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Environmental Quality Design: In Situ Thermal Remediation

FOR THE COMMANDER:

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Chief of Staff

Purpose. This Engineer Manual provides guidance for the screening and selection of in situ thermal remediation technologies, including steam enhanced extraction, electrical resistance heating, and thermal conductive heating. It helps distinguish appropriate applications, identify key design and operational considerations, and support oversight. The intended audience includes engineers, geologists, hydrogeologists, soil scientists, and others with technical backgrounds but limited experience with in situ thermal remediation technologies.

Applicability. This Engineer Manual applies to all U.S. Army Corps of Engineers commands having civil works and/or military programs with hazardous, toxic, or radioactive waste project responsibilities.

Distribution Statement. This publication is approved for public release and unlimited distribution.

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*This manual supersedes EM 200-1-21, dated 30 May 2014.

SUMMARY of CHANGE

EM 200-1-21

In Situ Thermal Remediation

This revision, dated 17 February 2026:

- Validation of references and addition of web addresses.
- Update of terminology and acronyms.
- Addition of an overview of the smoldering technology, heat-enhanced soil vapor extraction, and heat-enhanced bioremediation.
- Addition of discussion on the use of natural gas/propane-fired thermal conduction heating.
- Update on the recent usage statistics for in situ thermal remediation.
- Update to Chapter 10 sections on contracting for in situ thermal remediation, and clarification of regulatory authorities. Also, deleted the section on patent issues that had been in Chapter 10.

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Chapter 1 Introduction

1-1. Purpose

This Engineer Manual (EM) provides guidance for the screening and selection of in situ thermal remediation (ISTR) technologies, including steam enhanced extraction (SEE), electrical resistance heating (ERH), and thermal conductive heating (TCH). It helps distinguish appropriate applications, identify key design and operational considerations, and support oversight. The intended audience includes engineers, geologists, hydrogeologists, soil scientists, and others with technical backgrounds but limited experience with ISTR technologies.

1-2. Distribution statement

This publication is approved for public release and unlimited distribution.

1-3. References

See Appendix A.

1-4. Records management (recordkeeping) requirements

The records management requirement for all record numbers, associated forms, and reports required by this publication are addressed in the Army Records Retention Schedule. Detailed information for all related record numbers is located on the U.S. Army Corps of Engineers (USACE) Records Management Site <https://usace.dps.mil/sites/INTRA-CIOG6/SitePages/Records-Management.aspx>. If any record numbers, forms, and reports are not current, addressed, or published correctly, see DA Pam 25-403 for guidance.

1-5. Associated publications

This section contains no entries.

1-6. Background

Many sites are contaminated with organic compounds, including chlorinated solvents, oils and petroleum products, polychlorinated biphenyls (PCBs), and wood-preserving chemicals, above and below the water table. These sites occur in both saturated and unsaturated zones at federal installations and former industrial properties. Sites with non-aqueous phase liquids (NAPLs), especially below the water table, are difficult to remediate using conventional methods such as groundwater extraction, bioremediation, or soil vapor extraction (SVE). NAPL often serves as a long-term source of dissolved contamination. In response, more aggressive technologies have been developed, including in situ chemical oxidation, surfactant/solvent flushing, and ISTR. ISTR is the most widely applied and effective of these approaches.

a. *In situ thermal remediation methods.*

(1) *Heat transfer.*

(a) Heat can be transferred into the subsurface through the following methods.

1. Conduction of heat from heaters placed in trenches or wells, known as TCH.
2. Passing electrical currents through soil to generate heat, known as ERH.
3. Injection of steam to mobilize contaminants, known as SEE.

(b) An analysis of over 600 projects (Horst et al. 2021) found these 3 methods were used in 95 percent of ISTR applications. They are therefore addressed in detail in this EM. Other ISTR technologies are briefly discussed below. TCH, ERH, and SEE are typically applied with vapor extraction, while steam injection often includes liquid recovery. Depending on site conditions, these methods may be applied individually or in combination to treat the vadose zone and the saturated contamination. Further descriptions are provided in Chapter 2.

