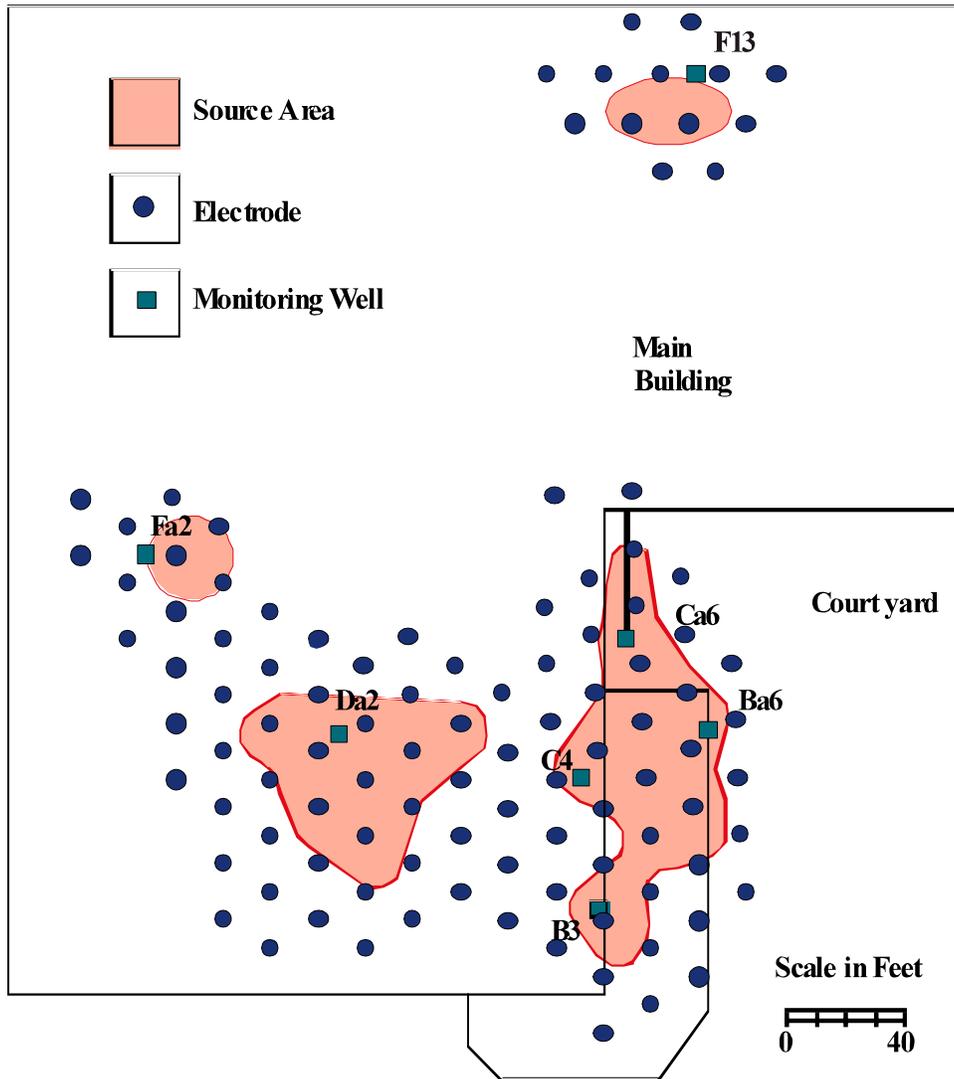
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Telephone: (217) 782-5504
E-mail: epa4207@epa.state.il.us

MATRIX DESCRIPTION

MATRIX AND CONTAMINANT IDENTIFICATION

Type of Media Treated With Technology System: Source zone (saturated and unsaturated)

Primary Contaminant Groups: Chlorinated Solvents (TCE and TCA, as well as degradation products cis- and trans-1,2-dichloroethene, 1,1-dichloroethene, 1,1-dichloroethane, vinyl chloride and chloroethane)

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[1]   Now at: URS/Radian International, One Continental Towers, 1701 Golf Road, Suite 1000, Rolling Meadows, IL 60008, greg_smith@radian.com

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SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [3,4,7,13]

The facility overlies heterogeneous silty sands with clay lenses to 18 feet bgs and a hydraulic conductivity ranging from 10^{-4} to 10^{-5} cm/sec. Below 18 feet bgs, a dense clay till or ground moraine forms an aquitard with a hydraulic conductivity of 10^{-8} cm/sec. Groundwater is encountered at 7 feet bgs. The majority of the remaining DNAPL at the site was pooled on top of the clay till at 18 feet bgs.

At the initiation of ERH, aqueous phase concentrations and concentration trends indicated the presence of DNAPL. Sampling indicated that DNAPL resided in proof-rolled clays at depths of 5 to 8 feet bgs, and in the soil pores from the water table (7 feet bgs) to depths of 18 to 20 feet bgs. Concentrations in groundwater at the initiation of SPH for cis-1,2-dichloroethene (DCE) were as high as 160 mg/L, for TCE as high as 130 mg/L, and for TCA as high as 150 mg/L.

Table 1 lists the matrix characteristics affecting treatment cost or performance for this application.

Table 1. Matrix Characteristics [3,4,7,13]

Parameter	Value
Soil Classification	Heterogeneous sandy and silty clays
Clay Content and/or Particle Size Distribution	Two discrete clay intervals: 1) silty clay from 5 to 18 feet bgs, and 2) denser clay below 18 feet bgs
Depth to Groundwater	7 feet bgs
Hydraulic conductivity	Ranges from 10^{-4} to 10^{-5} centimeters/second (cm/sec) in silty sand and less than 10^{-8} cm/sec in the denser clay
Air permeability	Not available
Porosity	Not available
Presence of NAPLs	DNAPL present
Moisture content	Typical for water saturated clay (quantitative information not available)
Total organic carbon	0.12%
Electrical resistivity of soil	3 ohms

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY

Electrical Resistive Heating (Six-Phase Heating™) and air stripping for extracted groundwater condensate

TREATMENT SYSTEM DESCRIPTION AND OPERATION [1,3,4,5,6,7,8,9,13]
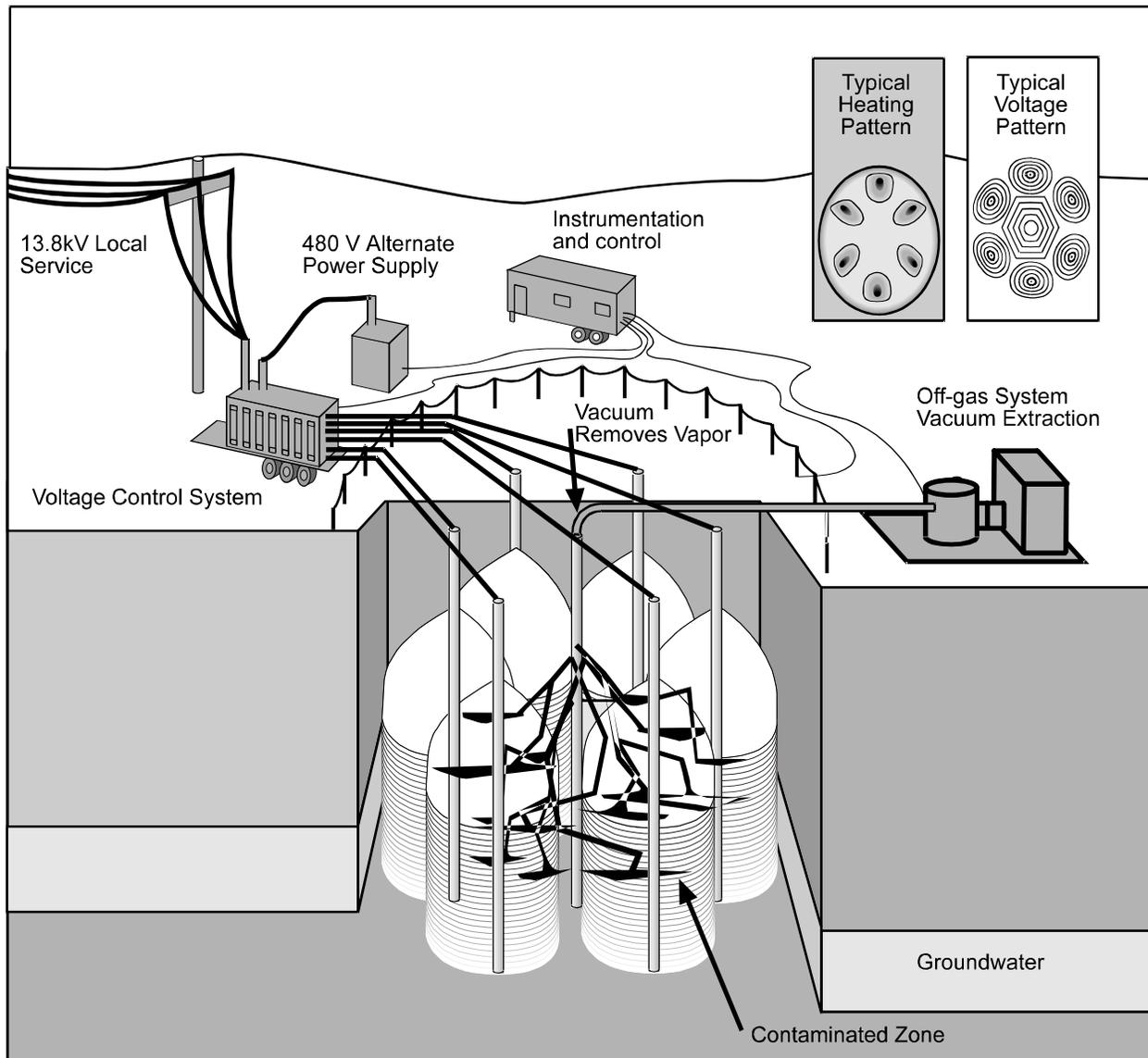
For the Skokie site, a network of 107 electrodes was designed and installed in the initial treatment area, with 85 of the electrodes constructed beneath the floor of a warehouse building. After November 20, 1998, the system was shut down for about a month while 78 more electrodes were installed (185 electrodes total). All electrodes were designed to be electrically conductive throughout a depth interval of 11 to 21 feet bgs and to increase the subsurface temperature in the depth interval of 5 to 24 feet bgs to the boiling point of water. A network of 37 soil vapor extraction wells, screened to 5 feet bgs, were used to capture vapors. The off gas system consisted of a vacuum extraction blower and a steam condenser. Figure 1 shows the location of the electrodes and monitoring wells at the site, while Figure 2 shows typical ERH equipment layout.

The ERH process operated at the Skokie site from June 4, 1998 to November 20, 1998 to remediate the initial estimated 23,000 cubic yards of contaminated soil. Results of sampling conducted in December 1998 indicated there was a potential for vinyl chloride to be produced outside the initial treatment area at levels in excess of the Tier III cleanup levels. As a result, the treatment area was expanded, restarted in December 1998, and operated until April 30, 1999.

During system operation, the ERH process was controlled remotely via software, allowing real-time adjustment of electrode voltage to control power delivered to the soil. According to the vendor, thermocouples placed in the soil were used to monitor the heating pattern as a basis for adjusting the distribution of power and to assist in determining the best electrical configuration for power delivery as the cleanup progressed. The electrical configuration was adjusted in the field by reconnecting electrical jumpers between electrodes to re-focus electrical energy as needed to maintain rapid treatment. During all phases of the operation, the total power, energy delivered, and electrical current, voltage, and power factors were measured and recorded along with soil temperatures using a computer based data acquisition and control system.

During treatment, the source zone was heated to 100° C, and the system achieved an operating vacuum of 7.5 inches of mercury. Electric power input was 1,775 Mw-hrs from June 4 to November 20, 1998. Information on power input was not provided for December 1998 to May 1999.

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Figure 2. Typical ERH Equipment Layout [7]

Treatment progress was monitored by measuring vapor concentrations in the soil off-gas exiting the condenser and by periodically monitoring in situ concentrations through groundwater samples collected from wells. The off-gas measurements were used to estimate the rate of contaminant removal and total removed mass throughout the site operation. According to the vendor, approximately 99% of the removed mass was found to remain in the vapor phase past the off-gas condenser while the remaining 1% was collected in the condensed phase. This partitioning reflects the relatively high volatility and modest solubility of the contaminants. The condensate was treated with air stripping prior to discharge.

Groundwater monitoring data were available for March 1998, before the ERH was initiated, and from April 1998 through May 1999. During ERH treatment, up to 40 well points (from the previous steam injection system) were sampled on a periodic basis. According to the vendor, all of these well points were abandoned in July 1999 in accordance with Cook County Department of Public Health-approved procedures.

TIMELINE [3,4,5,8,9,13]

- 1991-3/98   Steam injection and soil and groundwater extraction used at site
- 6/4/98   ERH system began operation
- 8/4/98 (approx.)   Temperatures throughout entire soil volume reach boiling point of water
- 10/98   ERH system temporarily shut off
- 12/98   Additional ERH system began operation
- 4/30/99   System shut off and demobilization began
- 7/29/99   Illinois EPA issues a no further remediation letter
- 5/99-12/99   Post-remedial monitoring conducted

TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [4,10,13,14]

Table 2 shows the Tier III cleanup criteria for groundwater proposed by the vendor and approved by Illinois EPA as the cleanup goals for the site. According to Illinois EPA's Site Remediation Program guidelines, Tier III allows conduct of variable-scale risk assessment activities and more complex contaminant fate and transport modeling than is allowed in more stringent cleanup tiers. The more stringent Tier I standards are shown for comparison.

Table 2. Cleanup Criteria for Skokie Site (Tier III) [13,14]

Contaminant	Tier III Cleanup Level for Groundwater (µg/L)	Tier I Cleanup Level for Groundwater (µg/L)
cis 1,2-Dichloroethene (DCE)	35,500	200
1,1,1-Trichloroethane (TCA)	8,850	1,000
Trichloroethene (TCE)	17,500	25

TREATMENT PERFORMANCE [4,6,8,9,13]

Performance data are available for the remediation of the initial 23,000 cubic yards of remaining contamination at the site conducted from June to November 1998 (Table 3) and for the remediation of the additional 11,000 cubic yards of contamination at the site conducted from December 1998 to April 1999 (Table 4). Groundwater monitoring continued after system shutdown in April and data are available through May 1999. Figures 3, 4, and 5 show the changes in groundwater contaminant concentrations by well for DCE, TCA, and TCE, respectively, from March 1998 through May 1999.

As shown in Table 3, by November 20, 1998, the Tier III cleanup goals had been achieved for the three constituents of concern in all seven wells. In addition, as of November 1998, contaminant concentrations in a number of wells had been reduced to the more stringent Tier I cleanup levels. For example, the Tier I cleanup level for TCA had been met in all seven wells, for DCE in one well, and for TCE in two wells.

In October 1998, following 18 weeks of ERH operation, elevated levels of TCE (81,000 µg/L) were detected in well Ca6. According to the vendor, the source of the high concentrations of TCE was not known. To address the elevated concentrations: 1) well Ca6 was converted to an electrode to improve heating;

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and 2) Fenton's reagent was added in and around the catch basin to oxidize oils which may have potentially leaked from the catch basin. By November 1998, TCE concentrations in the Ca6 well area had decreased to levels ranging from 250 µg/L to 1,600 µg/L.

Table 4 presents a summary of groundwater monitoring data for the remediation of the additional area of contamination, conducted from December 1998 to April 1999. As shown in Table 4, concentrations of DCE and TCE were higher than the Tier III cleanup levels in well Ca6 in January 1999. By February 1999, TCE concentrations in this well had decreased to between the cleanup levels. As of April 1999 contaminant concentrations in all wells were below the cleanup goals and the system was shut down. Groundwater monitoring data for May 1999 showed that contaminant concentrations remained below cleanup levels.

Groundwater samples were collected monthly and analyzed via head space extraction using an HP 5890 gas chromatograph equipped with an electron capture detector (GC/ECD). A subset of the sample population was analyzed using a gas chromatograph with a mass spectrometer (GC/MS) following EPA Method 8240. Contaminant concentrations in the collected condensate were monitored periodically. Off-gas concentrations exiting the condenser were monitored using a flame ionization detector (FID).

The Illinois Environmental Protection Agency issued a letter on July 29, 2002 granting the site's request for a no further action determination and provided several conditions and terms for the determination, including installation of a passive ventilation system (vent wells) to provide a preferential pathway for vapors to migrate.

Two additional rounds of groundwater monitoring sampling were performed following completion of ERH in April 1999. Table 5 shows the concentrations of TCE, TCA, and DCE in groundwater monitoring wells from May 1999 (1 month after completion of the remediation) and December 1999 (8 months after completion of the remediation). During this time, the concentrations of TCE, TCA, and DCE remained below the Tier III groundwater cleanup levels, and contaminant concentrations remained stable or continued to decrease.

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Table 3. Monthly Groundwater Quality During ERH Remediation of Area of Remaining Contamination [4]
(June 1998 to November 1998)

Well No.	Constituent	Tier III Clean-up Level (µg/L)	Prior to SPH Remediation 3/24/98 (µg/L)	During Remediation 6/26/98 (µg/L)	7/15/98 (µg/L)	8/20/98 (µg/L)	9/17/98 (µg/L)	10/6/98 (µg/L)	11/20/98 (µg/L)
B3	cis 1,2-DCE	35,500	48,000	22,000	390	18,000	4,200	780	390
	1,1,1-TCA	8,850	82,000	4,000	500	17,000	500	500	500
	TCE	17,500	34,000	640	240	58,000	2,900	790	250
Ba6	cis 1,2-DCE	35,500	9,800	18,000	NR	NR	3,500	200	1,200
	1,1,1-TCA	8,850	88,000	52,000	NR	NR	2,600	50	50
	TCE	17,500	7,000	23,000	NR	NR	10,000	510	470
C4	cis 1,2-DCE	35,500	43,000	160,000	22,000	47,000	16,000	1,300	550
	1,1,1-TCA	8,850	11,000	13,000	8,800	1,000	1,000	100	100
	TCE	17,500	75,000	24,000	89,000	120,000	17,000	1,600	ND
Ca6	cis 1,2-DCE	35,500	1,800	52,000	1,800	52,000	8,400	22,000	250
	1,1,1-TCA	8,850	10,000	NR	1,200	4,200	2,000	2,000	20
	TCE	17,500	83,000	NR	5,200	230,000	12,000	81,000	1,600
Da2	cis 1,2-DCE	35,500	18,000	8,100	4,000	11,000	9,100	7,300	3,000
	1,1,1-TCA	8,850	28,000	94,000	51,000	5,600	5,000	500	100
	TCE	17,500	47,000	130,000	230,000	44,000	370,000	8,800	320
F13	cis 1,2-DCE	35,500	510	500	1,000	218	120	480	38
	1,1,1-TCA	8,850	16,000	150,000	14,000	2,000	100	250	250
	TCE	17,500	800	2,800	1,000	830	400	260	12
Fa2	cis 1,2-DCE	35,500	3,900	2,400	50	850	590	470	210
	1,1,1-TCA	8,850	24,000	810	420	200	100	50	50
	TCE	17,500	22,000	4,800	880	3,100	280	1,200	12
Average	cis 1,2-DCE	35,500	17,900	37,600	4,900	21,500	6,000	4,600	800
	1,1,1-TCA	8,850	37,000	52,300	12,700	5,000	1,600	500	200
	TCE	17,500	38,400	30,900	54,400	76,000	58,900	13,500	400

Figure 3. Monthly Cis-DCE Concentrations (: g/L) In Groundwater in Initial Area of Contamination (March 1998 to May 1999, log-scale) [4]
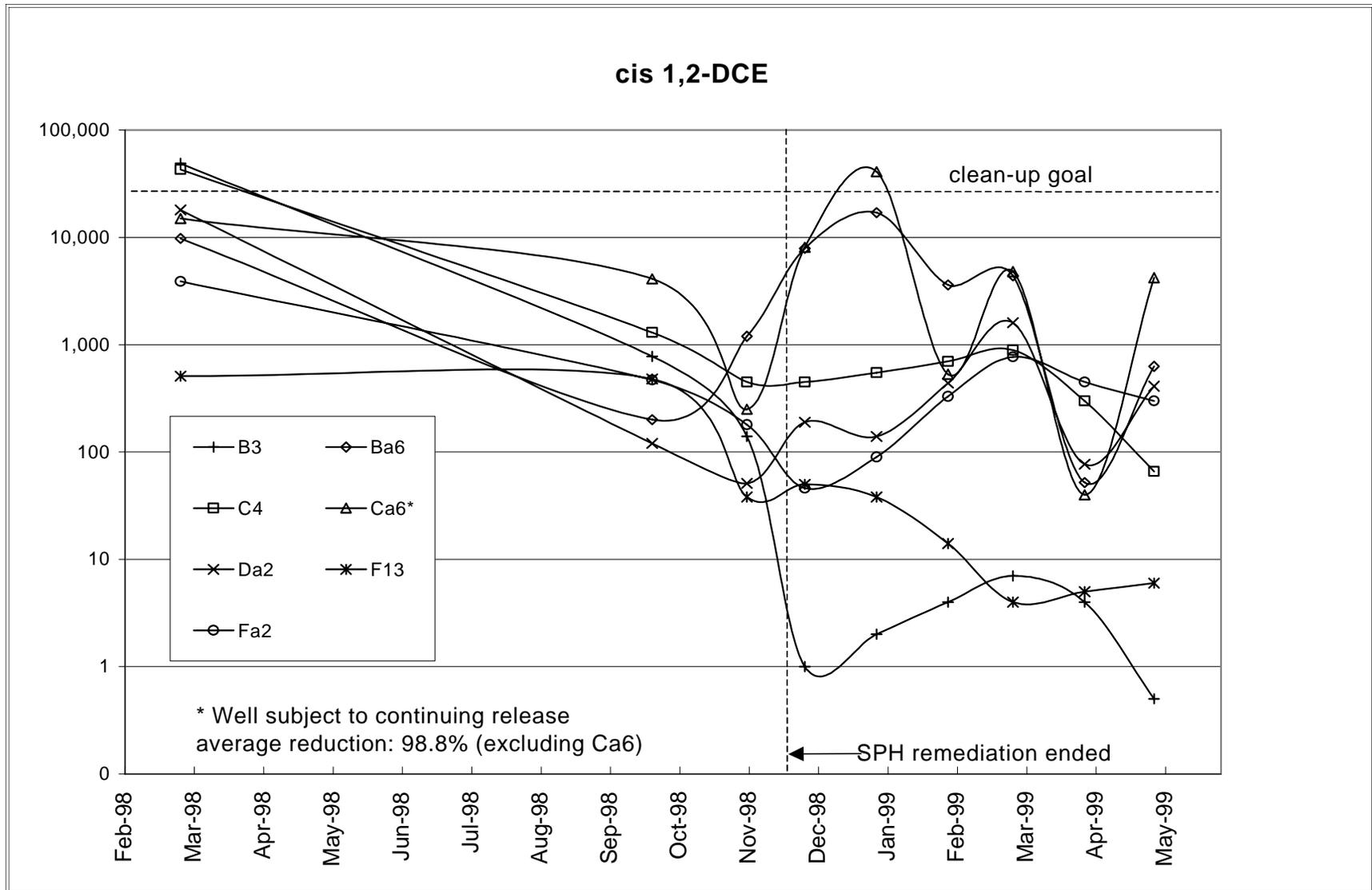
Figure 4. Monthly 1,1,1-TCA Concentrations (:g/L) in Groundwater in Initial Area of Contamination (March 1998 to May 1999, log-scale) [4]
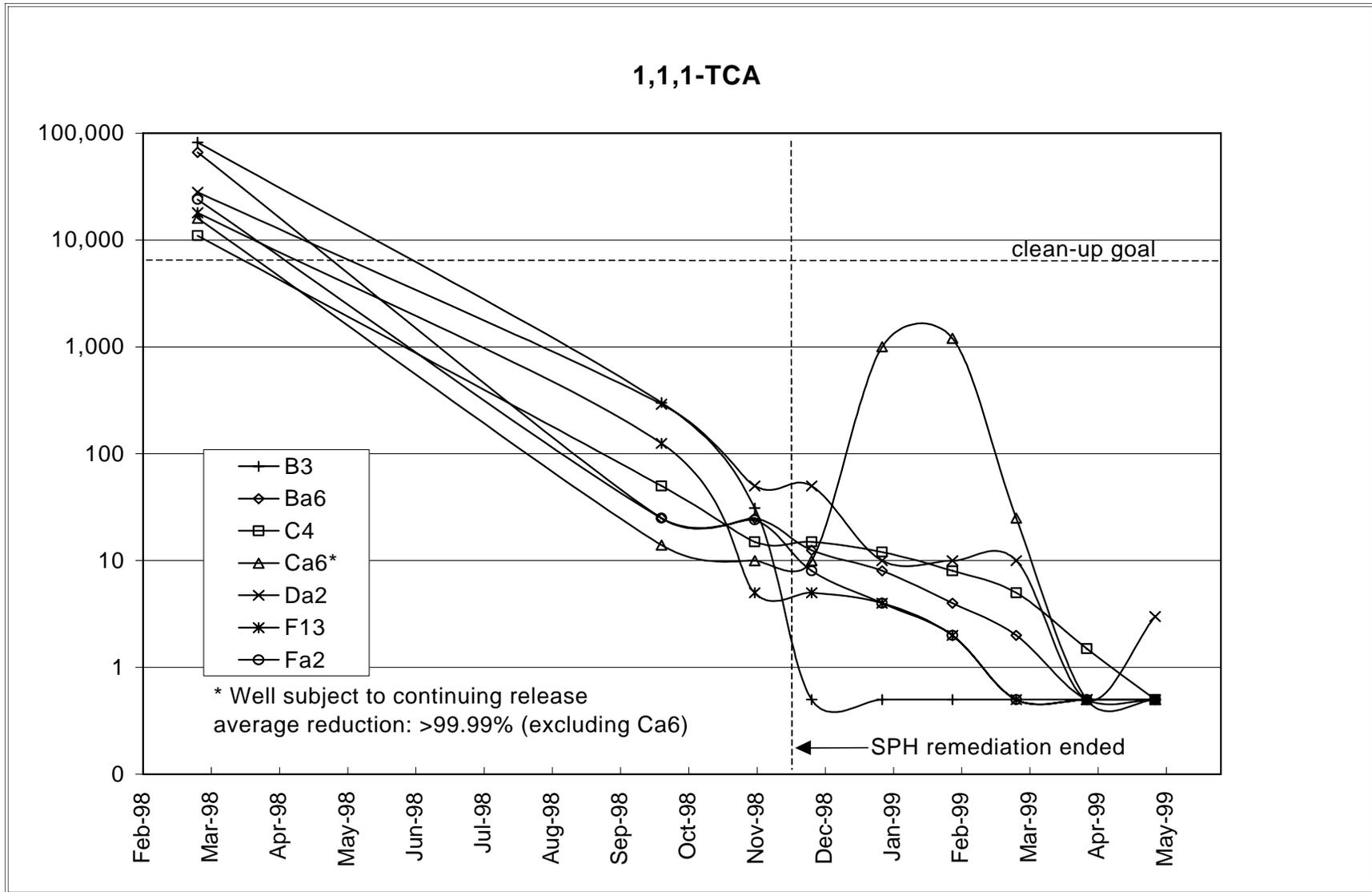
Figure 5. Monthly TCE Concentrations (: g/L) in Groundwater in Initial Area of Contamination (March 1998 to May 1999, log-scale) [4]
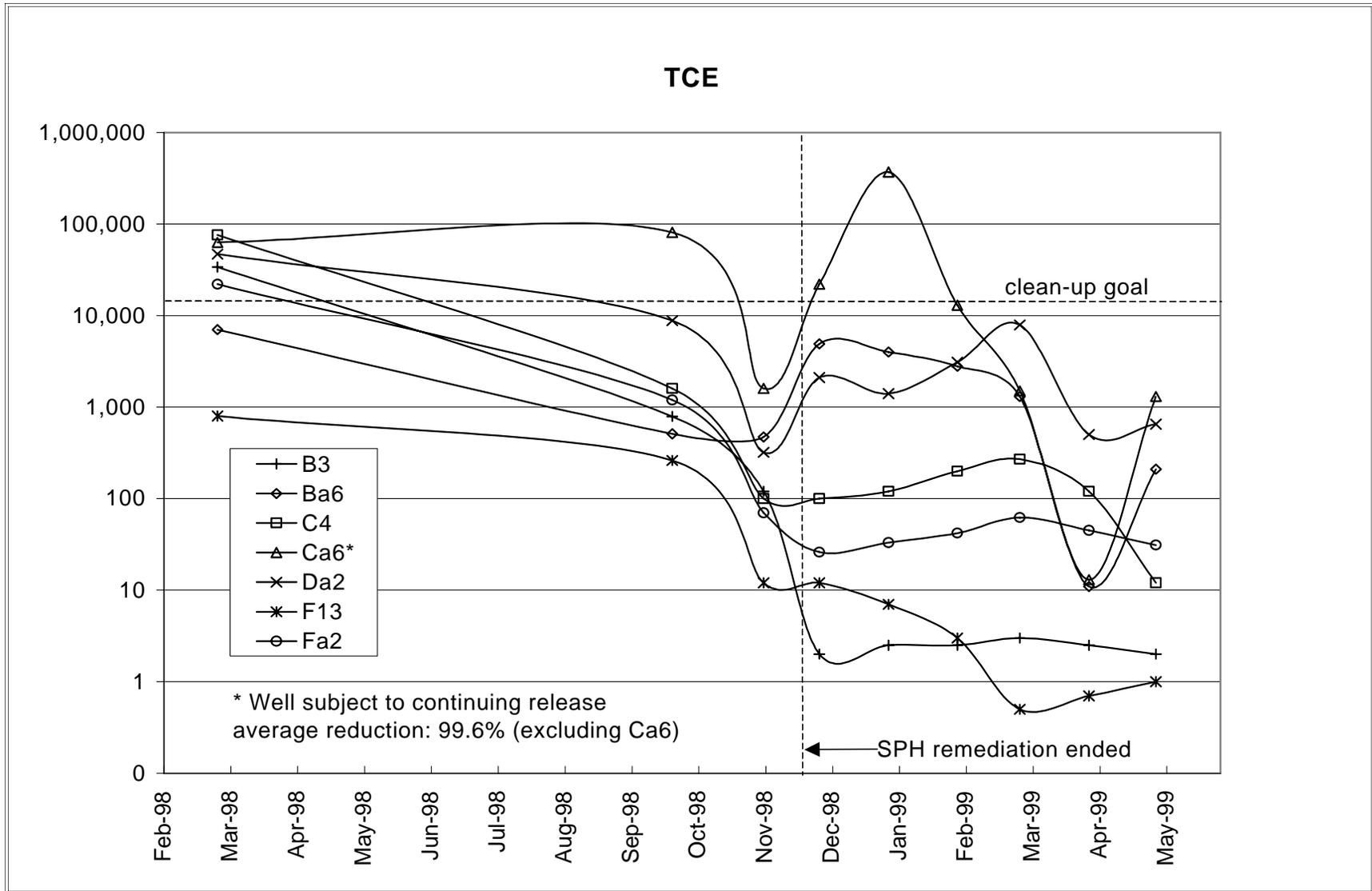
Table 4. Monthly Groundwater Quality During ERH Remediation of Additional Area of Contamination [11] (December 1998 to May 1999)

Well No.	Constituent	Tier III Clean-up Level (: g/L)	December-98 (: g/L)	January-99 (: g/L)	February-99 (: g/L)	March-99 (: g/L)	April-99 (: g/L)	May-99 (: g/L)
B3	cis-1,2-DCE	35,500	1	NR	NR	7	NR	<1
	1,1,1-TCA	8,850	<1	NR	NR	<1	NR	<1
	TCE	17,500	2	NR	NR	3	NR	2
Ba6	cis-1,2-DCE	35,500	7,900	17,000	3,600	4,400	52	630
	1,1,1-TCA	8,850	<25	<25	<25	<25	<1	<1
	TCE	17,500	4,900	4,000	2,800	1,300	11	210
C4	cis-1,2-DCE	35,500	450	NR	NR	890	NR	66
	1,1,1-TCA	8,850	15	NR	NR	<10	NR	<1
	TCE	17,500	100	NR	NR	270	NR	12
Ca6	cis-1,2-DCE	35,500	8,100	41,000	530	4,800	40	4,200
	1,1,1-TCA	8,850	<20	<2,000	1,200	<50	<1	<25
	TCE	17,500	22,000	370,000	13,000	1,500	13	1,300
Da2	cis-1,2-DCE	35,500	190	140	NR	1,600	77	410
	1,1,1-TCA	8,850	<100	<20	NR	<20	<1	3
	TCE	17,500	2,100	1,400	NR	7,900	500	650
F13	cis-1,2-DCE	35,500	50	NR	NR	4	NR	6
	1,1,1-TCA	8,850	<10	NR	NR	<1	NR	<1
	TCE	17,500	12	NR	NR	<1	NR	1
Fa2	cis-1,2-DCE	35,500	46	NR	NR	770	NR	300
	1,1,1-TCA	8,850	8	NR	NR	<1	NR	<1
	TCE	17,500	26	NR	NR	62	NR	31
Average*	cis-1,2-DCE	NR	2,391	8,306	2,065	1,782	56	240
	1,1,1-TCA	NR	14	341	606	8	1	1
	TCE	NR	4,163	125,000	7,900	1,577	196	150

*Not detects (<) were assumed to be present at one-half the detection limit in computing average concentrations.
NR - not reported

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Table 5. Groundwater Quality After ERH Remediation [15]

Well No.	Constituent	5/99 (µg/L)	12/99 (µg/L)
A6	cis 1,2-DCE	1,100	5
	1,1,1-TCA	ND	7
	TCE	1,000	ND
Ba3	cis 1,2-DCE	390	150
	1,1,1-TCA	ND	ND
	TCE	ND	ND
D3	cis 1,2-DCE	3	19
	1,1,1-TCA	ND	ND
	TCE	32	ND
D7	cis 1,2-DCE	1,300	160
	1,1,1-TCA	ND	ND
	TCE	250	ND
D9	cis 1,2-DCE	300	140
	1,1,1-TCA	ND	ND
	TCE	1	1
E5	cis 1,2-DCE	740	430
	1,1,1-TCA	ND	ND
	TCE	4	ND
F9	cis 1,2-DCE	760	900
	1,1,1-TCA	ND	ND
	TCE	6	ND
F13	cis 1,2-DCE	12	26
	1,1,1-TCA	ND	ND
	TCE	1	3
G3	cis 1,2-DCE	460	12
	1,1,1-TCA	ND	ND
	TCE	12	ND
Ga8	cis 1,2-DCE	150	27
	1,1,1-TCA	ND	ND
	TCE	ND	ND
Ga13	cis 1,2-DCE	90	10
	1,1,1-TCA	ND	ND
	TCE	19	3
Ja4	cis 1,2-DCE	180	94
	1,1,1-TCA	ND	ND
	TCE	ND	2
Ja9	cis 1,2-DCE	100	53
	1,1,1-TCA	ND	ND
	TCE	ND	ND

ND = Not detected, detection limit not provided.

COST OF THE TECHNOLOGY SYSTEM

COST DATA [5,7,12]

While data about the total cost of remediation efforts to date was confidential, the vendor provided costs on a per unit basis for the full-scale ERH remediation through November 1998 (initial treatment of 23,100 cubic yards). The cost of $32 per cubic yard included the installation and operation of the ERH power system and electrodes, vapor extraction and condensate treatment, project permitting, preparation of work plans, electrical use, waste disposal, interim sampling, and progress reporting. As of November 20, 1998, a total of 1,775 MW-hr of electrical energy had been consumed by the ERH system at a cost of as much as $14,000/month plus $40 per MW-hr for a total cost for electricity of $148,000. This corresponded to $6.40 per cubic yard of treatment volume, or 20% of the total cost of $32 per cubic yard.

In addition, the vendor provided a unit cost for treatment from December 1998 through May 1999 (treatment of 11,500 cubic yards). This unit cost also was $32 per cubic yard.

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED

The ERH system used at this site achieved the established Tier III cleanup goals for the remediation of the initial estimated 23,000 cubic yards of remaining contamination at the site in about six months and for the remediation of the additional 11,500 cubic yards of contamination at the site in about five months. In addition, the concentrations of constituents in a number of wells had been reduced to the more stringent Tier 1 standards.

REFERENCES

1.   Eastep, Lawrence W., Illinois Environmental Protection Agency. Review of Remedial Action Completion Report. July 29, 1999.

2.   Beyke, Gregory, CES, et al. DNAPL Remediation Closure With Six-Phase Heating. The Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Monterrey, CA. Pages 183-189. May 22-25, 2000.

3.   Fleming, David. Corporate Development Leader, Current Environmental Solutions (CES). Personal communication with Bryan Smith, Tetra Tech EM Inc., December 1998.

4.   CES. "Applications Analysis Report: DNAPL Remediation in the Saturated Zone Using Six-Phase Heating™." Former Manufacturing Facility in Chicago [Skokie], Illinois. November 1998.

5.   CES. "Skokie Site Update and Cost and Effectiveness Information." November 1998.

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6. CES. "Soil Vapor Extraction to the Sixth Degree." Reprint from *Soil and Groundwater Cleanup* magazine. July 1997.

7. Heath, Bill. Comments on Draft Cost and Performance Report. Six-Phase Heating™ (SPH) at a Former Manufacturing Facility near Chicago, Illinois. March 1999.

8. Heath, Bill. Update on site activity. Personal communication with Bryan Smith, Tetra Tech EM Inc., April 28, 1999.

9. Beyke, Greg. Update on site activity. Personal communication with Bryan Smith, Tetra Tech EM Inc., April 29, 1999.

10. Illinois Environmental Protection Agency. *Site Remediation Program*. http://www.epa.state.il.us/land/site-remediation/overview.html

11. Beyke, Greg. E-mail to Bryan Smith, Tetra Tech EM Inc. Skokie Groundwater Data. May 6, 1999.

12. Beyke, Greg. Update on site activity. Personal communication with Bryan Smith, Tetra Tech EM Inc., April 29, 1999 and with Richard Weisman, Tetra Tech EM Inc. on June 29, 1999.

13. Smith, Gregory. Comments on Draft Report for Six-Phase Heating Application, Skokie, IL. July 23, 1999.

14. Komperda, Stan. Comments on Draft Report for Six-Phase Heating Application, Skokie, IL via personal communication with Richard Weisman, Tetra Tech EM Inc., July 26, 1999.

15. Smith, Gregory, et al. Closure of Trichloroethene and 1,1,1-Trichloroethane DNAPL Remediation Using Thermal Technologies. The Second International Conference on Remediation of Chlorinated and Recalcitrant Compounds. Monterrey, CA. Pages 167-174. May 22-25, 2000.

16. Komperda, Stan, Illinois EPA. Personal communication with Mary Sherrill, Tetra Tech EM Inc. August 21, 2002.

17. Adams, Tim, ENSR. Personal communication with Mary Sherrill, Tetra Tech EM Inc. September 4, 2002.

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COST AND PERFORMANCE REPORT

Electrical Resistive Heating at the
Poleline Road Disposal Area, Arrays 4, 5, and 6
Fort Richardson, Alaska

June 2003

SITE INFORMATION

IDENTIFYING INFORMATION [2]

Site Name: Poleline Road Disposal Area (PRDA), Arrays 4, 5, and 6
Location: Fort Richardson, Alaska
Regulatory Context: CERCLA
ROD Date: August 8, 1997
Technology: Electrical Resistive Heating (ERH)
Scale: Field demonstration

TECHNOLOGY APPLICATION [2]

Period of Operation: July through October 1999

Type/Quantity of Material Treated During Application: Source zone - Estimated to be 13,000 tons or 7,333 yd^3 based on a treatment area of approximately 110 ft long by 50 ft. wide by 36 ft. deep.

BACKGROUND [2,6]

Fort Richardson, established in 1940 as a military staging and supply center during World War II, is located approximately 10 miles northeast of Anchorage, Alaska and occupies about 56,000 acres. Its current mission is to provide services, facilities, and infrastructure to support the rapid deployment of Army forces. The site was added to the National Priority List (NPL) in June 1994. In December 1994, the Army, the Alaska Department of Environmental Conservation (ADEC), and EPA signed a Federal Facilities Agreement (FFA) to address contamination at the site. The FFA divided Fort Richardson into four Operable Units. This report addresses the use of ERH at the Poleline Road Waste Disposal Area (PRDA) which is part of Operable Unit B (OUB).

The PRDA is a 1.5 acre area that was used as a disposal area from 1950 to 1972. PRDA was divided into four areas: .Areas A-1, A-2, A-3, and A-4. Shallow trenches (8 to 10 ft. deep) were used for the disposal of a wide variety of wastes including chemical warfare agents and training materials, smoke bombs, and other materials. During operation, a layer of bleach and lime was placed in the bottom of the trench, with the contaminated materials placed on a pallet in the trench. Diesel fuel was poured on the waste and ignited. After cooling, chlorinated solvents, including trichloroethene (TCE), tetrachloroethene (PCE), and 1,1,2,2-tetrachloroethane (PCA) were mixed with lime or bleach and poured over the materials to neutralize the chemical agents.

Results of a geophysical survey showed that Areas A-3 and A-4 contained the greatest amount of buried waste. Sampling of these areas showed that soil and groundwater has been contaminated with chlorinated solvents including TCE, PCE, and TCA. A removal action was conducted in these two areas in 1993 and 1994 to remove contaminated soil and debris. Soil was excavated to a depth of up to 14 ft (depth at which groundwater was encountered). Excavated soils that exceeded the removal action concentration levels (TCE-600 : g/kg), PCE (100 : g/kg), and TCA (30 : g/kg) were stockpiled for treatment.

Areas A-1 and A-2 were not sampled because of the potential for buried unexploded ordnance. Results of soil and groundwater sampling in surrounding areas showed relatively lower contaminant concentrations, therefore no treatment was performed in them. During the remedial investigation, chlorinated solvents were found in soil and groundwater in Areas A-3 and A-4. TCE, PCE, and PCA were found at levels as high as 2,030 : g/kg for PCA, with the soil determined to be a continuing source of groundwater

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contamination. All four main water bearing zones at the site were determined to be contaminated with TCE and PCE at levels as high as 1,900 : g/L for TCE.

To evaluate the effectiveness of potential remedial technologies, a treatability study of SVE and air sparging groundwater was conducted in 1996. The results of the study indicated that SVE had the potential to reduce contamination at the site but that air sparging would not be effective in remediating groundwater contamination.

ERH was then evaluated as a potential remediation technology for the site. Two field demonstrations of ERH were performed at the site. A 1997 ERH field demonstration was used to treat 7,150 tons of soil in Areas A-3 and A-4, and involved three heating arrays (labeled 1, 2, and 3). The results of this demonstration are presented in the report *Cost and Performance Report Soil Vapor Extraction Enhanced by Six-Phase Heating at Poleline Road Disposal Area, OU-B Fort Richardson Alaska*, prepared by the U.S. Army Corp of Engineers, Hazardous, Toxic, Radioactive Waste Center of Expertise.

This report describes the second ERH field demonstration, in Area A-3 using heating arrays labeled 4, 5, and 6, that was conducted from July through October 1999.

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MATRIX DESCRIPTION

MATRIX AND CONTAMINANT IDENTIFICATION [2]

Type of Media Treated: Source zone (saturated and unsaturated)

Primary Contaminant Group: Chlorinated solvents - TCE, PCE, PCA

SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [2,6]

The subsurface soil at ths site is primarily high density glacial tills, including silty sands with some gravel and a few clay-sized particles. Four water-bearing intervals have been identified at PRDA: a perched groundwater interval, a shallow aquifer, an intermediate aquifer, and a deep aquifer. Zones of high-density tills separate the saturated intervals. Groundwater was encountered at a depth of 4 to 14 ft. bgs. Between 4 and 12 ft. bgs the groundwater encountered was perched, and groundwater encountered below 12 ft. was in the shallow aquifer. The deep aquifer and glacial tills overlie bedrock composed of a hard black fissile claystone with fine sandy siltstone interbeds. Bedrock is encountered from approximately 80 to 170 ft. bgs and has an unknown thickness.

Contaminants in soil and groundwater at the PRDA include TCE, PCE, and PCA. Sampling data indicated that the soil between 16 and 27 ft. bgs had the highest contaminant concentrations. Groundwater contamination was present in all four intervals. In addition, DNAPL has been observed. Table 1 lists the matrix characteristics affecting treatment cost or performance for this application.

Table 1: Matrix Characteristics Affecting Treatment Cost or Performance [2,6]

Parameter	Value	Measurement Procedure
Soil Classification	SP-gravelly sand GP-sandy gravel GM-silty sandy gravel	Unified Soil Classification System
Clay Content and/ or Particle Size Distribution	Low clay content; silt, sand and gravel observed	Visual
Moisture Content	7.3-13.9%	Method 7-2.2, Methods of Soil Analysis
Soil Air Permeability	1.6×10^{-7} cm^2	Calculated using field measurements and steady state equation

Table 1: Matrix Characteristics Affecting Treatment Cost or Performance [2,6] (continued)

Parameter	Value	Measurement Procedure
Porosity	21-27%	Estimated from soil classification and particle size distribution
Depth bgs or Thickness of Zone of Interest	8 to 35 ft. bgs	Soil and groundwater sampling data
Total Organic Carbon	0.19-0.66%	ASA 90-3.2
Presence of Nonaqueous Phase Liquids (NAPLs)	DNAPL found in a 2" monitoring well (site personnel did not identify separate phase DNAPL in other areas of the site)	Visual
Electrical Conductivity	Acceptable	Not Available

Table 2 lists the contaminants of concern found at the site, the maximum concentration in the groundwater or soil, and the Remedial Action Objectives (see further discussion below under technology performance).

Table 2. Maximum Contaminant Concentrations in Soil and Groundwater Before Treatment and Remedial Action Objective [2]

Contaminant	Maximum Groundwater Concentration (mg/L)	Groundwater Remedial Action Objective (mg/L)	Maximum Soil Concentration (mg/kg)	Soil Remedial Action Objective (mg/kg)
Benzene	0.017	0.005	NA	NA
Carbon Tetrachloride	0.037	0.005	NA	NA
cis-1,2-Dichloroethene	0.73	0.07	NA	NA
trans-1,2-Dichloroethene	0.73	0.1	NA	NA
PCE	0.30	0.005	120	4.0
TCE	7.8	0.005	640	0.015
PCA	18.0	0.052	12,000	0.1

NA - Information not available

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY [2]

Electrical Resistive Heating (Six-Phase Heating[TM])

TREATMENT SYSTEM DESCRIPTION AND OPERATION [2,6]

The ERH system used for this demonstration (Figures 1 and 2) was constructed in three phases. The electrode arrays for these three phases were identified as Arrays 4, 5, 6. Each phase included an array of seven electrodes, 3 SVE wells, and two thermocouple. A 300 kW transformer supplied power to the electrodes. The electrodes were spaced approximately 19 ft. apart, and electrodes in one row were offset from electrodes in adjacent rows by approximately 9.5 ft.. Electrodes were installed to a depth of 38 ft. to treat an area approximately 110 ft. long by 50 ft. wide by 35 ft. deep.

Array 5 was installed from May 18-27, 1999; Array 4 from June 7-15; and Array 6 from July 12-20. The ERH field demonstration was conducted from July to October 1999. Parameters monitored during the demonstration included transformer voltage, amperages, and total power; soil temperature from thermocouples which measured soil temperature at six locations within the treatment areas at depths of 12, 25, and 38 ft; and soil resistivity. Other parameters monitored included vacuum pressure, concentration of VOCs in condensed off-gas, and off-gas vacuum flow. During operation, an on-site computer was used to adjust voltages on the transformer to maintain a power input of 700 to 800 kW. The vacuum applied by the blower was adjusted by opening or closing a vacuum relief valve located just between the condenser and the blower. The system was designed to increase the temperature of the soil to 100°C. The soil temperature achieved during the demonstration ranged from 44 to 100°C. The highest soil temperatures achieved during the demonstration ranged from 55 to 82°C at 12 ft., 98 to 100°C at 25 ft., and 43 to 80°C at 38 ft.. The soil temperature at 38 ft. was less than at 25 ft. because there was less moisture at that depth (moisture was removed from the area by the SVE system) thereby decreasing the soil conductivity.

The SVE system was operated two weeks prior to ERH system start up to allow testing of the SVE system. The SVE system was then shut down until August 1999 (the time at which the output of the ERH system had reached 1099 V). The SVE system was used to remove steam and contaminant vapors. The extracted soil gas vapor was passed through a condenser, a condensate holding tank and an off-gas treatment unit. No information was provided about the type of off-gas treatment.

Condensate and condenser off-gas samples were collected approximately every other day during operation and analyzed for VOCs. Instrument readings and analytical results were used to calculate the mass of contaminants removed via the extracted soil gas and condensate water. Table 3 presents information on the soil temperatures achieved during operation.

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Figure 1. Treatment Area and Location of Sampling Points for the Electrical Resistive Heating Treatment at the Fort Richardson Site [2]
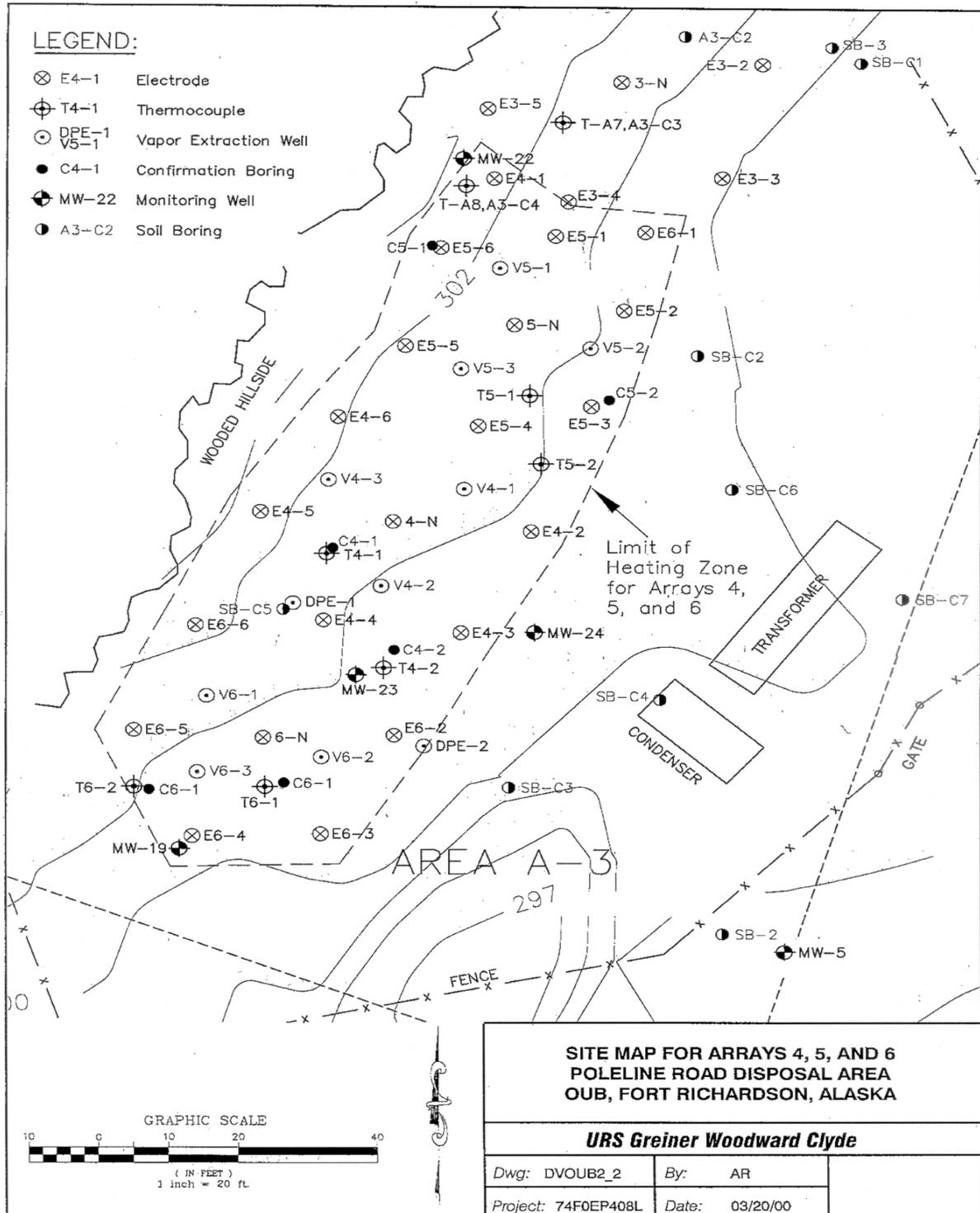
Figure 2. Process Flow Diagram of Electrical Resistive Heating System Used at the Fort Richardson Site [2]
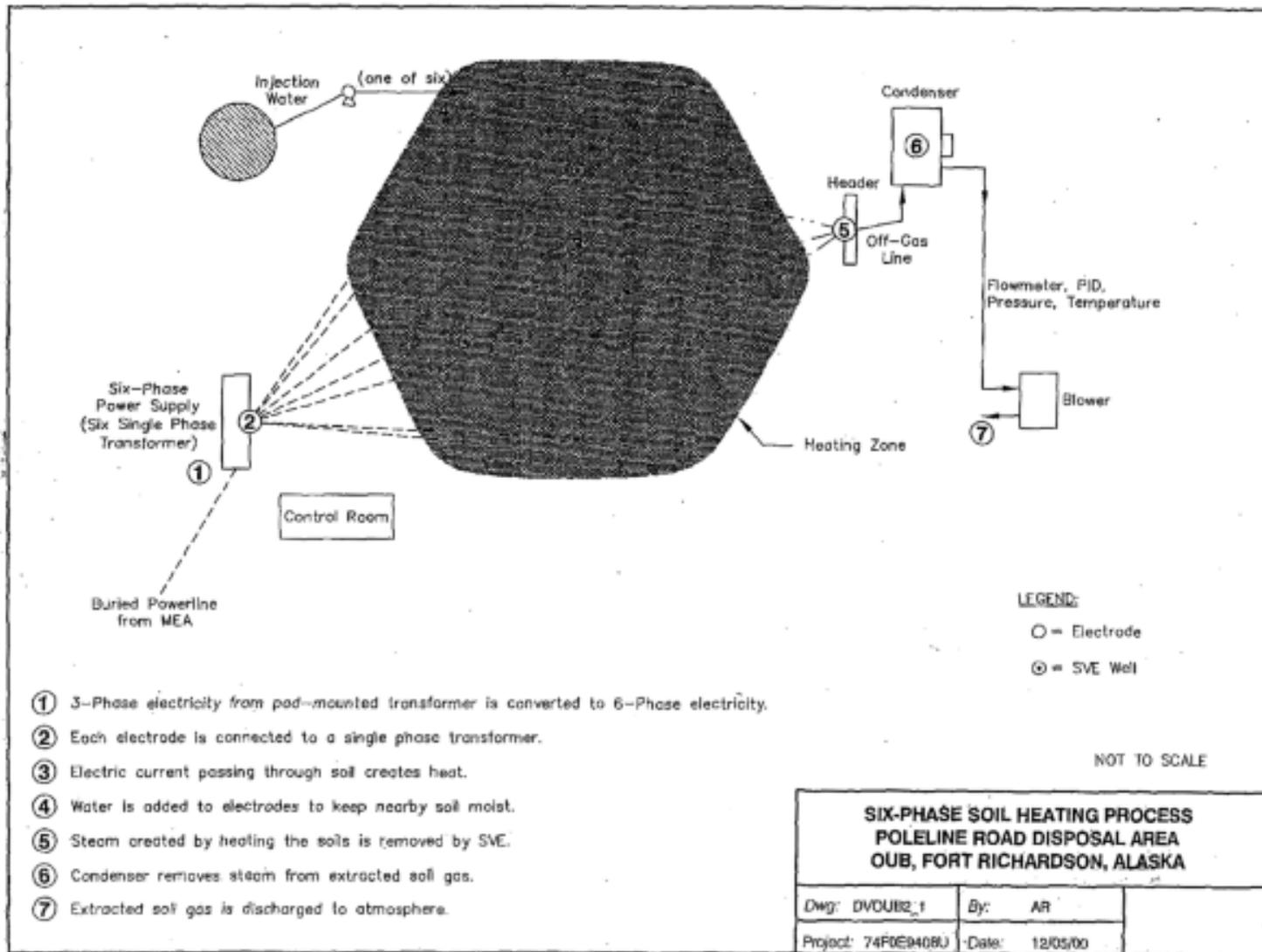
① 3-Phase electricity from pad-mounted transformer is converted to 6-Phase electricity.

② Each electrode is connected to a single phase transformer.

③ Electric current passing through soil creates heat.

④ Water is added to electrodes to keep nearby soil moist.

⑤ Steam created by heating the soils is removed by SVE.

⑥ Condenser removes steam from extracted soil gas.

⑦ Extracted soil gas is discharged to atmosphere.

SIX-PHASE SOIL HEATING PROCESS
POLELINE ROAD DISPOSAL AREA
OUB, FORT RICHARDSON, ALASKA

| Dwg: DVOUB2_1 | By: AR | |
| Project: 74F0E9408U | Date: 12/05/00 | |

Table 3. Temperature Achieved During ERH Operation [2]

Thermocouple Location	Depth (ft)	Highest Temperature Achieved (ºC)	Date
T4-1	12	80	Sept 26, 1999
T4-1	25	100	Sept 26, 1999
T4-1	38	61	Oct 10, 1999
T5-1	12	78	Oct 3, 1999
T5-1	25	98	Oct 3, 1999
T5-1	38	55	Oct 10, 1999
T6-1	12	77	Oct 10, 1999
T6-1	25	100	Sept 26, 1999
T6-1	38	100	Oct 3, 1999
T4-2	12	80	Oct 3, 1999
T4-2	25	100	Sept 26, 1999
T4-2	38	58	Oct 3, 1999
T5-2	12	82	Sept 14, 1999
T5-2	25	100	Aug 15, 1999
T5-2	38	63	Sept 14, 1999
T6-2	12	55	Oct 2, 1999
T6-2	25	87	Oct 3, 1999
T6-2	38	43	Oct 8, 1999

TIMELINE [1,2]

- August 1997   Record of Decision signed
- June - December 1997   First ERH treatment application
- July - October 1999   Second ERH treatment application

TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [2,6]

The objective of this field demonstration was to evaluate the effectiveness of ERH in reducing the concentration of chlorinated solvents in groundwater. Performance of the system was evaluated by monitoring the ability of the system to:

- Heat the soil in the study area

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- Increase the removal rate of contaminants, as compared to previous ERH tests conducted at the site
- Effectively remove VOCs from the soil and groundwater

The remedial action criteria were established in the ROD, based on MCLs in the State of Alaska, and are listed by contaminant in Table 2.

TREATMENT PERFORMANCE [2]

Performance data for the ERH system included mass removal data, groundwater concentration data, and soil concentration data. Groundwater monitoring data are available for three wells in the area treated: MW-19, MW-22, and MW-23. In addition, four soil borings were collected from the treatment area and analyzed before treatment: T4-1, T4-2, T6-1 and T6-2.

The mass of TCE, PCE, and PCA removed by the system was estimated based on the estimated mass removed via the off-gas and condensate. The estimated mass of TCE, PCE, and PCA removed in the off-gas was 1,008 pounds, 53 pounds, and 324 pounds, respectively. The estimated mass of TCE, PCE, and PCA removed in the condensate was 10 pounds, 0.25 pounds, and 55 pounds, respectively.

Tables 4 and 5 present data on concentrations of contaminants in groundwater and soil, respectively, for samples collected before ERH treatment (March 1999), and after the treatment was completed (November 1999).

Table 4. Groundwater Performance Date for ERH at the Fort Richardson Site [2]

Analyte	Remedial Action Objective (mg/kg)	Month Sampled	Concentration and Detection Limit (mg/L)		
			MW-19	MW-22	MW-23
Benzene	0.005	March	ND(0.001)	ND(0.01)	ND(0.01)
		November	ND(0.001)	ND(0.001)	ND(0.001)
Carbon tetrachloride	0.005	March	ND(0.001)	ND(0.01)	ND(0.01)
		November	ND(0.001)	ND(0.001)	ND(0.001)
Cis-1,2-dichloroethene	0.07	March	0.014	0.180	0.230
		November	0.01	0.058	0.300
Trans-1,2-dichloroethene	0.1	March	0.006	0.060	0.230
		November	0.0013	0.015	0.036
PCA	0.052	March	0.690	2.800	17.000
		November	0.850	0.810	0.100
PCE	0.005	March	0.007	0.062	0.072
		November	ND (0.001)	0.029	0.0010
TCE	0.005	March	0.280	1.700	3.100
		November	0.021	1.600	0.970

Table 5. Soil Performance Date for ERH at the Fort Richardson Site[2]

Analyte	Remedial Action Objective (mg/kg)	Month Sampled	Concentration and Detection Limit (mg/kg)			
			T4-1	T4--2	T6-1	T6-2
PCA	0.1	March	12,000	67	530	0.07
		November	ND (0.03)	ND (0.034)	ND (0.033)	ND (0.032)
PCE	4.0	March	120	1	3.1	0.09
		November	0.012	0.098	0.71	ND (0.032)
TCE	0.015	March	640	6	200	1.7
		November	12	0.087	63	0.84

As shown in Table 4, groundwater contaminant concentrations generally decreased between March 1999 and November 1999, with PCA, PCE and TCE decreasing an average of 49 percent, 75 percent and 56 percent, respectively. Concentrations of PCA in groundwater from MW-19 increased between March and November 1999. According to the vendor, because only a portion of the contaminated area was treated, and MW-19 was on the edge of the treatment area, this increase may have been due to contaminant migration from outside the treatment area. Concentrations of cis-1,2-dichloroethene, a breakdown product of TCE, increased in MW-23. As of November 1999, concentrations of PCA, PCE, TCE, and cis-1,2-DCE were above the remedial action objectives in groundwater.

As shown in Table 5, concentrations of PCA, PCE and TCE in soil decreased from March to November 1999. PCA and PCE were reduced to below the remedial action objectives. However, TCE concentrations remained above the remedial action objective, with concentrations ranging from 0.087 to 63 mg/kg.

Temperature data collected from thermocouples at the site showed that soil and groundwater temperatures could be increased to 100ºC, however, this temperature was not consistently achieved throughout the treatment area. The temperature in Array 6 was only raised to 90ºC for a short time, and the percent reduction in this array was the lowest of the three arrays.

The residual groundwater contaminant plume is being monitored in 22 groundwater wells on a quarterly basis. This monitoring includes two wells in the area treated, MW-19 and MW-23. Figures 3, 4, 5, and 6 show the concentrations of TCE and PCA in these wells in November 1997 and April 2001, respectively.

In MW-19, concentrations of both contaminants were greater than 100 : g/L before treatment. After treatment, the concentrations of each of these contaminants was reduced to less than 1 : g/L. In MW-23, concentrations of both contaminants were greater than 1,000 : g/L before treatment. After treatment, the concentrations of these contaminants remained at more than 100 : g/L.

Figure 3. Residual Groundwater Plume Monitoring Data at the Fort Richardson Site: TCE in MW-19 (log scale) [7]
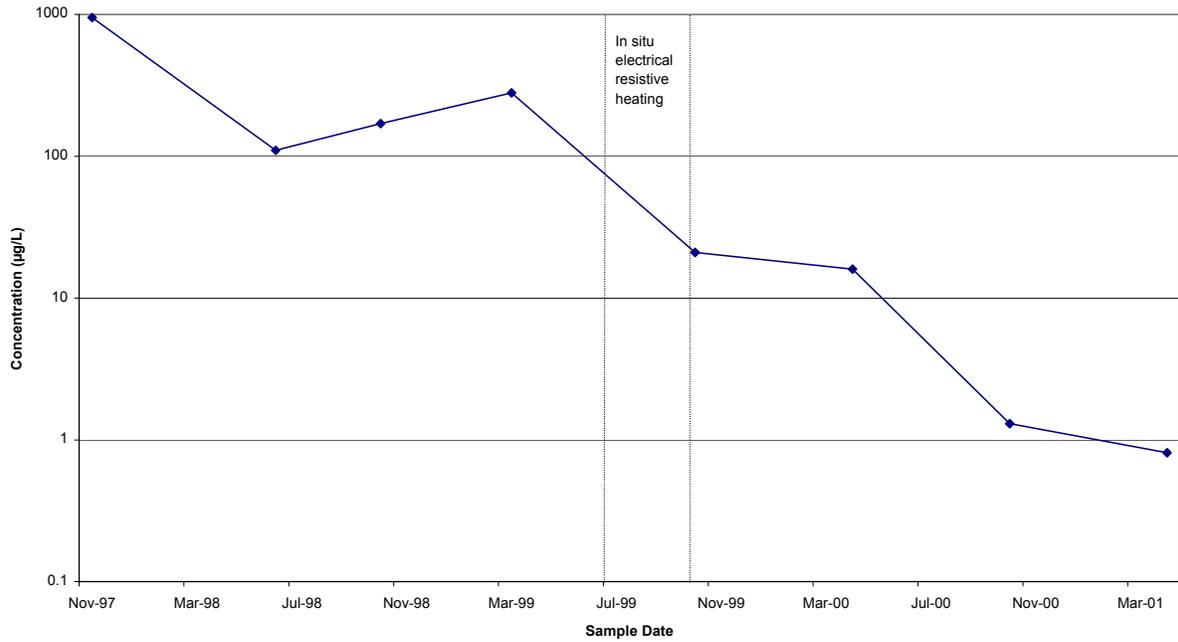

Figure 4. Residual Groundwater Plume Monitoring Data at the Fort Richardson Site: PCA in MW -19 (log scale) [7]

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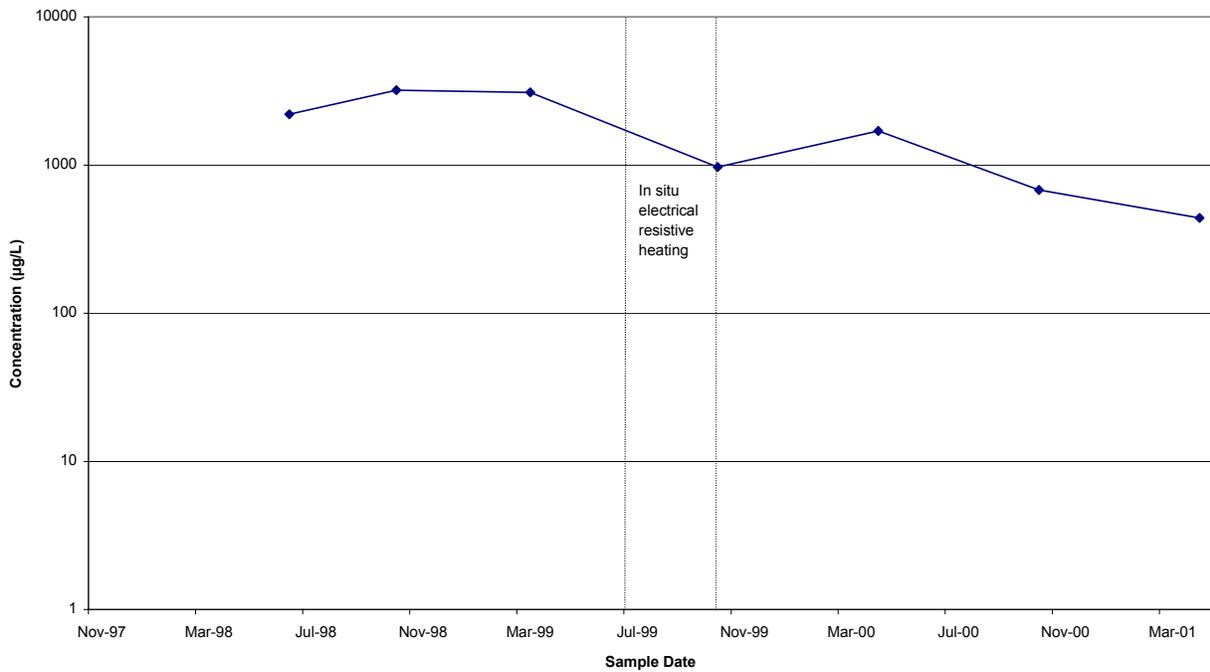Technology Innovation Office

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Figure 5. Residual Groundwater Plume Monitoring Data at the Fort Richardson Site: TCE in MW-23 (log scale) [7]
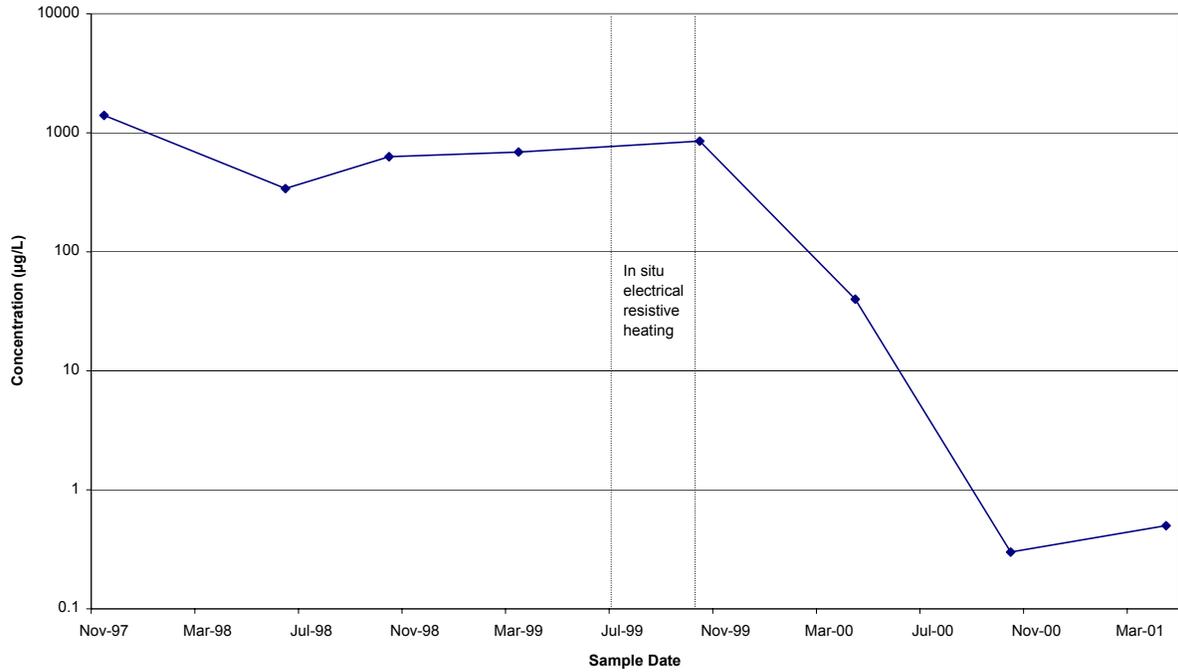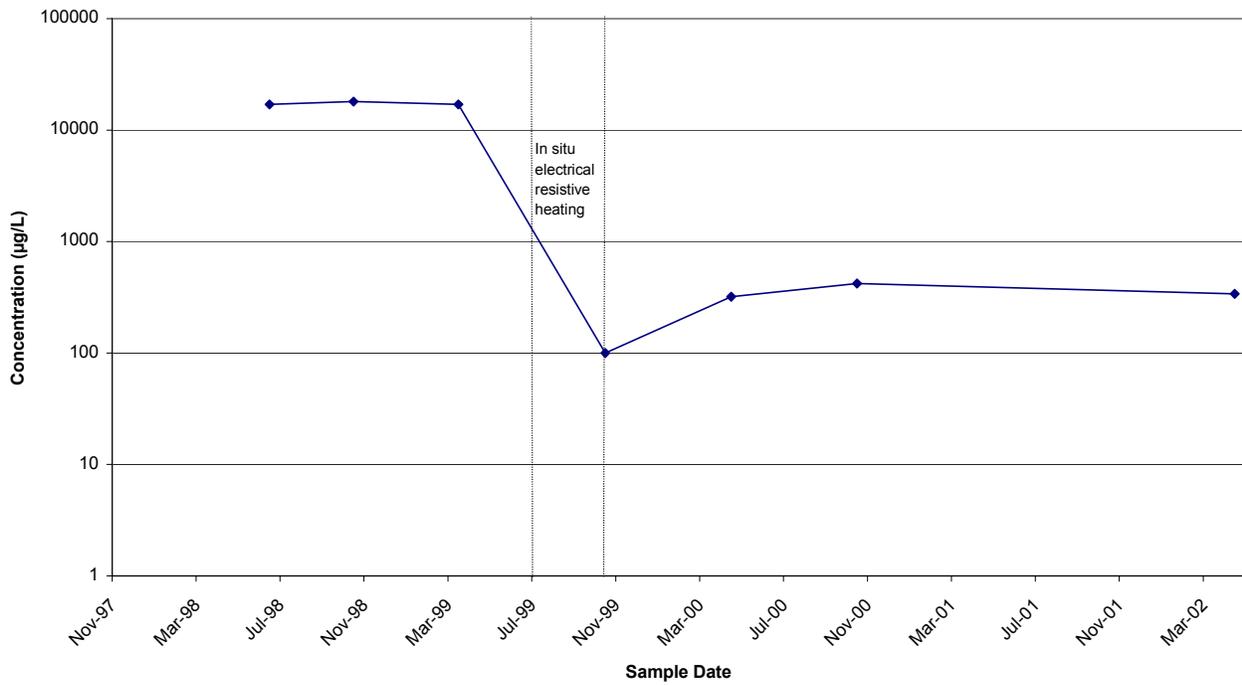

Figure 6. Residual Groundwater Plume Monitoring Data at the Fort Richardson Site: PCA in MW-23 (log scale) [7]

COST OF THE TECHNOLOGY SYSTEM

Cost information was not provided for this application.

OBSERVATIONS AND LESSONS LEARNED

The field demonstration of ERH reduced soil and groundwater contaminant concentrations in Area A-3. Groundwater contaminant concentrations were reduced by as much as 75 percent, though concentrations remained about the remedial action objective for the site. Concentrations of PCA, PCE and TCE in soil decreased during this period. PCA and PCE were reduced to below the remedial action objectives; however, TCE concentrations in soil remained above the remedial action objective.

REFERENCES

1.   Tetra Tech EM, Inc. Record of Telephone Conversation Regarding the Poleline Road Disposal Area Between Mary Sherrill, Tetra Tech EM, Inc. and Mark Prieksat, Department of Defense Environmental Resources Department. August 19, 2002.

2.   URS Corporation. "Design Verification Study Arrays 4, 5, and 6, Operable Unit B, Poleline Road Disposal Area, Fort Richardson, Alaska," Prepared for the Alaska District, U.S. Army Corp of Engineers. March, 2001.

3.   URS Corporation. "Long Term Groundwater Monitoring Report, Operable Unit B, Poleline Road Disposal Area, Fort Richardson, Alaska," Prepared for the Alaska District, U.S. Army Corp of Engineers. July, 2001.

4.   URS Corporation. "Long Term Groundwater Monitoring Report, Operable Unit B, Poleline Road Disposal Area, Fort Richardson, Alaska," Prepared for the Alaska District, U.S. Army Corp of Engineers. October, 1999.

5.   U.S. Army Corp of Engineers, Hazardous, Toxic, Radioactive Waste Center of Expertise, "Cost and Performance Report Soil Vapor Extraction Enhanced by Six-Phase Heating at Poleline Road Disposal Area, OU-B Fort Richardson Alaska. October 1999.

6.   U.S. EPA. Record of Decision for Operable Units A and B, Fort Richardson, Anchorage, Alaska. EPA-541-R-97-202. August 1997.

7.   URS Corporation. "Long Term Groundwater Monitoring Report, Operable Unit B, Poleline Road Disposal Area, Fort Richardson, Alaska," Prepared for the Alaska District, U.S. Army Corp of Engineers. November, 2000.

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COST AND PERFORMANCE REPORT

Electrical Resistive Heating at the
ICN Pharmaceutical Site
Portland, OR

February 2004

SITE INFORMATION

IDENTIFYING INFORMATION

Site Name: ICN Pharmaceuticals Incorporated
Location: 6060 NE 112th Ave., Portland, Oregon
Regulatory Context: Oregon Department of Environmental Quality (DEQ) oversight
Technology: Electrical resistive heating (ERH)
Scale: Full-scale

TECHNOLOGY APPLICATION

Period of Operation: May 2000 to December 2001

Type/Quantity of Material Treated during Application [4]: Source zone - Estimated 48,000 to 65,000 cubic yards based on a treatment area of three-quarters to one acre in size and a depth of 40 ft. Groundwater - Plume size estimated to be 120 ft by 80 ft

BACKGROUND [1,2]

The ICN Pharmaceuticals site, located in Portland, Oregon, was used as a clinical laboratory from 1961 to 1980. The laboratory used a variety of organic and inorganic compounds with wastes from laboratory operations disposed in a dry well which was about 20 ft deep. In 1980, the laboratory was shut down and materials and machinery were removed. In 1993 and 1994, the laboratory building and associated structures were removed from the site. Results of groundwater investigations at the site identified the former dry well as the source of groundwater contamination. The groundwater in the vicinity of the former dry well was determined to be contaminated with volatile organic compounds (VOCs) including trichloroethene (TCE), cis-1,2-dichloroethene (DCE), vinyl chloride (VC), benzene, and toluene. TCE, DCE, and VC were detected in the groundwater at concentrations greater than 1% of their solubility, suggesting the presence of dense non-aqueous phase liquid (DNAPL). On August 23, 1999, a record of decision (ROD) was signed for the site to address the groundwater contamination in the area of the dry well. ERH, in conjunction with SVE, was implemented at the site to treat the DNAPL source and dissolved phase VOCs in groundwater.

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MATRIX DESCRIPTION

MATRIX AND CONTAMINANT IDENTIFICATION [1,2]

Type of Media Treated: Source zone (saturated and unsaturated)

Primary Contaminant Groups: Chlorinated solvents - TCE, cis-1,2-DCE, VC

SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [2,4]

The site geology consists of fluvial and lacustrine depositional sequences (Overbank) to a depth of approximately 60 feet bgs. Silts and sands are discontinuously interlayered throughout the Overbank deposits. The water table is encountered in the Overbank at approximately 8 ft bgs. Troutdale Gravel Aquifer (TGA) underlies the Overbank formation and consists of unconsolidated and cemented gravels of the Troutdale Formation. The TGA is approximately 175 feet thick in the site area (60 to 235 feet bgs). A confining layer encountered at a depth of 235 ft bgs at the base of the TGA consists of sand, silt, and clay of lacustrine origin and is approximately 100 feet thick at the site.

DNAPLs were present in the Overbank, with dissolved phase VOCs present in both the Overbank and TGA layers. The areal extent of the DNAPL source in the Overbank was estimated to be three-quarters to one acre in size, extending about 120 ft to the south of the dry well with a width of about 80 ft.

Table 1 lists the matrix characteristics affecting technology cost and performance for this application:

Table 1. Matrix Characteristics Affecting Technology Cost or Performance [1,2,4]

Parameter	Value
Soil Classification	Silts and sands
Clay Content and/or Particle Size Distribution	Upper 15 feet of the Overbank consists predominantly of silts. Silts and sands are discontinuously interlayered throughout the Overbank Deposits.
Depth to Groundwater	The water table was encountered in the silts at approximately 8 ft bgs
Hydraulic conductivity	The transmissitivity of the Overbank ranges from 5 to 11 gpd/foot. The conductivity ranges from 2.6x10-5 to 5.2x10-5 cm/sec.
Air permeability	Not available
Porosity	Not available
Presence of NAPLs	Suggested presence of DNAPL
Total organic carbon	Not available
Electrical resistivity of soil	Not available

Table 1. Matrix Characteristics Affecting Technology Cost or Performance [1,2,4] (continued)

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY

Electrical Resistive Heating (Six-Phase Heating^{TM})

TREATMENT SYSTEM DESCRIPTION AND OPERATION [1,4,5]

The ERH system at the site was operated from May 2000 to December 2001. The initial ERH system consisted of 60 electrodes installed to a depth of 58 feet. The electrodes were placed in hexagonal arrays of 6 electrodes each, with a seventh neutral electrode in the middle of each array. The annular spaces in the boreholes into which the electrodes were installed were packed with steel shot to improve conductivity and increase the effective diameter of the electrodes. In addition, impermeable seals were placed in the annular spaces to prevent hot vapors and liquids from escaping through the boreholes. Each electrode was capable of directing power to three zones in the Overbank: 20-30 ft bgs, 34-44 ft bgs, and 48-58 ft bgs. A 95 kW transformer was used to convert standard three-phase electrical power to six separate phases. The system was monitored using 13 subsurface pressure monitoring points and 8 subsurface thermocouples. The treatment system began operating in May 2000. The initial heating was limited to the bottom interval (45 to 58 ft bgs) to establish a "hot floor" and prevent downward migration of contamination. No information was provided about how long this initial heating was conducted or when heating in other zones began.

During the operation, steam and hot water were observed outside the treatment area. In addition, steam and hot water at the surface of the site were identified as a health and safety hazard at the site. In December 2000, 50 "electrode vents" screened from 25-35 feet bgs were placed along the perimeter of and throughout the treatment area to control the migration of steam and hot water. In addition, because the steam and hot water were contaminated, the treatment area was expanded in May 2001. The additional treatment areas were located along the eastern, southern, and northern portions of the initial treatment area where contaminated steam and hot water had been observed.

Nine electrodes, four "electrode vents", two groundwater monitoring wells, and one thermocouple were installed in the eastern portion of these expanded treatment areas. In the southern portion, 4 electrodes, 11 "electrode vents" screened from 25-35 ft bgs, two groundwater monitoring wells, and two thermocouples were installed. In the northern portion 2 "electrode vents" were installed.

In August 2001, a blower failed, and steam and vapors could not be removed from an unspecified portion of the treatment area. The system was turned off in this area. A new blower was installed in September 2001 and the treatment was restarted.

When the ERH remediation area was expanded, in December 2000 and May 2001, electrodes were placed within close proximity to the security fence that surrounded the perimeter of the ERH remediation area. As a result, an induced voltage was detected during a routine step-and-touch voltage survey on the security fence gate. The voltage on the fence was an induced voltage caused by the fence crossing through the electro magnetic field (EMF) generated by the power transfer between the different phased electrodes. This condition was further enhanced by the concurrent operation of two separate treatment zones at least 100 yards apart, where the same perimeter fence encircled both zones. This configuration caused an increased difference in voltage potential at any point where the fence was broken (e.g., at a gate). This problem was remedied by making sure that the fence line remained unbroken, so that it formed one continuous loop. This corrective action was accomplished by grounding the gates to a wire mesh screen that was buried beneath shallow soils, and attached to both adjacent fence sections. The fence was also grounded on both sides of the site (i.e. separate treatment zones) to help decrease the voltage potential at the fence. Before these two corrective actions were implemented voltage at the fence was as high as 40 V at any point where the fence line was broken, after the fixes the voltages were below 12 V for the remainder of the project.

A soil vapor extraction (SVE) system was used to recover the steam and contaminant vapors from the unsaturated region immediately above the heated region. The initial 53 vapor extraction wells were screened from 5-10 feet bgs. The SVE system was designed to separate the vapor and liquid phases and separately treat the two effluent streams. The vapor treatment system consisted of a heat exchanger/ condenser, followed by granular activated carbon and potassium permanganate treatment. Recovered water was discharged to a municipal sewer. As of September 2002, the SVE blower remained in operation, at the request of the DEQ, to collect any remaining vapors generated from the subsurface. Groundwater monitoring is continuing, with data available through June 2002.

TIMELINE

- August 1999   ROD signed for the site
- May 2000   Full-scale operation began
- December 2000   50 "electrode vents" added
- May 2000   Treatment expanded with the addition of 13 electrodes and 19 "electrode vents"
- December 2001   Remediation completed; ERH system was shut off
- December 2001 - September 2002   Groundwater monitoring performed

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TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [2]

The Remedial Action Objectives for this site, specified in the Record of Decision (ROD), were to:

- Prevent and contain migration of separate-phase DNAPL during treatment
- Reduce contaminant groundwater concentrations to levels that indicate DNAPL has been removed or treated

The ROD specified that the primary goal of the action was to remediate DNAPL and that the residual risk to human health and the environment and the need for further remediation would be assessed following

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remediation of the DNAPL. No numeric clean-up levels for contaminants were identified in the ROD, therefore the cleanup goals were based on Oregon maximum contaminant levels (MCLs).

TREATMENT PERFORMANCE [1,4]

Figure 1 shows the location of the shallow, intermediate, and deep monitoring wells at the site, relative to the area that was treated. TCE, DCE, and VC concentrations were monitored in the Overbank area and DCE, VC, and benzene concentrations were monitored in the TGA layer. Table 2 shows the maximum groundwater contaminant concentrations before treatment, when the ERH system was shut down (December 2001), and six months later (June 2002). As of December 2001, maximum groundwater contaminant concentrations in the Overbank area had been reduced from 150,000 µg/L to 100 µg/L for TCE, from 370,000 µg/L to 1,300 µg/L for DCE, and from 24,000 µg/L to 50 µg/L for VC. Through June 2002, TCE concentrations decreased to 8.11 µg/L while DCE and VC concentrations were unchanged. The concentrations of all three contaminants were above Oregon MCLs.

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Figure 1. Application and Monitoring of ERH at the ICN Pharmaceuticals Site in Portland, Oregon [1[
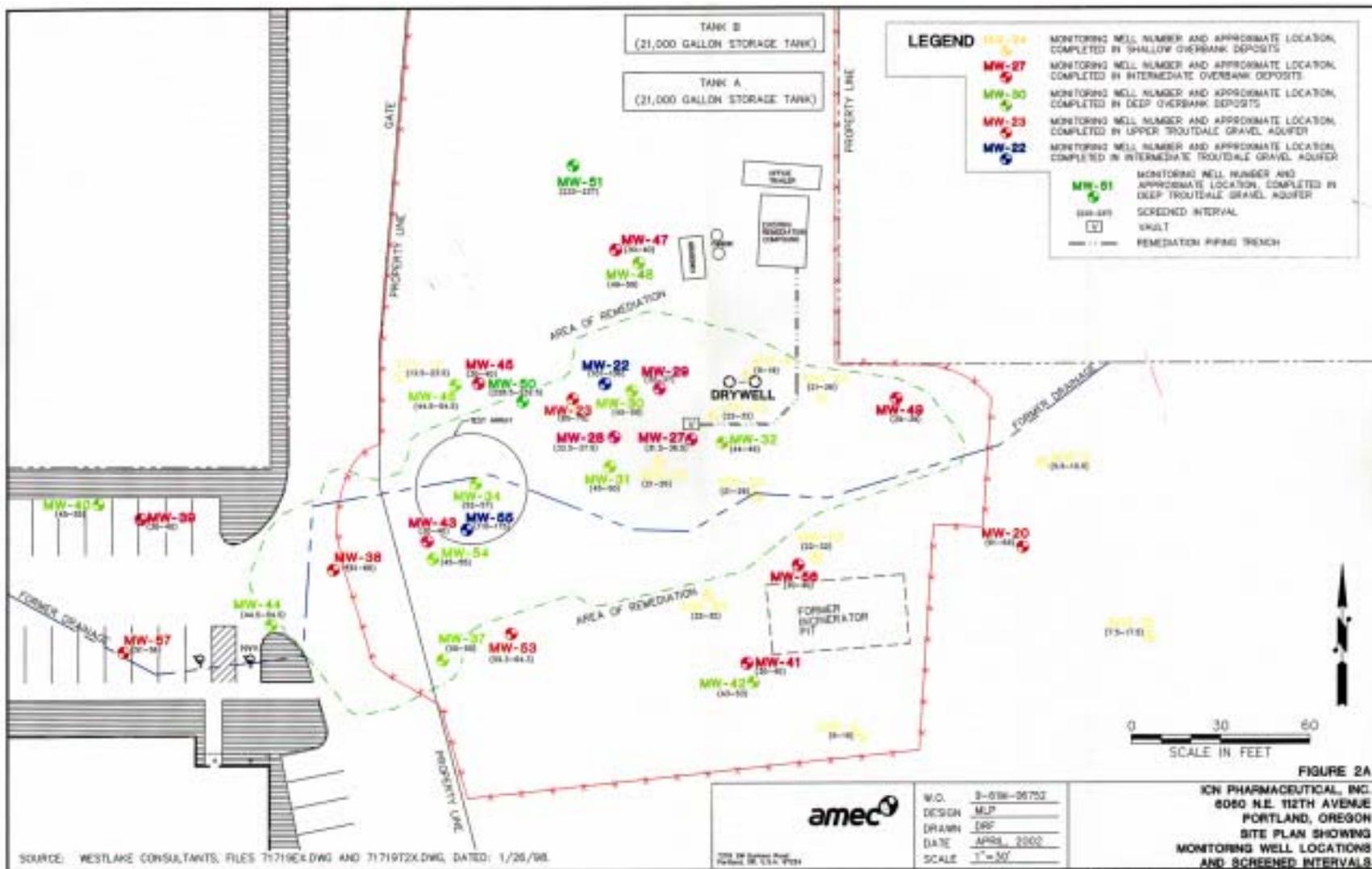
Table 2. ERH Groundwater Monitoring Results, Maximum Concentrations Measured [1,4]

Contaminant	Oregon MCLs (µg/L)	Concentrations in Overbank (µg/L)			Concentrations in TGA (µg/L)		
		Initial Concentrations Before ERH Treatment	December 2001 (when system was shut down)	June 2002 (6 months after system shut down)	Initial Concentrations Before ERH Treatment	December 2001 (when system was shut down)	June 2002 (6 months after system shut down)
TCE	5	150,000	100	8.11	ND	Not available	Not available
DCE	70	370,000	1,300	1,300	1.71	49.5	ND
VC	2	24,000	50	50.5	2.11	ND	NA
Benzene	Not available	51	Not available	Not available	5.98	200	>0.35
Toluene	5,600	Not available	Not available	Not available	16.4	Not available	Not available

Initial contaminant concentrations in the TGA layer were at or below the Oregon MCLs. As of December 2001, the concentrations of DCE and benzene had increased to 49.5 µg/L and 200 µg/L, respectively. VC concentrations decreased from 2.11 µg/L to not detected. According to the vendor, the increase in benzene concentrations indicated a possible compromise in 3 well casings which provided a conduit for contamination migration from the Overbank layer. These wells were abandoned in April 2002. As of June 2002, benzene was detected at levels above the PRG of 0.35 µg/L.

Because dissolved phase VOCs remained above DEQ generic risk-based screening levels at various locations at the site, biosparging was planned for September 2002, as part of the IRAM. Groundwater monitoring at the site is continuing. Information was not provided about whether the biosparging was implemented and any potential results of the biosparging.

Figures 2 through 5 show the concentrations of DCE over time in the source zone (intermediate well MW-28 and deep well MW-31), the treated area outside the source zone (MW-25), and downgradient from the treated area (MW-53). As shown in these figures, DCE concentrations in the source zone treatment area wells decreased following ERH treatment of the source, with the concentrations in the downgradient wells remaining relatively level.

COST OF THE TECHNOLOGY SYSTEM

COST DATA

No cost data were provided for this application.

Figure 2. ICN Site: cis-1,2-DCE Concentrations in Source Zone (MW-28)
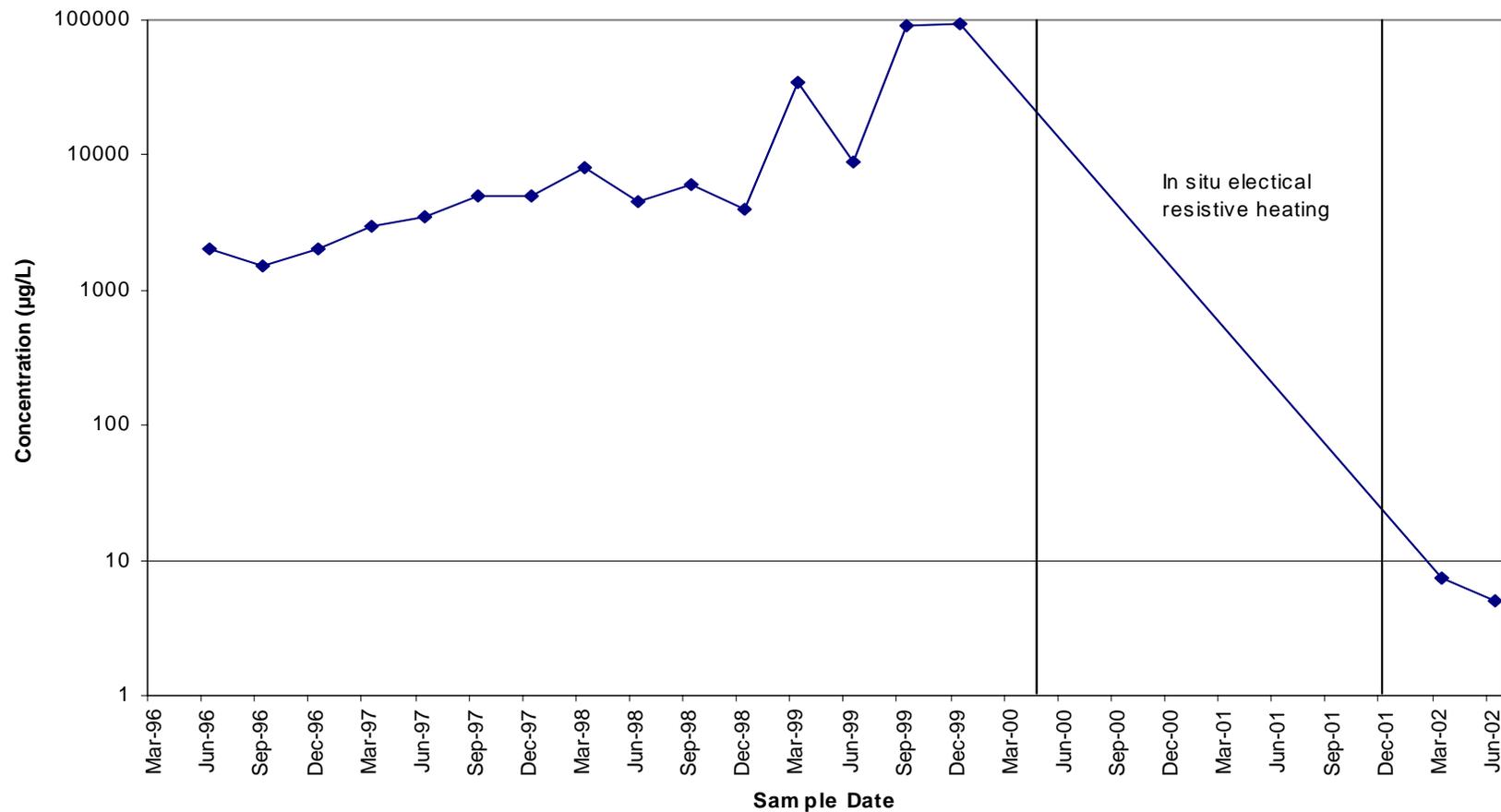**May 1996 - June 2002 (log scale) [1]**

**Figure 3. ICN Site: cis-1,2 DCE Concentrations in Source Zone (MW-31)
May 1996 - June 2002 (log scale) [1]**
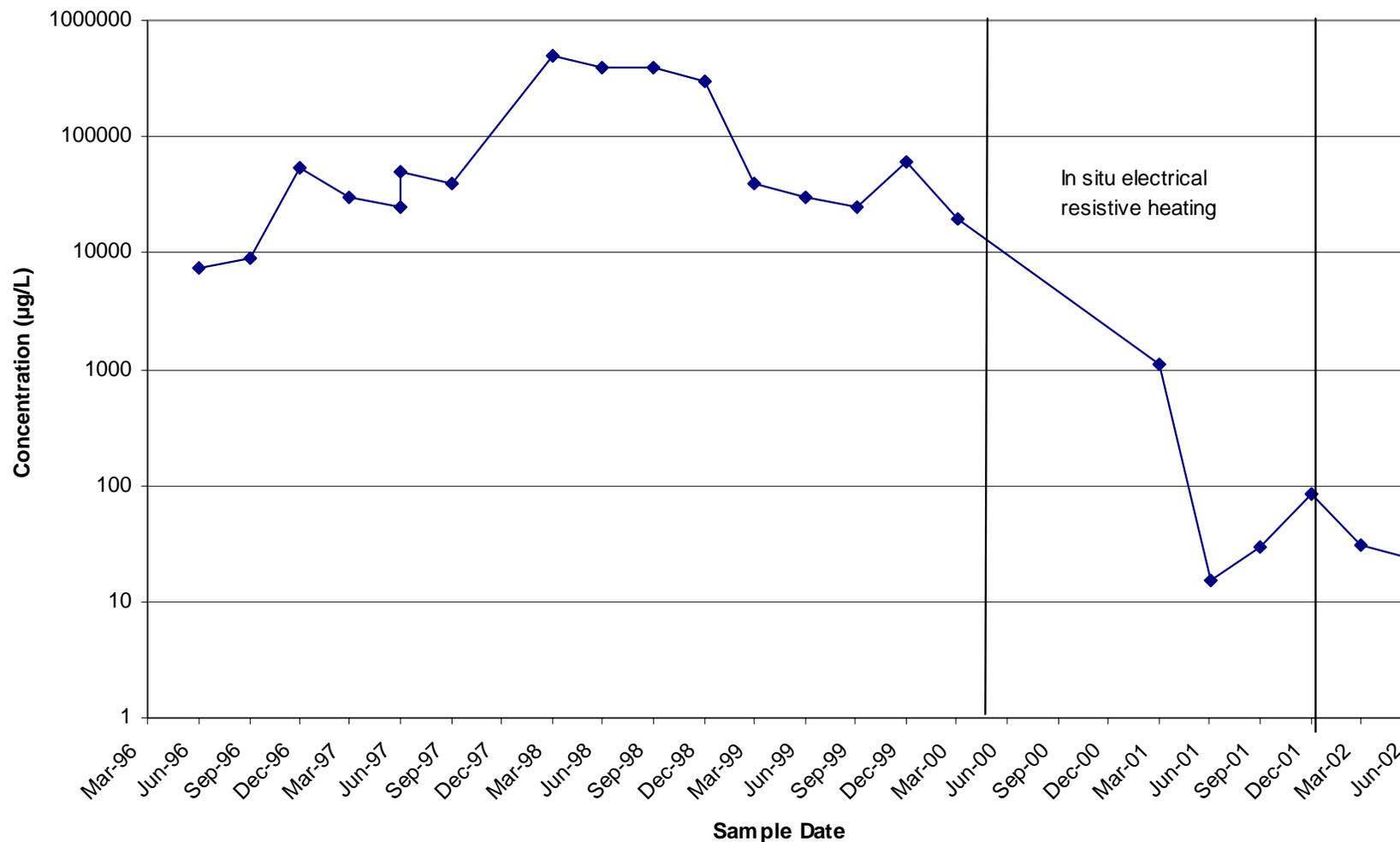
Figure 4. ICN Site: cis-1,2-DCE Concentrations in Treatment Area (MW-25)
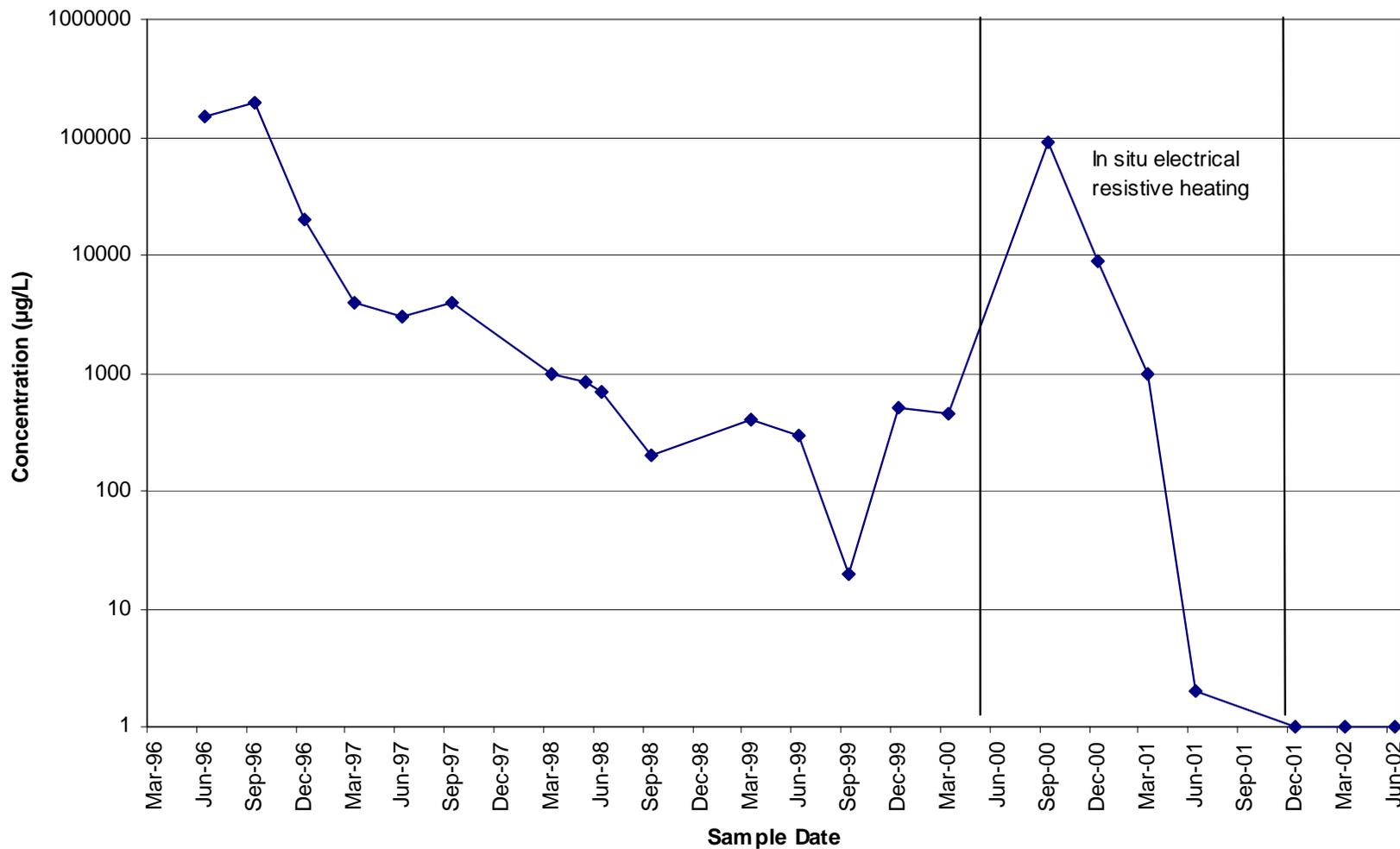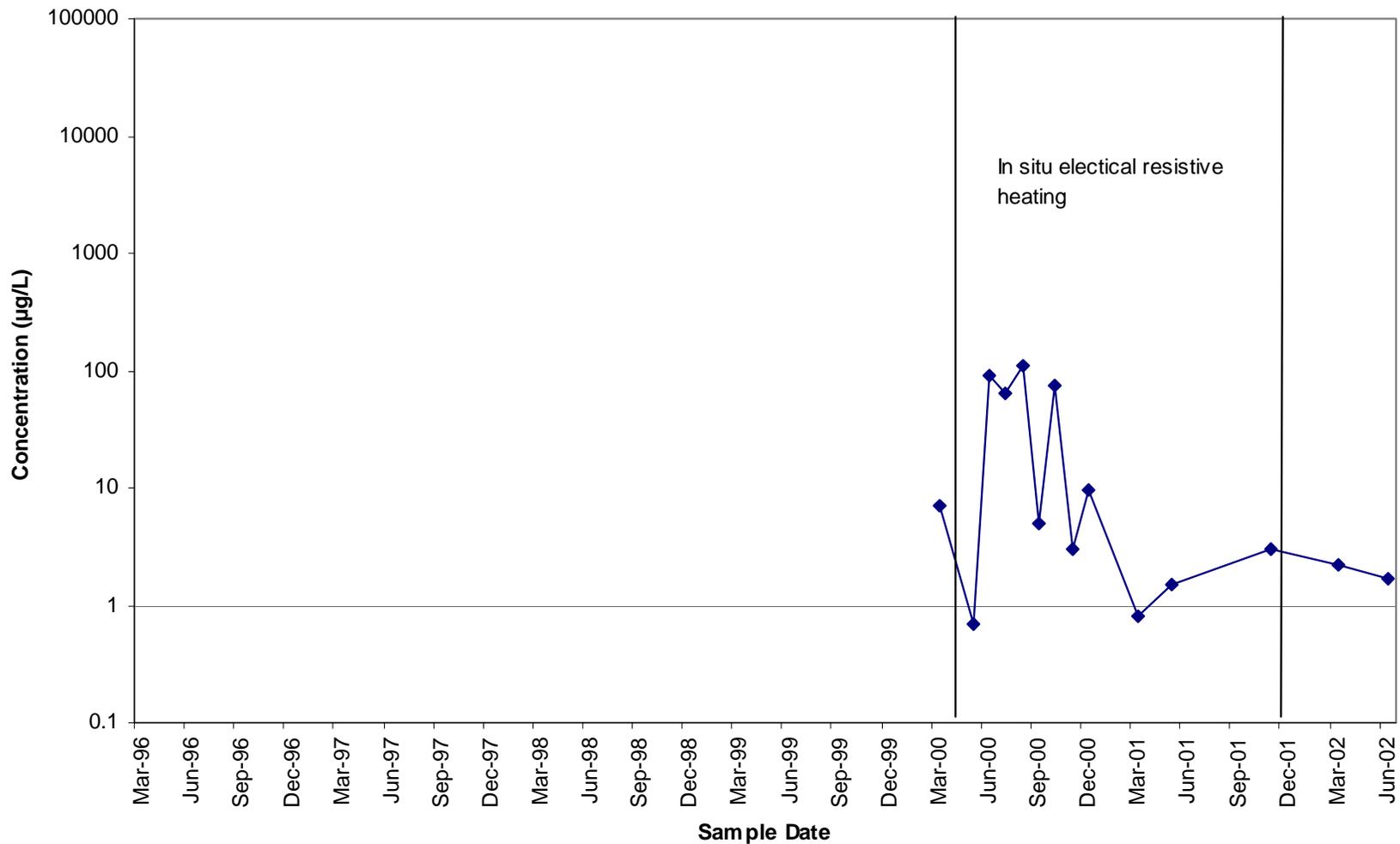**May 1996 - June 2002 (log scale) [1]**

Figure 5. ICN Site: cis-1,2-DCE Concentrations in Downgradient Area (MW-53)
May 1996 - June 2002 ((log scale) [1]

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED

ERH reduced concentrations of TCE, DCE, and VE in the source zone by more than 99 percent. However, after 18 months of treatment, contaminant concentrations remained above the state MCLs. Further treatment using biosparging was planned to address these elevated concentrations.

The vendor provided the following observations:

- At some locations, steam pressures built up inside monitoring wells to the extent that some wells vented steam for several hours. The steam moved out laterally along more permeable pathways. Vertical movement upward was inhibited by cooler temperatures within 20 feet of the surface and by less permeable soils, creating a high pressure zone. Removal of a well cap could release the pressure and cause steam and hot water to flash up the well casing. As a solution, existing 3/8-inch diameter vent lines from the electrodes were replaced with larger (1-inch diameter) tubing. These electrode vents were also connected to the vapor extraction system

- Several modifications to the system were required as a result of the high temperatures achieved during the remediation and modifications needed to handle boiling water. These included replacing PVC in wells with CPVC to minimize heat damage, replacing bentonite with concrete as a seal, and modifications to groundwater sampling using bailers.

- Biological growth increased significantly during heating. The condenser/heat exchanger required frequent cleaning. As a solution, a knockout tank was added to the system to remove some of this material before to it entering the heat exchanger. The heat exchanger still required frequent cleaning, but the problem was reduced.

REFERENCES

1. AMEC Earth & Environmental, September 2002. "Quarterly Monitoring and Project Status Report, ICN Pharmaceuticals, Inc. Site, June 2002".

2. Record of Decision, Selected Remedial Action for ICN Pharmaceuticals, Inc. DNAPL Contamination, Multnomah County, Oregon, August 23, 1999.

3. Notice of Selected Environmental Cleanup Method, ICN Pharmaceuticals DNAPL Contamination, September 1, 1999.

4. ITRC Team Case Study Report, ICN Pharmaceuticals Site, Portland, Oregon, Undated.

5. Jennifer Sutter, Oregon DEQ. E-mail comments to James Cummings, EPA. ICN Stray Voltage Discussion. January 5, 2004.

COST AND PERFORMANCE REPORT

Electrical Resistive Heating at the
Avery Dennison Site
Waukegan, Illinois

June 2003

SITE INFORMATION

IDENTIFYING INFORMATION [1,2]

Site Name: Avery Dennison Site
Location: Waukegan-Gurnee Industrial Park, Illinois
Regulatory Context: Illinois EPA Site Remediation Program
Technology: Electrical Resistive Heating
Scale: Full Scale

TECHNOLOGY APPLICATION [1,2]

Period of Operation: December 1999 to November 2000

Type/Quantity of Material Treated during Application: Source zone - Estimated to be 16,000 yds^3 based on an estimated soil density of 1.3 tons per yd^3, corresponds to 21,000 tons treated.

BACKGROUND [1,2]

The Avery Dennison site is located in the Waukegan-Gurnee Industrial Park in Waukegan, Illinois. From 1975 through 1992 film coating operations were performed at the site. Methylene chloride (MeCl) used in these operations was unloaded in the northeast corner of the building, and transferred by underground piping to above-ground storage tanks in the northwest corner of the building. In May 1985, an inventory check indicated that approximately 1,585 gallons of MeCl had been released from an underground pipe. Site investigations indicated that the released MeCl was present in the soil and groundwater beneath the loading area, the bulk storage tank area, the underground transfer pipe, and a former stormwater drainage system. The site is described in terms of the western and eastern portions.

In 1985, cleanup activities began at the site, including the removal of the above-ground storage tanks, 260 yds^3 of soil from beneath the tanks, and 175 feet of storm sewer and surrounding fill. In addition, 4,600 gallons of contaminated groundwater and 14,000 gallons of rainwater that collected in the excavation were removed. In 1988, a subsurface grout curtain was installed around the former bulk storage area.

In 1991, a soil vapor extraction system (seven vapor extraction wells) was installed. Over the next several years, several remediation technologies were used at the site and operated until 1994, at which time the operation of the system was discontinued. The vendor had determined that the relatively impermeable silty-clay soils at the site rendered the treatment ineffective. From 1992 through 1998, pump and treat of groundwater was performed with four of the extraction wells converted to air sparging wells in 1994. The air sparging and pump and treat wells were shut down in 1998. A risk-based analysis of groundwater contamination performed by the vendor indicated that additional remediation of groundwater was not required. The results of additional investigations indicated that DNAPL was present in soil at the site. ERH was used from December 1999 through November 2000 to address the DNAPL source in the unsaturated zone.

CONTACTS [1,2]

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MATRIX DESCRIPTION

MATRIX IDENTIFICATION [1,2]

Type of Media Treated With Technology System: Source Zone (unsaturated)

Primary Contaminant Groups: Chlorinated Solvents (MeCl)

SITE HYDROGEOLOGY AND EXTENT OF THE CONTAMINATION [1,2]

The topography of the site is generally flat, with a slight manmade slope that drains toward stormwater collection drains. The geology underlying the site is predominantly heterogeneous silty-clay, glacial till to a depth of about 180 feet below ground surface (bgs). Discontinuous silty sand and sand lenses are present at some locations within the till. Bedrock (Niagaran dolomite) is encountered at depths ranging from 180 to 270 feet bgs. Depth to groundwater ranges from approximately 6 feet to 25 feet bgs.

Approximately 17,000 ft^2 of soil along the north side of the building on the site was contaminated with MeCl to depths as great as 24 ft bgs, with concentrations as high as 40,000 mg/kg. MeCl concentrations in the soil in this area averaged 1,900 mg/kg.

Table 1 lists the matrix characteristics affecting the technology cost and performance for this application.

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Table 1. Matrix Characteristics Affecting Technology Cost or Performance [1,2]

Parameter	Value
Soil Classification	Glacial till consisting of silty clay
Clay Content and/or Particle Size Distribution	Silty clay
Depth to Groundwater	Between 6 and 25 feet bgs
Hydraulic conductivity	Not available
Air permeability	Not available
Porosity	Not available
Presence of DNAPLs	Suggested presence of DNAPL
Moisture content	Not available
Total organic carbon	Not available
Electrical resistivity of soil	Not available

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY [2]

Electrical resistive heating

TREATMENT TECHNOLOGY DESCRIPTION [1,2]

ERH was used to treat MeCl-contaminated soil at the site from December 1999 to November 2000. The treatment area was divided into 20 treatment cells. For each treatment cell, electrodes were installed around the perimeter to a depth of 24 feet. A total of 95 copper electrodes were installed including 6 installed below an active street, and 16 installed inside the existing building. Two thermocouples were installed in the center of each treatment cell, at the shallowest and deepest levels of contamination, 4 and 24 feet bgs. In addition, 34 recovery wells were installed at 20 locations to extract soil vapor and steam. The designed power input was 610 kW. The treatment system was expected to raise soil temperatures at a rate of at least 1°C per day until a temperature above 75°C was achieved.

Operation of the western portion of the treatment zone began in December, 1999. The subsurface temperature in this area was 13°C prior to treatment. After four weeks of operation, the expected targets had not been met. The average soil temperature was 34°C, the average heating rate was 0.4°C per day, and input to the subsurface was about 320 kW. The vendor determined that the copper electrodes had oxidized, which reduced conductivity, and that many of the down hole connections between the power cables and the electrodes were damaged, though the reason for the damage was not identified. In January 2000, 1-inch galvanized steel pipes were installed around each electrode, and the power cables were attached to the pipes above ground. Typically, five pipes were installed around each of the copper electrodes to add conductive surface area and improve power output. When the system was restarted, the heating rate was 1°C per day and the power input to the subsurface was 410 kW.

Operation of the eastern portion of the treatment zone began in June, 2000. Galvanized steel pipe electrodes were installed. Most of the treatment system was shut down in October, 2000. While operational data were not provided for this portion of the treatment zone, the vendor indicated that the heating rate and power input were similar to that achieved in the western portion using galvanized steel pipe electrodes (heating rate of 1°C per date and power input of 410 kW). However, soil samples in four

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treatment cells indicated that concentrations of MeCl remained above the treatment goals. Additional galvanized steel pipe electrodes were added to these cells, and the treatment system was operated in the four cells for another month, and was shut down in November, 2000. The maximum temperature achieved ranged from 65°C to 100°C. The average delivery of power to the subsurface was 320 kW, less than the expected delivery of 610kW.

TIMELINE [1,2]

- 1985   Removal Action
- 1988   Installation of grout curtain around the former bulk storage area.
- 1991-1994   Seven point soil vapor extraction at former bulk storage area. This was ineffective and discontinued at the end of 1994.
- 1992-1994   Pump and treating of groundwater
- 1994-1998   Air sparging of groundwater
- December 1999   ERH initiated in western portion
- June 2000   ERH initiated in eastern portion
- November 2000   ERH completed

TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [1,2]

The remediation objective was to reduce the concentration of MeCl in the soil to below 24 mg/kg, based on Illinois EPA's Tiered Approach to Corrective Action Objectives (TACO).

TREATMENT PERFORMANCE [1,2]

A total of 125 soil samples were collected and analyzed for MeCl. Average MeCl concentrations in soil were reduced to 2.51 mg/kg, below the cleanup goal. Based on the results of the confirmatory samples, the Illinois EPA issued a No Further Remediation (NFR) letter for this property.

The soil vapor extraction system removed VOCs at a rate of approximately 3 pounds per day. According to the vendor, the amount of MeCl in the extracted vapor was less than expected. Additional sampling and analysis was conducted to determine whether MeCl was being removed by degradation processes, including biodegradation, hydrous/pyrolysis oxidation (HPO), and hydrolysis. In May 2000, one background soil sample and four soil samples in the treatment area were collected. As shown in Table 2, biological activity in the background and 30°C samples were moderate. While no microbial activity was identified in the samples at 70°C and 100°C, the vendor concluded that biological degradation was not contributing significantly to MeCl removal. The concentration of soluble chloride in each of the soil samples in the treatment area were above background levels. According to the vendor, the elevated soluble chloride levels indicated that thermally enhanced degradation was occurring. Additional sampling of extracted vapor and analysis for carbon dioxide and methane were conducted to determine whether the degradation mechanism was HPO or hydrolysis. According to the vendor, methane in the extracted vapor was negligible, while carbon dioxide was at 4 times the background level. Based on these results, the ERH vendor concluded that HPO was a significant contributor to the degradation of MeCl, while hydrolysis was not. No further information on the degradation mechanism was provided.

Table 2. Results of Sampling and Analysis to Identify MeCl Degradation Mechanisms [1]

Sample Location	Temperature (°C)	Microbiological Activity	Soluble Chloride (mg/L)
Background	10	moderate	<50
Thermocouple 17	30	moderate	240
Thermocouple 6	70	none	340
Thermocouple 2	100	none	445
Electrode 2	100	none	230

COST OF THE TECHNOLOGY SYSTEM

No cost information was provided for this application.

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED [1,2]

ERH reduced MeCl concentrations in 16,000 yds^3 of soil to below the remediation objective in about a year. MeCl soil concentrations were reduced from as high as 40,000 mg/kg with an average concentration of 1,400 mg/kg to an average concentration of 2.51 mg/kg.

According to the vendor, ERH was selected to remediate soil at the site because of a variety of factors, including the location of existing structures and the low permeability of the soil. The presence of the Avery Dennison building and a neighboring building just to the north made excavations to the depths required to meet remediation objectives (approximately 24 feet) impractical. A previous application of SVE to the site from 1991 to 1994 was unsuccessful due to the low permeability of the soil.

The treatment system's ability to transfer power to the subsurface soils was hindered by equipment failures, including power cable failures and corrosion of copper electrodes. The use of additional galvanized steel pipe electrodes with above-ground power cable connections improved power input, but the system did not achieve the expected power input levels. As a result, the planned operating temperature of greater than 75°C was not achieved in all treatment areas, and the treatment time was extended from the originally anticipated 25 weeks to 47 weeks.

Analyses of soil samples for microbial activity and soluble chloride levels, and analyses of extracted vapor samples for methane and carbon dioxide were performed by the vendor to identify whether degradation of MeCl was contributing to the remediation. The vendor concluded from the results of these analyses that in addition to extraction through the vapor recovery system, MeCl was removed by degradation, primarily via HPO.

REFERENCES

1.   Nienkerk, Monte M., et al. 2001. "Cleanup of Methylene Chloride Spill." Vendor report. August, 2001.

2.   Jeff L. Pope, and Monte M. Nienkerk, CPG. 2002. "In Situ Remediation of Methylene Chloride in Low Permeability Soils Using Electrical Resistive Heating." Undated. http://www.claytongrp.com/insiturem_art.html

COST AND PERFORMANCE REPORT

In Situ Conductive Heating at the
Confidential Chemical Manufacturing Facility
Portland, IN

June 2003

SITE INFORMATION

IDENTIFYING INFORMATION

Site Name: Confidential Chemical Manufacturing Facility
Location: Portland, Indiana
Regulatory Context: Voluntary cleanup
Technology: In Situ Conductive Heating
Scale: Full-scale

TECHNOLOGY APPLICATION [1,2]

Period of Operation: July to December 1997

Type/Quantity of Material Treated During Application: Source zone (unsaturated) - Estimated area treated was 5,000 cubic yards or 6,500 tons of soil

BACKGROUND [1,2]

The 16 acre site is a chemical manufacturing facility located in the southern portion of Portland, Indiana, southeast of the Salmonie River. The site has the operated since 1886, first as a lumber yard, then for wheel manufacturing. From 1937 to the mid-1970's, the site was used for the manufacture of hard rubber products used in automobiles and then for the manufacture of plastic exterior automobile parts. The site has four buildings: the north plant building, a parts storage building, a paint storage building, and a former boiler house. According to the plant manager, the north plant building is currently being used part time for the reworking of automotive parts.

Sampling conducted as part of a due diligence assessment in June 1994 showed the presence of volatile organic compounds (VOCs) in soil and groundwater. Results of additional investigations performed from July 1995 to February 1996 confirmed the presence of VOCs in subsurface soils in two areas identified as GP-31, adjacent to the loading dock at the north building, and GP-28, about 300 feet (ft). southeast of the loading dock. Results of groundwater sampling conducted in August 1995 showed that VOCs were not present in the sand and gravel aquifer beneath the site at levels higher than the cleanup goals.

CONTACTS

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MATRIX DESCRIPTION

MATRIX AND CONTAMINANT IDENTIFICATION [1,2]

Type of Media Treated With Technology System: Source zone (unsaturated)

Primary Contaminant Groups: Chlorinated Solvents

SITE HYDROGEOLOGY AND EXTENT OF CONTAMINATION [1,2]

Figure 1 is a cross-section of the site. The site geology included fill, a combination of sand, clayey sand and construction debris, to a depth of about 7 ft. Till consisting of moist, damp, silty clay extended to a depth ranging from 18 to 19 ft, with sand seams running through the till. Below the till was a sand and gravel layer extending to a depth of 30 ft and consisting of poorly sorted sand. Groundwater was encountered in the sand and gravel layer at depths of 22-25 ft. The estimated hydraulic conductivity of this zone was 10^{-8} cm/sec.

Contamination in GP-31 covered an area of 150 ft by 50 ft to a depth of 18 ft and primarily consisted of trichloroethene (TCE) and tetrachloroethene (PCE), detected at levels up to 79 mg/kg and 3,500 mg/kg, respectively. The high concentration of PCE in the GP-31 area suggested the presence of DNAPL. The contamination in the GP-28 area covered an area of 30 ft by 20 ft to a depth of 11 ft and primarily consisted of 1,1-dichloroethene (DCE), detected at a maximum concentration of 0.65 mg/kg.

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Figure 1. Representative Cross Section of Treated Subsurface [1]

Figure 1. Representative Cross Section of Treated Subsurface [1] — Cross Section A – A', Portland, Indiana (Metcalf & Eddy)

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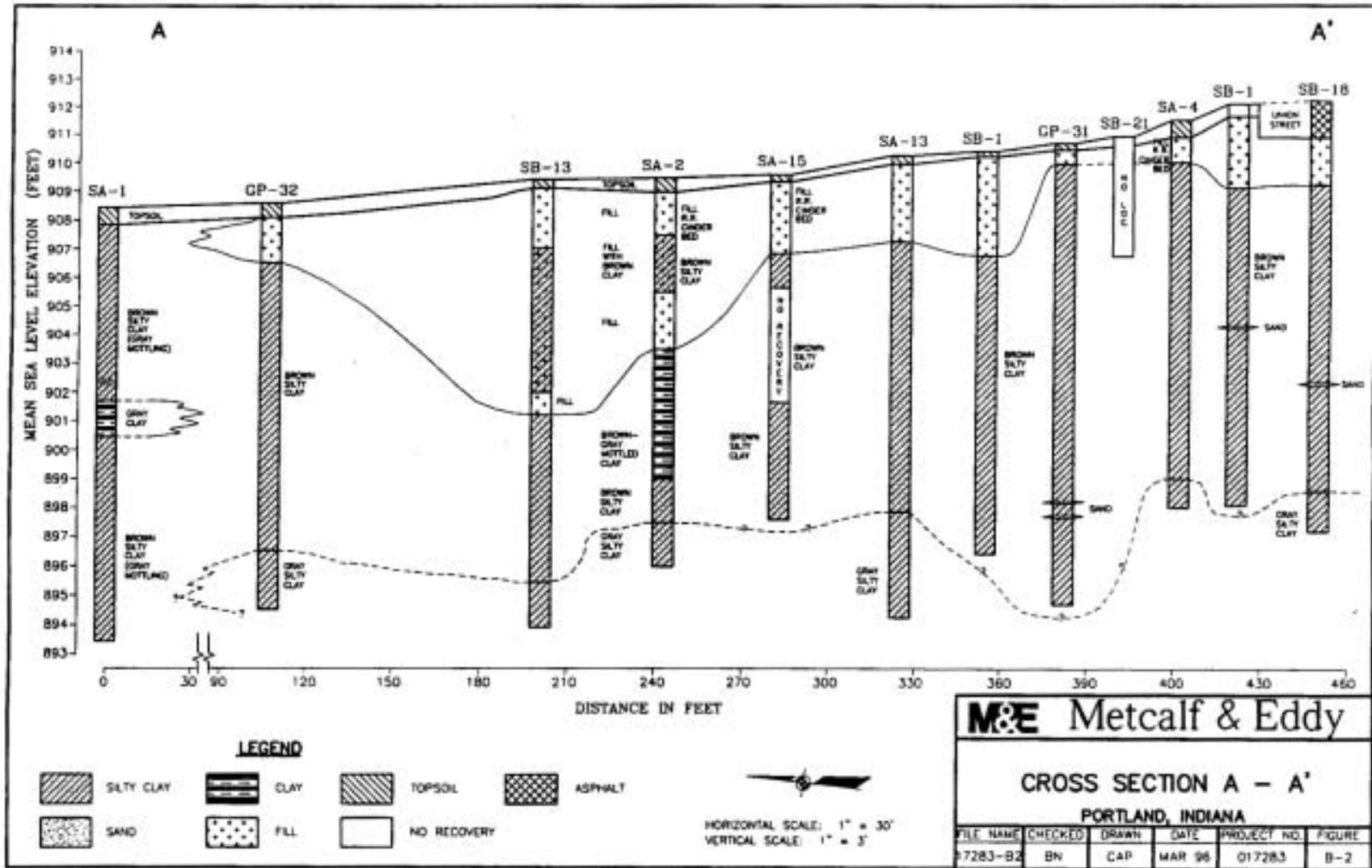
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Table 1 lists the matrix characteristics affecting treatment cost or performance for this application.

Table 1. Matrix Characteristics [1]

Parameter	Value
Soil Classification	Heterogenous zones of clay, sand, gravel, and debris fill
Clay Content and/or Particle Size Distribution	Fill consisting of sand, clayey sand, gravel, and construction debris from 1 to 7 ft bgs. Silty clay with discontinuous sand seams containing perched groundwater beneath the fill to 18 to 19 ft bgs. Sand and gravel from the silty clay to 30 ft bgs.
Depth to Groundwater	Aquifer located 22 to 25 ft bgs, perched groundwater in sand seams at shallower depths
Hydraulic conductivity	10^{-8} cm/sec in the silty clay layer. Information not available for the fill and sand and gravel layers.
Porosity	Not available
Air Permeability	Not available
Presence of NAPLs	Suggested presence of DNAPL
Moisture content	Not available
Total organic carbon	Not available

TECHNOLOGY SYSTEM DESCRIPTION

TREATMENT TECHNOLOGY

In situ conductive heating (In Situ Thermal Desorption™)

TREATMENT SYSTEM DESCRIPTION AND OPERATION [1,2]

The in situ conductive heating system used at this site consisted of three free-standing trailers - a control trailer containing instrumentation, an electrical substation providing power for the system (1 to 1.5 MW), and an off gas vapor treatment trailer containing a flameless thermal oxidizer. The heater/vacuum wells were operated at 1,400 - 1,600 °F. Heat was injected into the subsurface and soil gas was extracted under a vacuum.

For area GP-31, a total of 130 heater/vacuum wells were installed on 7.5 foot triangular spacing to a depth of 19 ft, as shown in Figure 2. Twenty-five of these wells were drilled through the concrete loading dock. For Area GP-28, 18 heater/vacuum wells were installed on 7.5 foot triangular spacing to depths of 12 ft, with approximately 1 well per 50 square ft of surface area treated.

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Figure 2. Heater/Vacuum Well Layout for Loading Dock Area[1] [2]
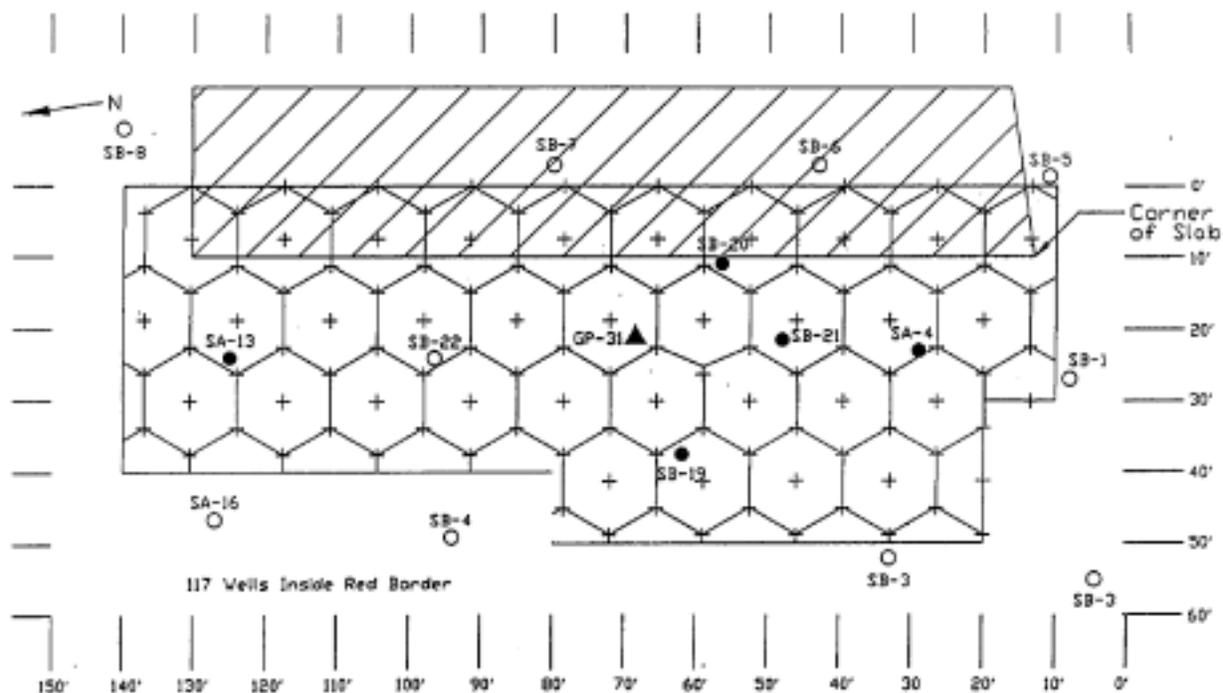
[1]   Circles and triangles that are filled in indicate locations where the PCE concentrations exceeded the cleanup goals prior to treatment. Open circles indicate locations where the PCE concentrations were below the cleanup goals prior to treatment. The "+" symbols indicate the locations of the heater/vacuum wells.

The well was 4.5 inches in diameter with sand packed liners in 6 inch augured holes. The heaters were extended 3 ft below the deepest contaminated layer. The surface area between wells was covered by an impermeable silicone rubber sheet to prevent fugitive emissions. A thermally insulated mat was used to minimize surface heat loss. During installation, the thick fill in the northernmost part of the site was found to be saturated with water originating from a railroad gravel bed. After pumping failed to dry the area, a 5 ft deep dewatering trench was installed.

Subsurface temperature in the treatment zone was monitored using 91 hollow logging tubes placed in the areas expected to be the coldest locations in each triangular heater pattern, which were at the centroids of the triangles. The maximum soil temperature achieved in the treatment area at a depth of 13 ft ranged from 212°F to 500°F. During operation, recharge of water in the wet till region prevented temperatures in this area from rising above 212°F; however, all temperatures in the area were at least as high as the boiling of water.

Off-gases were treated with an 1800 scfm flameless thermal oxidizer with an operating temperature range of 1800 - 1900°F. Off-gases were cooled by a heat exchanger, then passed through a carbon absorption bed. Off-gases were monitored for hydrogen chloride, which was used as an indicator of the decomposition of chlorinated solvents.

TIMELINE [1,2]

- 1994 - 1996   Site investigations performed
- July - Dec 1997   Remediation performed
- Date not provided   Indiana EPA issues a no further action letter

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TECHNOLOGY SYSTEM PERFORMANCE

PERFORMANCE OBJECTIVES [1,2]

Cleanup goals were based on the Indiana Department of Environmental Management (IDEM) Tier II Clean-Up Goals for Industrial Land Use. The soil cleanup goals were 8 mg/kg for PCE, 25 mg/kg for TCE, and 0.080 mg/kg for 1,1-DCE.

TREATMENT PERFORMANCE [1,2]

Prior to discontinuing heating, about 50 soil samples were collected from the coldest locations (centroids) furthest from each heater well and analyzed for VOCs. The results from the soil samples, along with data from temperature profiles and HCl monitoring, were used to determine whether additional heating was required. Based on the results, heating was discontinued in December 1997. Before confirmation sampling was conducted, soil temperatures were monitored for about 6 months as the soil within the treatment area cooled to below 100°F. Confirmation sampling was conducted in accordance with the random sampling methodology required by the IDEM Voluntary Remedial Program Resource Guide. With the exception of GP-31, SA-13, and SA-4, a 1 foot sampling interval was used for each confirmatory soil boring location. Sample intervals for borings GP-31, SA-13, and SA-4 correspond to the intervals where the highest concentrations of VOCs were detected in the subsurface soils prior to treatment.
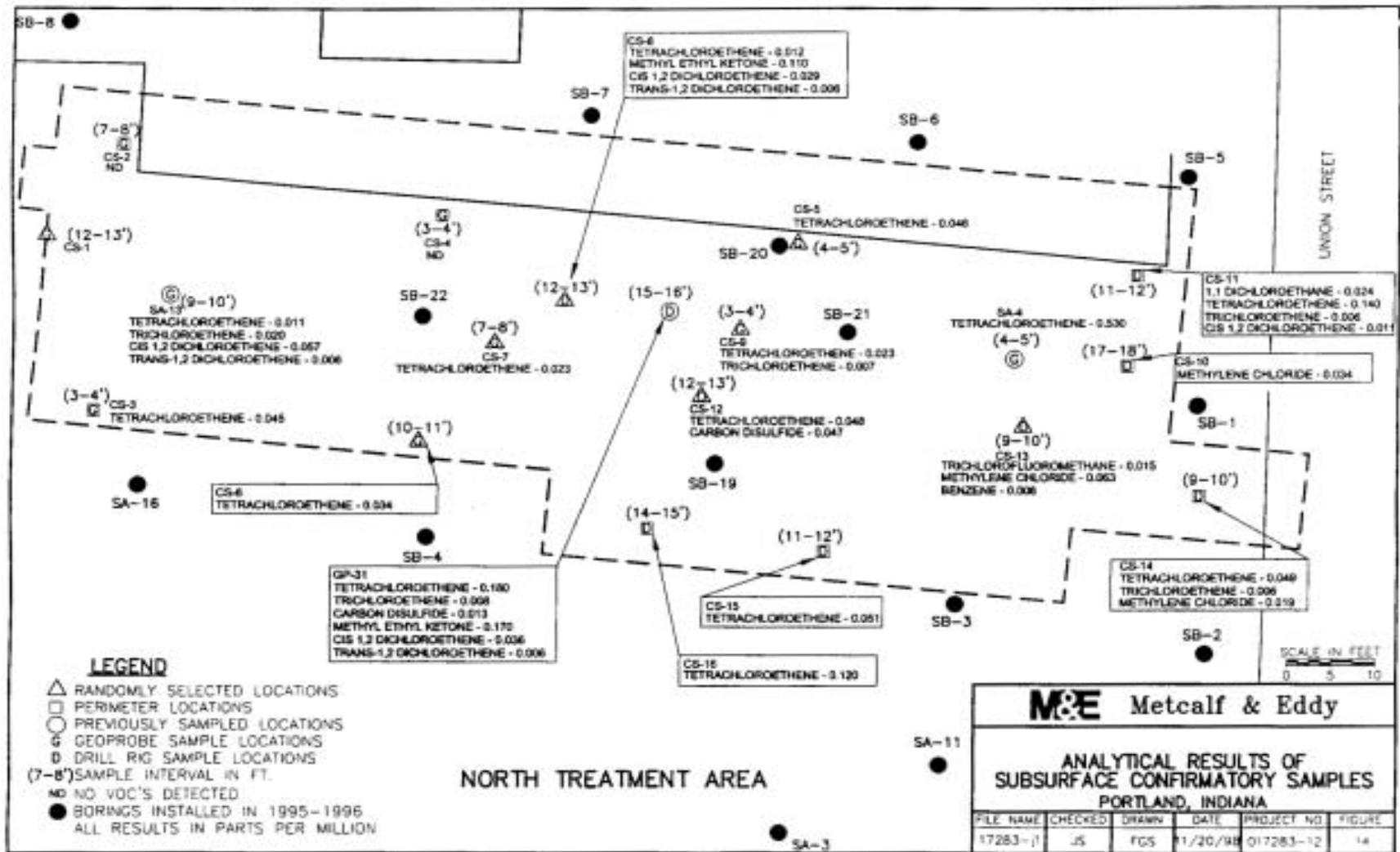
Sampling locations SA-13, GP-31, SA-4, SB-20, SB-19, and CS-12 had relatively higher concentrations of PCE and TCE before treatment, at the depths shown in Table 2. This table shows that the concentrations of PCE and TCE in the soil at these locations was less than the cleanup goals after treatment. Figure 3 shows the after-treatment results for confirmatory samples across area GP-31. This figure shows that contamination had not spread outside the treatment area. No confirmation samples were available for the smaller, DCE contaminated zone (area GP-28).

Table 2. Comparison of Selected Pre-Heating and Post-Heating Contaminant Concentrations [1]

		Contaminant Concentration (mg/kg)	
Sampling Location	**Depth (ft)**	**Before Treatment**	**After Treatment (Cleanup goal - PCE 8; TCE 25)**
SA 13	9-10	PCE = 3,500 TCE = 79	PCE = 0.011 TCE = 0.020
GP 31	15-16	PCE = 570 TCE = NA	PCE = 0.18 TCE = 0.008
SA 4	4-5	PCE = 23 TCE = 0.25	PCE = 0.530 TCE = ND
SB 20	4-5	PCE = 2.9 TCE = 0.67	PCE = 0.046 TCE = ND
SB 19 CS 12 (8 ft away)	12-14	PCE = 76 TCE = 1.6	PCE = 0.048 TCE = ND

ND - non-detect (detection limits not provided)

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and Technology Innovation

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Figure 3. Subsurface Confirmatory Samples [1]

COST OF THE TECHNOLOGY SYSTEM

COST DATA

Cost data were not provided for this application.

OBSERVATIONS AND LESSONS LEARNED

OBSERVATIONS AND LESSONS LEARNED

In situ conductive heating treated 6,500 tons of soil contaminated with chlorinated solvents to below cleanup goals in six months.

During the installation stage, perched water was encountered in the thick fill in the northernmost portion of the site originating from railroad gravel bed. According to the vendor, after weeks of pumping failed to dry the area, a 5 foot deep dewatering trench was installed north of the last row of wells to reduce water inflow. However, during treatment system operation, water recharge occurred in this area. According to the vendor, while the soil temperature in this area reached the boiling point of water, allowing for remediation of the contaminants, the presence of the water prevented the soil temperatures in this area from exceeding 212°F.

To prevent migration of contaminants out of the treatment zone, and ensure effective heating of the entire treatment zone, heaters/vacuum wells were installed 3 ft below the deepest contaminated layer and at least one grid of wells was installed beyond the contaminant zone. This resulted in an increase in the size of the treatment area.

REFERENCES

1.   Vinegar, Harold J., G.L. Stegemeier, F.G. Carl, J.D. Stevenson, and R.J. Dudley. 1999. "In Situ Thermal Desorption of Soils Impacted with Chlorinated Solvents." Proceedings of the Annual Meetings of the Air and Waste Management Association, Paper No. 99-450.

2.   Baker, R.S., H.J. Vinegar, and G.L. Stegemeier. 1999. "Use of In-Situ Thermal Conduction Heating to Enhance Soil Vapor Extraction." Pp. 39-57. In: P.T. Kostecki, E.J. Calabrese, and M. Bonazountas (eds.). Contaminated Soils, Volume 4. Amherst Scientific Publishers, Amherst, MA.

3.   Stegemeier, G.L., and Vinegar, H.J. 2001. "Thermal Conduction Heating for In-Situ Thermal Desorption of Soils." Ch. 4.6, pp. 1-37. In: Chang H. Oh (Ed.). Hazardous and Radioactive Waste Treatment Technologies Handbook, CRC Press, Boca Raton, FL.

APPENDIX B

OTHER *IN SITU* THERMAL TREATMENT PROJECTS

Remediation of NAPLs Using Steam Enhanced Extraction and Electrical Resistive Heating at the Young-Rainey STAR Center, Northeast Site Area A, Largo, Florida

Electrical Resistive Heating at Air Force Plant 4, Fort Worth, Texas

Electrical Resistive Heating at Dry Cleaner, Suburban Chicago, Illinois

Thermal Conductive Heating at Confidential Ohio Site

REMEDIATION OF NON-AQUEOUS PHASE LIQUIDS (NAPLs) USING STEAM ENHANCED EXTRACTION AND ELECTRICAL RESISTIVE HEATING AT THE YOUNG-RAINEY STAR CENTER, NORTHEAST SITE AREA A, LARGO, FLORIDA

Site Type:	Young-Rainey Science, Technology, and Research (STAR) Center (formerly the Department of Energy's Pinellas Plant)
Site Location:	Largo, Florida
Technology Employed:	Steam Enhanced Extraction (SEE) and Electro-Thermal Dynamic Stripping (ET-DSP™)
Remediation Scale:	Full scale
Project Duration:	September 2002 to February 2003
Site Information:	Northeast Site Area A covered an area of approximately 10,000 square ft to a depth of 35 ft for a volume of 13,000 cubic yards

Contaminants: Principal NAPL contaminants of concern were trichloroethene (TCE) and toluene, both present as free product. Other NAPL contaminants of concern included methylene chloride and cis-1,2-dichloroethene (DCE), as well as total petroleum hydrocarbons (TPH). Soil concentrations of TCE and toluene were as high as 2,900 mg/kg and 1,000 mg/kg, respectively. Groundwater concentrations of TCE and toluene were as high as 26,000 µg/L and 20,100 µg/L, respectively. The estimated mass of NAPL contamination at the site prior to NAPL remediation was 5,500 lbs, including 2,600 lbs of VOCs and 2,900 lbs of TPH. The depth of contamination was estimated to be 29 ft bgs.

Hydrogeology: Area A is underlain by flat-lying sedimentary deposits, referred to as the surficial sand layer. The surficial sands, fine-grained, moderately to well-sorted sand with variable amounts of silt and clay, range in thickness from 26 to 34 ft. A 1 to 2 foot thick layer of silty, sandy clay with shell fragments is locally present at the base of the surficial sands. This layer is underlain by the Hawthorn formation, consisting of silty clay with variable amounts of gravel, underlain by weathered clay and limestone, a layer of silty, sand, phosphatic clay, and a layer of carbonaceous clay. The Tampa Limestone Member, starting at a depth of 100 ft, consists of interbedded clays and muddy carbonates, and forms the upper part of the Floridan Aquifer.

The local water table ranges from 1 to 6 ft bgs, depending on seasonal rainfall. An unconfined surficial aquifer, composed of relatively fine-grained sand, is present from 3 to 30 ft bgs at the site. The hydraulic conductivity of this aquifer is 1×10^{-3} cm/sec, with groundwater flowing east-southeast. This aquifer is underlain by the Hawthorn clay, which acts as an aquitard.

Project/Cleanup Goals: The purpose of this remediation effort was to remove NAPLs from the subsurface. Table 1 shows the cleanup goals for soil and groundwater at the site. Once the minimum operating temperature of 84°C was achieved, this temperature was to be maintained at all times.

Table 1: Groundwater and Soil Cleanup Goals

NAPL Component	Groundwater (µg/L)	Soil (mg/kg)
TCE	11,000	20.4
cis-1,2-DCE	50,000	71
Methylene Chloride	20,000	227
Toluene	5,500	15
TPH	50,000	2,500

Project Approach: A combination of SEE and ET-DSP™ was used to optimize the heating patterns at the site and to maximize contaminant removal, while maintaining hydraulic control. ET-DSP™ was used to heat the lower permeability zones at depths of 30 to 35 ft bgs (about 5 ft below the top of the Hawthorn) and in the upper sands at depths of 10 to 15 ft. A combination of ET-DSP™ and steam injection was used to heat the perimeter of the treatment area. Hydraulic and pneumatic control were achieved using liquid and vapor extraction. In addition, pressure cycling was used to optimize contaminant mass removal by varying the steam injection rates and the ET-DSP™ power delivery. Steam for the SEE component was provided by an 8,000 lbs/hr steam generator fired by diesel. Power for the ET-DSP™ component was provided by five 400 KW ET-DSP units. Air emissions equipment consisted of an air stripper and granular activated carbon (GAC) units in series. Temperature monitoring was conducted using thermocouples and Digitam temperature sensors.

In September 2002, when operations began at the site, the SEE/ET-DSP™ system included 15 steam injection wells around the perimeter of the treatment area; 28 extraction wells with ET-DSP™ electrodes located below the screened interval for heating the Hawthorn and the base of the surficial aquifer; 21 combined steam-injection/ET-DSP™ wells for heating the surficial aquifer, and 2 deep ET-DSP™ electrodes located in the Hawthorn that did not have extraction screens. A total of 36 temperature monitoring boreholes were located throughout the treatment area and 4 pairs of monitoring wells were installed outside the treatment area. During treatment operations, soil samples were collected to determine treatment effectiveness. In addition, soil sampling was conducted during operations to determine which areas had met cleanup goals and which areas needed additional efforts. This sampling identified a relatively cool area and a near-surface lens of resinous material where high levels of contamination remained. To address the remaining high levels of contamination, the system was expanded in January 2003 by adding 12 shallow steam injection wells. This improved steam delivery and heat distribution to the remaining contaminated area.

Project Contact: David Ingle, Environmental Restoration Program Manager, U.S. Department of Energy, (727) 541-8943, d.s.ingle@worldnet.att.net; Randy Juhlin, Project Manager, S. M. Stoller Inc., (970) 248-6502, Randall.Juhlin@gjo.doe.gov; Gorm Heron, Scientist and Engineer, SteamTech Environmental Services, Inc, 661-322-6478 heron@steamtech.com

Costs: The total project cost (including design, construction, operations, demobilization, sampling and analysis and preparation of required reports) was approximately $3.8 million.

Project Results:

Hydraulic and pneumatic control by liquid and vapor extraction was achieved in October 2002. The target operating temperature of 84°C was reached across the entire treatment area within 35 days of beginning thermal treatment (by mid-November 2002), with temperatures maintained at or above 100°C for at least 70 days. Steam injection rates varied between 100 and 5,000 lbs/hr during operation. Air injection rates were estimated to range from 1 to 10 scfm per well during injection events, and between 25 and 100 scfm for the system. A total of 4.7 billion BTU was delivered to the subsurface using the ET-DSP™, with power delivery varied from about 50 kW to just under 700 kW during system operation.

After about one month of pressure cycling operations, mass removal diminished, indicating that only a minor quantity of VOC mass was left. Interim soil samples were collected in areas where the temperature monitoring indicated that heating and treatment might have been least effective. On January 13, 2003 an area with resin was discovered, and soil samples collected above and below the resin layer showed VOC levels above the cleanup criteria. Shallow injection and extraction screens were added in the area where the resin was discovered. This modification led to a significant increase in VOC recovery rates for the following weeks, until rates diminished again. During this time, another 100 pounds of VOCs were removed, based on PID screening results.

During the last four weeks of operation, recovery rates diminished, and several pressure cycles and different sparging modes were tested in order to see if this would result in another spike in recovery. Because no substantial increases were observed, the system went into cool-down mode on February 17, 2003 and operation was ceased on February 28, 2003. The cool down and polishing included continued vapor and liquid extraction combined with air and cold water injection. Operations ended on March 24, 2003 when target cool down temperatures were reached.

Post-treatment soil and groundwater sampling showed that all samples were below the cleanup goals and most were below site MCLs, with nearly all VOCs removed, as shown in the attached tables. Hydraulic control was achieved and there was no evidence of horizontal or vertical migration of contamination from Area A. During pressure cycling, the mass recovery was highest during time of de-pressurization and during times when areas were heated to above 70 to 80°C. Removal efficiency for NAPLs was estimated to average 99.93 percent.

Lessons learned and suggestions for improving the system included heating the upper 10 ft of the treatment area more rapidly, using ET-DSP™ or steam injection wells at shallower depths; and improving the efficiencies of the liquid and vapor treatment systems.

Sources:

U.S. DOE Grand Junction Office. 2003. Pinellas Environmental Remediation Project, Northeast Site Area A NAPL Remediation Final Report. GJO-2003-482-TAC. September. www.gjo.doe.gov.

David Ingle, Environmental Restoration Program Manager, DOE. 2004. Comments on Thumbnail Sketch for Area A Remediation. E-mail to Jim Cummings, EPA. February 18 and February 19.

Confirmatory Sampling for Groundwater - Young-Rainey STAR Center, Area A
units are µg/L

Location	cis-1,2-DCE				Methylene Chloride				Toluene				TCE				Florida Petroleum Range Organics		
NAPL Remediation Goals	50,000				20,000				5,500				11,000				50,000		
Groundwater MCLs:	70				5				1,000				3				*		
Date	Apr 16-17	May 13-15	July 23-24		Apr 16-17	May 13-15	July 23-24		Apr 16-17	May 13-15	July 23-24		Apr 16-17	May 13-15	July 23-24		Apr 16-17	May 13-15	July 23-24
PIN15-CS-01	ND	3.3	76		ND	0.4 JB	ND		ND	ND	0.2 J		ND	0.58 J	12		ND	ND	ND
PIN15-CS-02	ND	0.74 J	52		ND	0.49 JB	ND		0.24 J	0.38 J	ND		ND	0.13 J	8		ND	320	ND
PIN15-CS-03	ND	ND	16		ND	1.2 JB	11		1.3	ND	ND		ND	ND	1.2		340	510	2000
PIN15-CS-04	0.3 J	0.45 J	0.18 J		ND	1.3 JB	ND		4.1	2.5	ND		ND	ND	ND		120 J	970	910
PIN15-CS-05	23	9.9	8.6		13	3.8 JB	ND		1.5	0.83 J	ND		0.63 J	0.35 J	ND		3200	6800	1300
PIN15-CS-06	0.5 J	36	27		4.2 J	150 B	12		0.59 J	ND	ND		ND	2.7	3.6		120 J	140 J	ND
PIN15-CS-07	ND	0.22 J	0.83 J		0.48 J	1.2 JB	ND		1.4	7	6.8		ND	ND	ND		1000	6700	9500
PIN15-CS-08	2.4	1.8	2.1		ND	1.8 JB	ND		17	8.3	7.6		ND	2	0.44 J		210 J	580	1700
PIN15-CS-09	ND	ND	ND		0.52 J	1.4 JB	ND		1.4	1.8	ND		ND	ND	ND		400	740	260 J
PIN15-CS-10	ND	ND	0.65 J		0.82 J	ND	0.62 J		1.4	1.2	1.7		ND	ND	ND		180 J	340	1200
PIN15-CS-11	ND	ND	ND		ND	ND	ND		0.49 J	1.5	1.1		ND	ND	ND		110 J	270 J	140 J
PIN15-CS-12	0.43 J	0.45 J	0.24 J		0.74 J	1.1 JB	0.51 J		4.5	2.5	3.2		0.28 J	0.42 J	ND		490	980	1300
PIN15-CS-13	ND	ND	ND		0.62 J	1.7 JB	0.3 J		1.3	0.85 J	0.58 J		ND	ND	ND		240 J	580	ND
PIN15-CS-14	ND	0.3 J	0.16 J		0.78 J	1.7 JB	ND		1	ND	0.75 J		ND	0.11 J	ND		120 J	400	ND
PIN15-CS-15	ND	ND	ND		0.68 J	ND	ND		4.7	ND	1.1		ND	ND	ND		1000	2400	2600
PIN15-CS-16	1.3	1.2	7.5		0.8 J	0.75 JB	ND		4.5	38	23		ND	29	6.8		ND	190 J	110 J
PIN15-0560	ND	ND	ND		ND	0.84 JB	ND		ND	ND	ND		ND	ND	ND		ND	ND	ND
PIN15-0561	ND	ND	ND		ND	0.55 JB	ND		ND	ND	ND		ND	ND	ND		ND	ND	ND
PIN15-0562	ND	ND	ND		ND	0.37 JB	ND		ND	ND	ND		ND	ND	ND		ND	ND	ND
PIN15-0563	1.5	1.6	1.8		ND	0.41 JB	0.32 J		0.3 J	0.54 J	ND		1.4	0.92 J	1.1		160 J	ND	ND
PIN15-0564	2.4	0.56 J	ND		ND	0.59 JB	ND		ND	ND	ND		0.12 J	0.2 J	ND		ND	ND	ND
PIN15-0565	ND	ND	ND		ND	0.85 JB	ND		ND	ND	ND		ND	ND	ND		ND	ND	ND
PIN15-0566	ND	0.35 J	1.4		ND	0.6 JB	ND		1.1	1.4	1.2		ND	ND	ND		ND	ND	ND
PIN15-0567	2.3	1.4	1.3		ND	ND	ND		ND	ND	ND		ND	ND	ND		ND	ND	ND

ND = Not Detected

J = Estimated value above the instrument detection limit but below the reporting limit.

B = Analyte also found in method blank.

* Florida Total Petroleum Hydrocarbons is not a COPC for the Northeast Site, but if it was, the MCL would be 5,000 µg/L.

Confirmatory Sampling for Soils - Young-Rainey STAR Center, Area A
units are µg/kg

Location	Date	Sample Depth	cis-1,2-DCE	Methylene Chloride	Toluene	TCE	Florida Petroleum Range Organics
NAPL Remediation Goals:		(fbs)	71,000	227,000	15,000	20,400	2,500,000
PIN15-CS-51	4/10/2003	6.8	ND	ND	13	ND	ND
PIN15-CS-51	4/10/2003	14.8	ND	ND	14	ND	ND
PIN15-CS-51	4/10/2003	22.8	ND	ND	15	ND	ND
PIN15-CS-51	5/21/2003	31-35	ND	ND	ND	ND	ND
PIN15-CS-51	5/21/2003	31-35 Dup	ND	7.4 J	ND	ND	ND
PIN15-CS-51	5/21/2003	33-37	ND	5.8 J	ND	ND	ND
PIN15-CS-52	4/10/2003	1.1	ND	ND	12	ND	46,000
PIN15-CS-52	4/10/2003	9.1	ND	ND	12	ND	ND
PIN15-CS-52	4/10/2003	17.1	ND	ND	11	ND	ND
PIN15-CS-52	4/10/2003	25.1	ND	ND	220	ND	ND
PIN15-CS-52	5/21/2003	31.1-35.1	ND	4.6 J	ND	ND	ND
PIN15-CS-53	4/10/2003	0.3	ND	ND	ND	ND	81,000
PIN15-CS-53	4/10/2003	8.3	ND	ND	11	ND	ND
PIN15-CS-53	4/10/2003	16.3	ND	ND	11	ND	5,600 J
PIN15-CS-53	4/10/2003	16.3 Dup	ND	3.9 J	12	ND	6,300 J
PIN15-CS-53	4/10/2003	24.3	ND	ND	ND	ND	ND
PIN15-CS-53	5/21/2003	30.3-34.3	ND	5 J	ND	ND	ND
PIN15-CS-54	4/9/2003	3.2	ND	ND	18	7.7	120,000
PIN15-CS-54	4/9/2003	3.2 Dup	ND	ND	18	3.8 J	240,000
PIN15-CS-54	4/9/2003	11.2	ND	ND	11	ND	54,000
PIN15-CS-54	4/9/2003	19.2	ND	ND	18	ND	16,000
PIN15-CS-54	4/9/2003	27.2	ND	ND	ND	ND	64,000
PIN15-CS-54	5/21/2003	33-37	ND	ND	ND	ND	ND
PIN15-CS-55	3/27/2003	5.9	ND	ND	14	ND	ND
PIN15-CS-55	3/27/2003	13.9	ND	ND	12	ND	ND
PIN15-CS-55	3/27/2003	21.9	ND	3.4 J	15	ND	ND
PIN15-CS-55	3/27/2003	29.9	ND	ND	12	ND	ND
PIN15-CS-55	5/22/2003	33-37	ND	ND	ND	ND	ND

Appendix B
Young-Rainey Area A

Confirmatory Sampling for Soils - Young-Rainey STAR Center, Area A
units are µg/kg

Location	Date	Sample Depth	cis-1,2-DCE	Methylene Chloride	Toluene	TCE	Florida Petroleum Range Organics
NAPL Remediation Goals:		**(fbs)**	**71,000**	**227,000**	**15,000**	**20,400**	**2,500,000**
PIN15-CS-56	4/10/2003	3.6	ND	ND	18	ND	310,000
PIN15-CS-56	4/10/2003	11.6	ND	ND	10	ND	ND
PIN15-CS-56	4/10/2003	19.6	ND	ND	13	ND	ND
PIN15-CS-56	5/23/2003	25.6-29.6	ND	ND	ND	ND	ND
PIN15-CS-56	5/23/2003	33-37	ND	ND	ND	ND	ND
PIN15-CS-57	4/9/2003	3.7	ND	ND	18	20	330,000
PIN15-CS-57	4/9/2003	11.7	ND	ND	16	ND	ND
PIN15-CS-57	4/9/2003	19.7	ND	ND	16	ND	ND
PIN15-CS-57	4/9/2003	27.7	ND	ND	ND	ND	ND
PIN15-CS-57	4/9/2003	27.7 Dup	ND	ND	14	ND	ND
PIN15-CS-57	5/21/2003	33-37	ND	ND	ND	ND	ND
PIN15-CS-58	4/9/2003	5.3	ND	ND	21	9.1	110,000
PIN15-CS-58	4/9/2003	13.3	ND	ND	10	ND	5,100 J
PIN15-CS-58	4/9/2003	21.3	ND	ND	12	ND	ND
PIN15-CS-58	4/9/2003	29.3	ND	ND	12	ND	ND
PIN15-CS-58	5/22/2003	33-37	ND	ND	ND	ND	ND
PIN15-CS-59	3/27/2003	3	5.8	ND	14	ND	36,000
PIN15-CS-59	3/27/2003	11	ND	ND	12	ND	ND
PIN15-CS-59	3/27/2003	19	ND	3.7 J	ND	ND	ND
PIN15-CS-59	3/27/2003	27	ND	ND	16	ND	ND
PIN15-CS-59	5/22/2003	33-37	ND	ND	ND	ND	ND
PIN15-CS-60	4/10/2003	1.8	ND	ND	16	3 J	86,000
PIN15-CS-60	4/10/2003	9.8	ND	ND	16	ND	ND
PIN15-CS-60	4/10/2003	17.8	ND	ND	14	ND	ND
PIN15-CS-60	4/10/2003	25.8	ND	ND	14	ND	ND
PIN15-CS-60	5/23/2003	31.8-35.8	ND	ND	ND	ND	ND
PIN15-CS-61	4/8/2003	2.9	ND	ND	43	7.4	47,000
PIN15-CS-61	4/8/2003	10.9	ND	ND	ND	ND	ND
PIN15-CS-61	4/8/2003	18.9	ND	ND	14	ND	ND

Confirmatory Sampling for Soils - Young-Rainey STAR Center, Area A
units are µg/kg

Location	Date	Sample Depth	cis-1,2-DCE	Methylene Chloride	Toluene	TCE	Florida Petroleum Range Organics
NAPL Remediation Goals:		(fbs)	**71,000**	**227,000**	**15,000**	**20,400**	**2,500,000**
PIN15-CS-61	4/8/2003	26.9	ND	ND	ND	ND	ND
PIN15-CS-61	5/21/2003	32.9-36.9	ND	5.9 J	ND	ND	ND
PIN15-CS-62	4/9/2003	6.7	65	ND	65	5.7	ND
PIN15-CS-62	4/9/2003	14.7	ND	ND	ND	ND	16,000
PIN15-CS-62	4/9/2003	22.7	ND	ND	16	ND	57,000
PIN15-CS-62	5/22/2003	28.7-32.7	ND	7.9 J	ND	ND	ND
PIN15-CS-62	5/22/2003	28.7-32.7 Dup	ND	3.6 J	ND	ND	ND
PIN15-CS-62	5/22/2003	33-37	ND	ND	7.6	ND	ND
PIN15-CS-63	3/24/2003	6	14	ND	11	ND	ND
PIN15-CS-63	3/24/2003	14	ND	ND	11	ND	ND
PIN15-CS-63	3/27/2003	22	ND	ND	ND	ND	ND
PIN15-CS-63	3/24/2003	30	ND	ND	ND	ND	ND
PIN15-CS-63	5/22/2003	33-37	ND	5.6 J	ND	ND	ND
PIN15-CS-64	4/10/2003	0.9	ND	ND	16	ND	550,000
PIN15-CS-64	4/10/2003	8.9	47	ND	220	110	ND
PIN15-CS-64	4/10/2003	16.9	ND	ND	14	ND	ND
PIN15-CS-64	4/10/2003	24.9	ND	ND	13	ND	ND
PIN15-CS-64	5/22/2003	30.9-34.9	ND	ND	ND	ND	ND
PIN15-CS-65	4/8/2003	5	120	ND	83	ND	110,000
PIN15-CS-65	4/8/2003	13	ND	3.2 J	12	ND	ND
PIN15-CS-65	4/8/2003	21	ND	ND	14	ND	ND
PIN15-CS-65	4/8/2003	29	ND	ND	ND	ND	ND
PIN15-CS-65	5/21/2003	33-37	ND	8.2 J	ND	ND	ND
PIN15-CS-66	4/10/2003	0.4	9.5	ND	12	25	95,000
PIN15-CS-66	4/10/2003	8.4	90	3 J	420	74	ND
PIN15-CS-66	4/10/2003	16.4	ND	ND	15	ND	ND
PIN15-CS-66	4/10/2003	24.4	ND	ND	12	ND	ND
PIN15-CS-66	5/22/2003	30.4-34.4	ND	4 J	ND	ND	8,800 J

Confirmatory Sampling for Soils - Young-Rainey STAR Center, Area A
units are µg/kg

Location	Date	Sample Depth	cis-1,2-DCE	Methylene Chloride	Toluene	TCE	Florida Petroleum Range Organics
NAPL Remediation Goals:		(fbs)	**71,000**	**227,000**	**15,000**	**20,400**	**2,500,000**
PIN15-CS-67	3/24/2003	5.1	ND	ND	14	ND	ND
PIN15-CS-67	3/24/2003	13.1	ND	ND	11	ND	ND
PIN15-CS-67	3/24/2003	21.1	ND	ND	ND	ND	ND
PIN15-CS-67	3/24/2003	29.1	ND	ND	17	ND	ND
PIN15-CS-67	5/20/2003	33-37	ND	6.6 J	ND	ND	ND
PIN15-CS-68	3/25/2003	0.6	ND	ND	15	ND	460,000
PIN15-CS-68	3/25/2003	8.6	ND	ND	11	ND	21,000
PIN15-CS-68	3/25/2003	16.6	ND	ND	13	ND	9,200 J
PIN15-CS-68	3/25/2003	24.6	10	6.2 J	62	ND	15,000
PIN15-CS-68	5/20/2003	30.6-34.6	ND	4.5 J	ND	ND	ND
PIN15-CS-69	3/25/2003	3.7	ND	3 J	11	ND	130,000
PIN15-CS-69	3/25/2003	3.7 Dup	ND	ND	ND	ND	130,000
PIN15-CS-69	3/25/2003	11.7	240	ND	ND	ND	26,000
PIN15-CS-69	3/25/2003	19.7	ND	ND	ND	ND	5,300 J
PIN15-CS-69	3/25/2003	27.7	ND	ND	12	ND	ND
PIN15-CS-69	5/20/2003	33-37	ND	ND	ND	ND	ND
PIN15-CS-70	3/25/2003	6.1	ND	ND	ND	ND	6,800 J
PIN15-CS-70	3/25/2003	14.1	ND	ND	11	130	ND
PIN15-CS-70	3/25/2003	22.1	ND	ND	ND	ND	ND
PIN15-CS-70	3/25/2003	30.1	ND	ND	12	ND	ND
PIN15-CS-70	5/20/2003	33-37	ND	ND	ND	ND	ND

ND = Not Detected

J = Estimated value above the instrument detection limit but below the reporting limit.

B = Analyte detected in the laboratory method blank.

ELECTRICAL RESISTIVE HEATING AT AIR FORCE PLANT 4, FORT WORTH, TX

Project Name: Aircraft Manufacturing Facility

Project Location: Fort Worth, TX

Technology Employed: Electrical Resistive Heating (ERH)

Remediation Scale: Full Scale

Project Duration: April 2002 to December 2002

Site Information: Soil and groundwater beneath Building 181 at Air Force Plant 4, in Fort Worth TX, was contaminated with TCE. An ERH system was installed inside the building and used to remediate TCE and DNAPL. The ERH system covered an area of about 0.5 acres within the building. The estimated treatment volume was 27,000 cubic yards.

Contaminants: TCE and DNAPL. Prior to remediation, the maximum TCE levels were 95,000 µg/L in groundwater and 91 mg/kg in soil.

Hydrogeology: The geology at the sit consisted of heterogeneous interbedded silt, clay, and gravel. The depth to groundwater was 27 ft. bgs.

Project/Cleanup Goals: The cleanup objectives were to reduce the average TCE concentrations in soil and groundwater by 90%, with a target of 11.5 mg/kg for soil and 10,000 µg/L in groundwater.

Project Approach: ERH was used to treat TCE and DNAPL in soil and groundwater beneath Building 181. A pilot test of ERH was conducted at the site from August to October 2000. In April 2002, TRS, as a subcontractor to URS Corp., designed, installed and operated a full-scale ERH system consisting of 60 electrodes and co-located vapor recovery wells covering an area of about ½ of an acre inside the building. The layout of the ERH system is shown in Figure 1.

Many of the ERH electrodes and co-located vapor recovery wells were installed underneath manufacturing equipment, chemical bath tanks, and piping racks, at angles up to 32°. Figure 2 shows one of the ERH electrodes and one of the co-located vapor and steam recovery wells that were installed through the concrete floor. In addition, several of the system components were installed below the floor grade in protected well vaults to allow for unrestricted access by operations personnel and vehicles. Vapors from the recovery wells were vented to the main eight-inch CPVC main vapor recovery pipe (Figure 2) that was used to transport vapors to GAC units. Safety features of the system included below grade completion, semi-permanent construction fencing, heavy-duty electrical cable and continuous indoor air monitoring. The system was operated from April to December 2002, on a 24 hours per day, 7 days a week schedule.

Continuous indoor air monitoring of TCE was performed using an INNOVA system . The INNOVA system consisted of an online gas chromatograph that sampled the indoor air every five minutes for ambient TCE concentrations. The system was designed to automatically shutdown the ERH system if background TCE concentrations in the indoor air exceeded 3 ppm. TCE concentrations in the indoor air did not exceed this threshold during ERH operations.

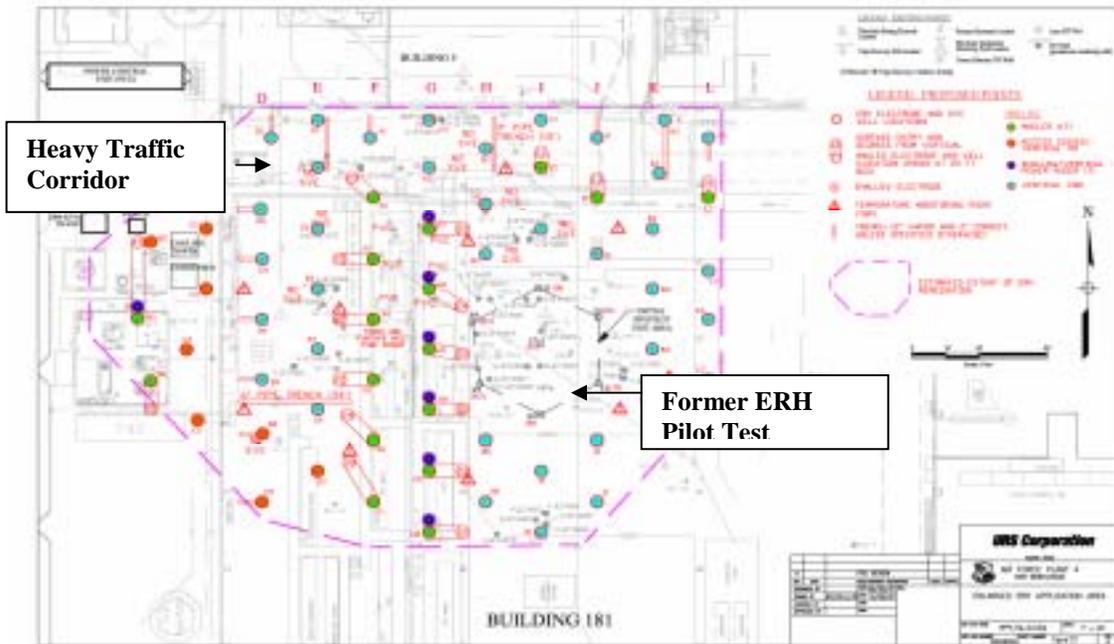**Figure 1. ERH System Layout Inside Building 181**

Figure 2. Main VR Piping Inside Building 181

Project Contact: The Remediation Design Engineer was Mr. Greg Beyke and the Operations Manager was Mr. Jerry Wolf.

Costs: The costs reported for the pilot test were $55 per cubic yard. No cost data were provided for the full-scale remediation.

Project Results: Figures 3 and 4 show the subsurface temperature versus depth (as of September 2002) and subsurface temperature versus time (as of December 2002), respectively. As shown in Figure 3, the majority of the subsurface temperatures reached or exceeded the boiling point of TCE (73°C) at depth. As shown in Figure 4, subsurface temperatures reached the boiling point for TCE in July 2002, with the average subsurface temperatures remaining steady through the end of the project.

Figure 5 shows the amount of condensate and TCE removed by the system through October 2002. During this time, almost 1,400 pounds of TCE and 160,000 gallons of condensate were removed. According to TRS, by December 2002, more than 1,600 pounds of TCE had been removed.

Figure 3. Subsurface Temperature vs. Depth (September 09, 2002)
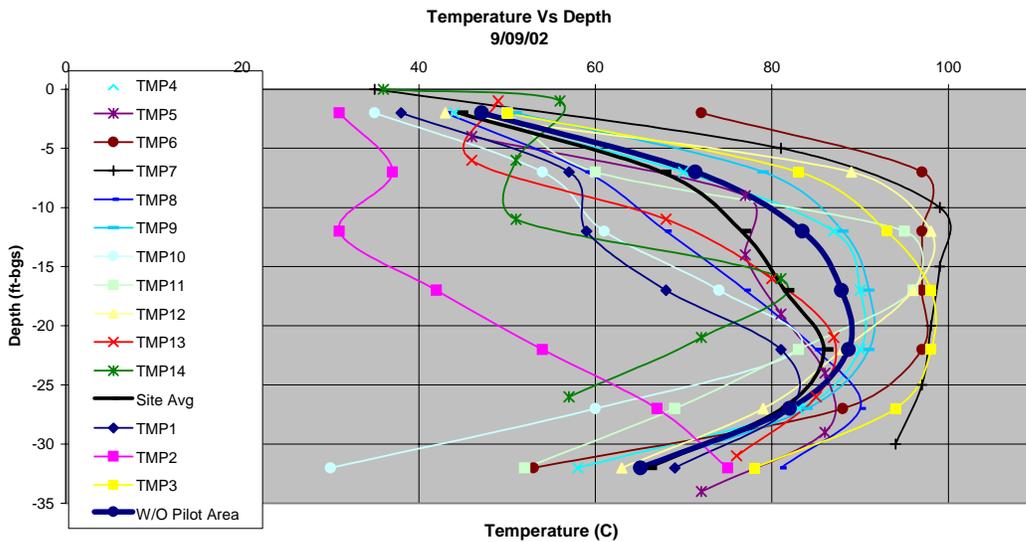
Figure 4. Average Subsurface Temperature vs. Time (December 10, 2002)
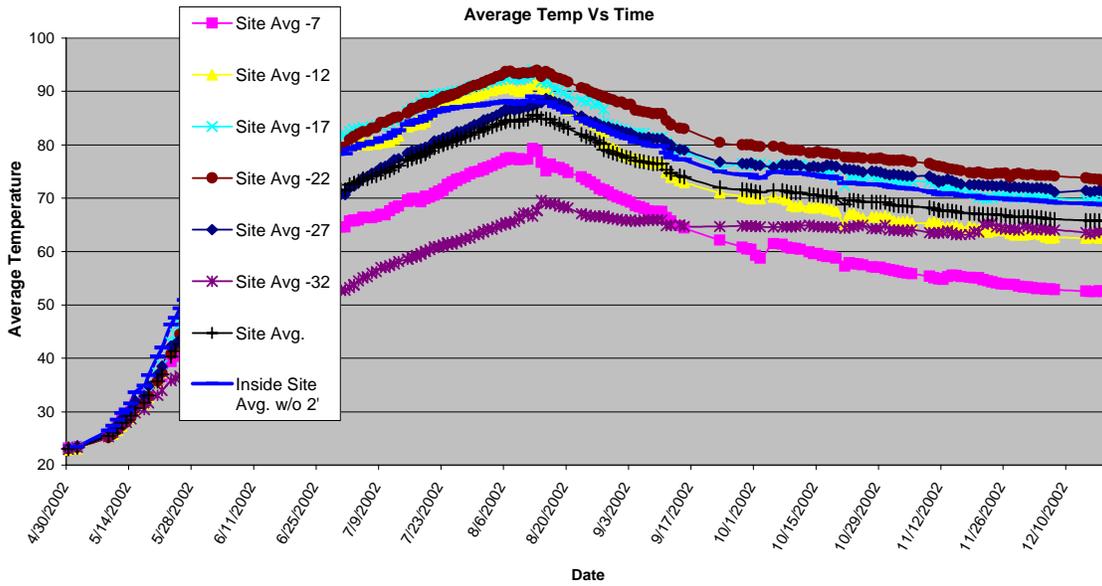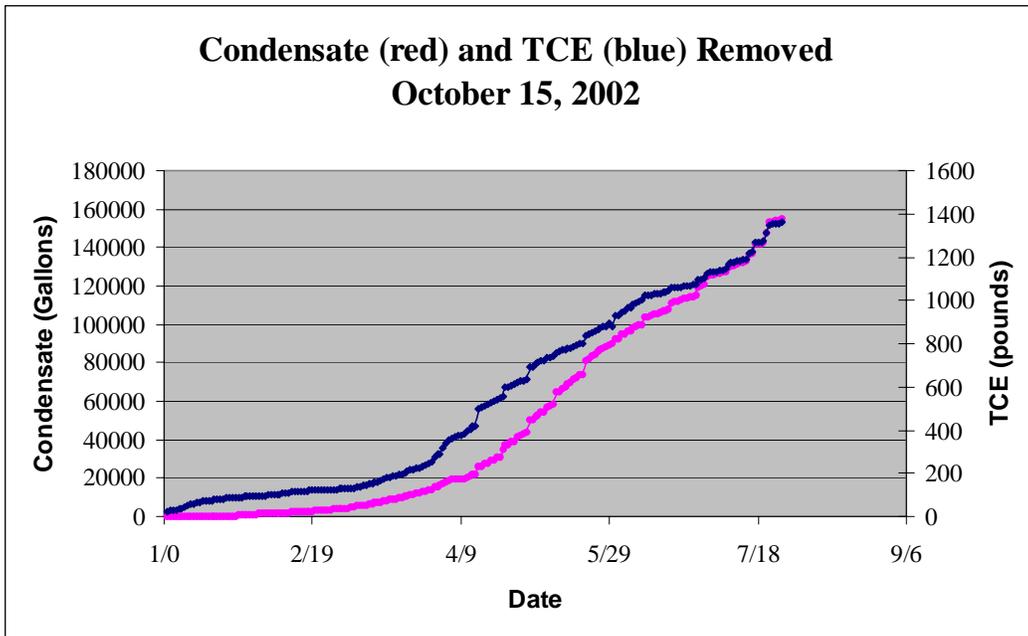

Figure 5. Condensate and TCE Removed Over Time

Figure 6 shows the average weekly power input overtime through December 13, 2002. The average input ranged from about 450 to 675 kilowatts (kW) between May and August, dropping to below 300 kW for the remainder of the system operation. A total of about 1,900,000 kilowatt-hours (kWh) of energy were input to the subsurface during ERH operations.

Figure 6. Average Weekly Power Input (kW)
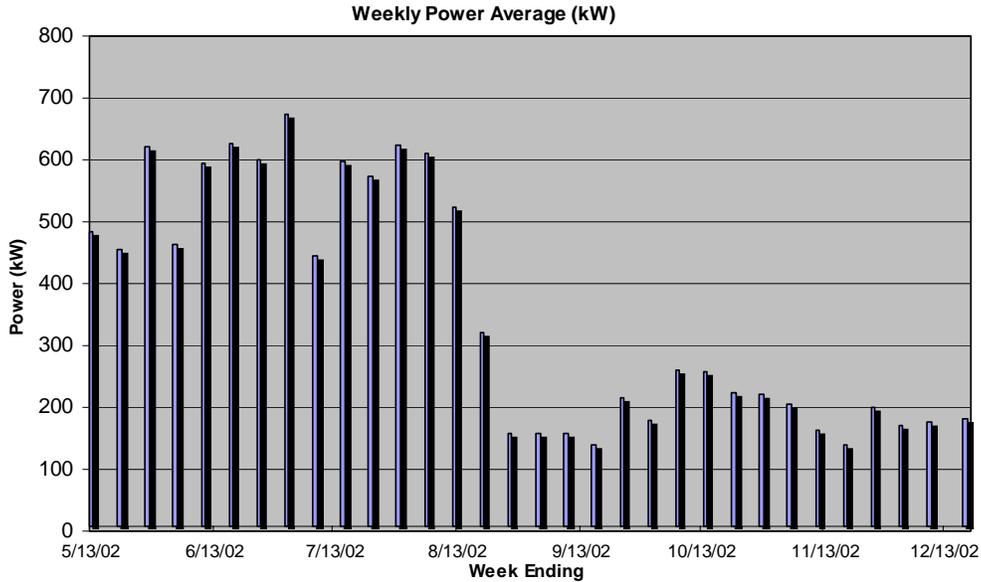
Figure 7 shows TCE concentrations in groundwater from April to November 2002. After eight months of operation, TCE groundwater concentrations were reduced an average of 93% from 95,000 µg/L to below the cleanup goal of 10,000 µg/L.

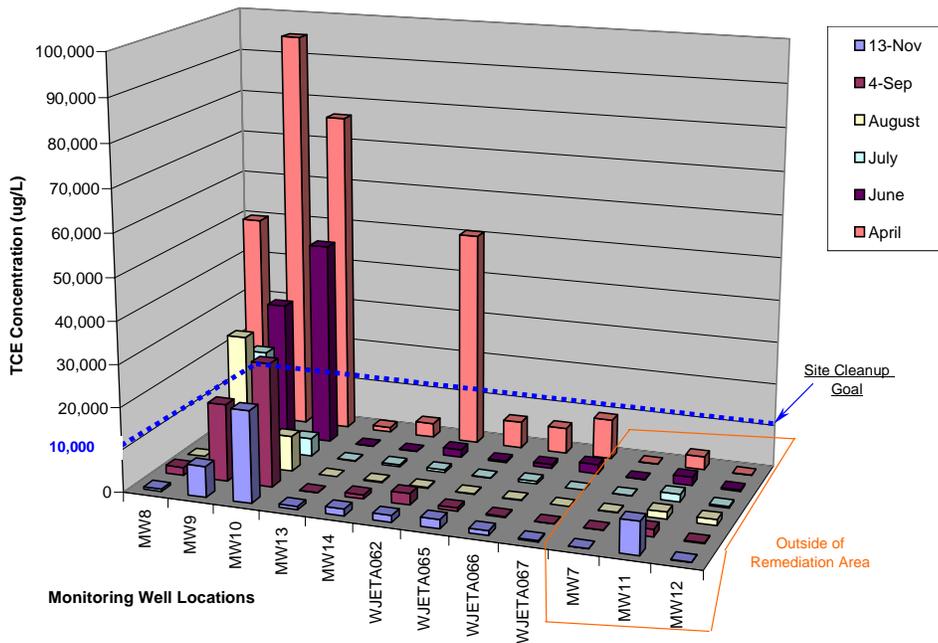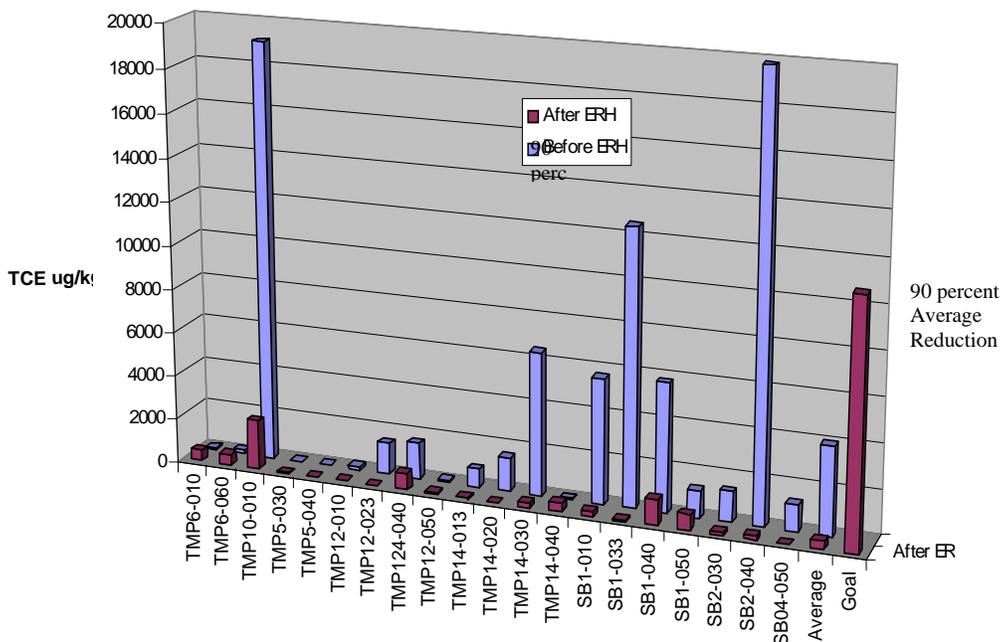## Figure 7. TCE Concentrations in Groundwater April – November 2002

Figure 8 shows TCE concentrations in soil from April to December 2002. TCE concentrations in soil were reduced an average of 90% to 0.391 mg/kg, below the cleanup goal of 11.5mg/kg.

Figure 8. TCE Concentrations in Soil April – December 2002

Sources:

TRS. March 2004. ERH Remediation – Air Force Plant – Fort Worth, Texas. http://thermalrs.com/TRSPages/Projects/Cproj1_AF_FWTX.html.

EPA. January 2001. In Situ Thermal Treatment Site Profile Database. Air Force Plant 4, Fort Worth, TX. http://www.cluin.org.

ELECTRICAL RESISTIVE HEATING AT DRY CLEANER, SUBURBAN CHICAGO, ILLINIOS

Site Type: Dry Cleaner Facility

Site Location: Chicago, IL

Technology Employed: Electrical Resistive Heating (ERH)

Remediation Scale: Full Scale

Project Duration: December 2002 to March 2003

Site Information: The site is a former drycleaner facility with a soil contamination depth of 4 to 20 ft. A ruptured sewer line released PCE to the soil 300 ft. downgradient from the drycleaner facility. The site infrastructure includes sewer lines, water lines, natural gas lines, and electrical conduits. The cleanup was performed under the Illinois EPA Voluntary Site Remediation Program.

Contaminants: Soil at the site was contaminated with VOCs, including PCE. The total estimated mass of VOCs in soil was 2,238 lbs. The maximum PCE concentration in soil was 13,000 mg/kg, with an average PCE concentration of 1,492 mg/kg.

Hydrogeology: The contaminated soil at the site was clayey glacial till deposits with very low permeability (hydraulic conductivity 10^{-8} cm/sec). Groundwater at the site was encountered below 50 ft.

Project/Cleanup Goals: The goal of the project was to remove residual DNAPL in soil to below 529 mg/kg. (The project's calculated saturation limit for site-specific soil with total organic carbon content > 1.6 %)

Project Approach: Initially, soil vapor extraction was performed at the site. A total of 70 4-inch-diameter SVE wells were operated for 4 years. The SVE system removed 200 pounds of VOCs. ERH was then used to remove the residual DNAPL in soils. This piping and associated equipment were removed from the site prior to installation of the ERH system.

The ERH system included a total of 17 electrodes installed to a depth of 21.5 ft. Vapor recovery wells were installed within the same boring and screened at depths from 22 to 24.5 ft. The spacing between electrodes was approximately 11 ft. The electrodes were arranged in 6 arrays to facilitate the soil heating process. In addition, 3 vertical vapor recovery wells screened from 8 to 18 ft. were installed to assist in recovery of heated vapors. A series of 11 lateral vapor recovery screens were place approximately 18-inches below grade to prohibit loss of vapors to the surface. A grid of galvanized metal wire was placed over the treatment area to capture any stray voltage and the entire area was covered with asphalt pavement.

The recovered vapor was passed through a condenser, and the air was emitted through a vent stack that extended approximately 20 ft. in the air. The air stream was passed through an activated carbon unit during the peak VOC removal period to meet the 8-pound-per-hour VOC emissions limit in the air permit.

Water collected from the condensation unit was cooled in a cooling tower and recirculated to the treatment area to provide moisture for the electrodes. In addition, a potable water source was also used to ensure that a sufficient amount of water was available to keep the electrodes moist.

The temperature profile for the project was: Start-up: 14.7°C; 30 days: 83.4°C; 60 days: 87.8°C; and 90 days: 93.6°C. The ERH system was operated from December 2002 to March 2003. Demobilization was also conducted in March.

Project Contact: Clayton Group Services, Inc. (Clayton) served as General Contractor. Thermal Remediation Services (TRS) provided the Electrical Resistive Heating.

<div style="text-align:center">

David Fleming   Russ Chadwick
Thermal Remediation Services   Clayton Group Services, Inc.
P.O. Box 50387   3140 Finley Road
Bellevue, WA 98015   Downers Grove, IL 60515
(425) 396-4266   (630) 795-3218

</div>

Costs: The estimated cost of the excavation alternative (shoring the building, utility relocation soil removal as hazardous waste and soil replacement) was $1.1 million. The total fixed price, guaranteed remediation for ERH was $695,000.

Project Results: Over 90% reduction of initial PCE concentration.

THERMAL CONDUCTIVE HEATING AT CONFIDENTIAL OHIO SITE

Site Type: Confidential chlorinated solvents site

Site Location: Ohio

Technology Employed: Thermal Conductive Heating

Remediation Scale: Full Scale

Project Duration: August 2002 to September 2003

Site Information: The site is an operating manufacturing facility that used chlorinated solvents. The vadose at three locations on the property was found to be contaminated with trichloroethene (TCE), tetrachloroethene (PCE), and 1,1,1-trichloroethane (TCA). The cleanup was conducted under the State Voluntary Cleanup Program.

Contaminants: The maximum contaminant concentrations in soil prior to remediation were: PCE, 370 mg/kg; TCE, 4,130 mg/kg; and TCA, 1,400 mg/kg.

Hydrogeology: Contaminated soil at the site consisted primarily of a low permeability silty-clay till unit. The thickness of the till unit requiring treatment is approximately 15 ft. beneath all three sites. Perched water in the silty-clay till unit was reported in several locations. The layer below the till is a sand and gravel layer, consisting of fine to coarse sand and locally occurring gravel. The regional water table was located within the sand and gravel layer, approximately 30 ft bgs. At the site, there was a perched water table at a depth of 3 ft. bgs.

Project/Cleanup Goals: The cleanup goals for soil were: 5.94 mg/kg for PCE; 1.056 mg/kg for TCE; and 28.6 mg/kg for 1,1,1-TCA.

Project Approach: Thermal conductive heating was used to treat contaminated soil at the site targeting three areas to a depth of 15 ft. The system included a total of 138 wells (45 heater/vacuum wells and 93 heater-only wells) and was used to treat a total of 11,000 cy of soil. The wells were installed in a hexagonal pattern within each area: Area 1 – 90 wells total covering an area approximately 14,200 ft^2 and 15 ft. deep (about 8,000 cy); Area 2 – 24 wells covering an area approximately 3,100 ft^2 and 15 ft. deep (about 1,700 cy); and Area 3 – 24 wells covering an area approximately 2,400 ft^2 and 15 ft. deep (about 1,300 cy).

The first area of contamination was adjacent to residences, located as close as 1 foot from the property line. A second area had a buried fire suppression line running through it, which was protected with an insulation jacket. The third area contained a former sludge lagoon.

The soil within the treatment areas were heated until the coolest regions (i.e., the centroids between the thermal wells) attained a temperature of 100°C. The primary mechanism for the removal of the chlorinated solvents was volatilization and steam stripping, although regions around the thermal wells attained temperatures in excess of 100°C (e.g., temperatures near the heater-vacuum wells were greater than 500°C). The heating duration required to achieve the remedial objectives was approximately 90 days. Vapors (steam and contaminants) produced during heating were removed from the subsurface via the heater-vacuum wells and treated above

ground using neutralization and granular activated carbon (GAC) prior to discharge to the atmosphere.

The system was constructed from December 2002 to April 2003. In situ thermal treatment was conducted from May to June 2003. Demobilization was conducted in August 2003.

Project Contact: TerraTherm, Inc. provided all project design, construction, operation and equipment.

Costs: Turnkey remedial costs including power, were $1.3 million or $118 per cy. The contract included a performance guarantee.

Project Results: Pending

APPENDIX C

IN SITU THERMAL TREATMENT TECHNOLOGY PROVIDERS

STEAM ENHANCED EXTRACTION

ENSR Corporation

27755 Diehl Rd.
Warrenville, IL 60555
(630) 836-1700
Timothy Adams
tadams@ensr.com

Integrated Water Resources

P.O. Box 2610
Santa Barbara, CA 93120
(805) 966-7757
mesa@integratedwater.com

Southern California Edison

Rosemead, CA
Craig Eaker
(626) 302-8531
craig.eaker@sce.com

SteamTech Environmental Services, Inc.

4750 Burr Street
Bakersfield, CA 93308
(661) 322-6478
Gorm Heron, Principal Environmental
Scientist/Engineer
heron@steamtech.com

THERMAL CONDUCTIVE HEATING

TerraTherm Environmental Services, Inc.

356-B Broad Street
Fitchburg, MA 01420
(978) 343-0300
Ralph Baker, President
rbaker@terratherm.com

ELECTRICAL RESISTIVE HEATING

Clayton Group Services

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Downers Grove, IL 60515
Monte Nienkerk, Senior Project Manager
(703) 390-0628

Current Environmental Solutions

350 Hills St.
Richland, WA 99352
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William Heath, Chief Operating Officer
bill@cesiweb.com

KAI Technologies, Inc.

16 Marin Way
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Bruce Cliff, Director of RF Sales
cliff@kaitech.com

McMillan-McGee

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mcgee@mcmillan-mcgee.com

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