(2) *Smoldering.* Smoldering destroys contaminants by using them as a fuel source for a flameless combustion reaction. Treatment begins with a short energy input to ignite subsurface contaminants, followed by continuous injection of an oxidant (such as oxygen) to sustain combustion. This approach is commonly known as self-sustaining treatment for active remediation (STAR), a vendor-patented application of in situ smoldering. Additional details are provided in paragraph 2–2d.

(3) *Vitrification.* This EM does not address in situ vitrification, a thermal stabilization method involving soil melting at temperatures above 1,200 °C (2,192 °F) followed by rapid cooling to glass-like material. In situ vitrification will immobilize non-volatile metals. It also pyrolyzes or combusts organic compounds (Chen et al. 2009). Due to high energy demand, in situ vitrification is limited to small volumes of waste.

(4) *In situ soil mixing with steam.* In soil mixing with large-diameter augers, steam can be injected into the disturbed subsurface to enhance contact with contaminated soils.

(5) *Radio frequency and microwave heating.* Radio frequency heating introduces electromagnetic energy into the soil at frequencies between 1 megahertz and 27 megahertz, generating heat through energy dissipation. Bench-scale testing began in the mid-1980s (Dev 1986), and a field-scale demonstration was conducted at Volk Field Air National Guard Base in 1989 (USEPA 1997). Radio frequency heating is also used in industrial processes such as food drying and asphalt heating. Only ~1 percent of ISTR projects reviewed by Horst et al. (2021) reported radio frequency heating use. Microwave heating uses the same principle at higher frequencies (between 300 megahertz and 300,000 megahertz). Its feasibility for full-scale in situ applications remains under evaluation (Ding et al. 2019).

(6) *Low-temperature heating.* Certain remedial processes are enhanced by moderate heating (< 70 °C or < 158 °F) and do not require extensive power, heater density, or recovery systems of full-scale ISTR. Low-temperature heating serves as a middle ground between non-thermal and high-temperature ISTR approaches.

(a) *Methods.* Low-temperature heating methods include the following.

1. Injection of hot air to enhance air sparging (AS) and SVE.
2. Use of geothermal systems (such as heat pumps, solar collectors, and boilers) to heat and circulate fluids through subsurface coils or pipes.
3. Hot water injection, with or without chemical or biological amendments.
4. The application of electrodes (ERH) or heaters (TCH) at lower power or wider spacing than full-scale ISTR.
5. Capture of residual heat from full-scale ISTR systems.

(b) *Heat-enhanced conventional methods.* Heat can improve recovery in SVE, AS, multiphase extraction, and groundwater recirculation by increasing contaminant mass transfer into the vapor and dissolved phases and by improving NAPL recovery (see paragraph 2–1).

(c) *Heat-enhanced chemical or biological treatment.* Increases in temperature accelerate the kinetics of many biotic and abiotic contaminant destruction processes. Biological degradation rates typically double with every 10 °C (50 °F) increase up to 40 °C (104 °F). Chemical reactions (such as hydrolysis and zero-valent iron-mediated reactions) and chemical oxidation (persulfate activation) are also temperature-dependent. The Environmental Security Technology Certification Program (ESTCP) demonstrated these effects at field scale (ESTCP 2012, ESTCP 2023) and are summarized by Horst et al. (2018). Further discussion is provided in paragraph 2–1c.

b. *Brief history of in situ thermal remediation.*

(1) The origins of several ISTR technologies can be traced to the oil industry. Steam injection has been used for an extended period to recover high-gravity oils (Ramey 1966). Its application to contaminated soil and groundwater remediation began in the 1980s in the Netherlands and the United States.

(2) ERH was adapted from oil recovery applications and developed in a six-phase configuration by Battelle Memorial Institute for the U.S. Department of Energy (DOE) at Pacific Northwest National Laboratory from 1988 to 1992 (Hadim et al. 1993). ERH was later tested at the Hanford and Savannah River sites in 1993, and its first dense non-aqueous phase liquid (DNAPL) removal was demonstrated at Dover Air Force Base in 1996. The first commercial application occurred in Illinois in 1996.

(3) Radio frequency heating was tested at bench scale in the mid-1980s (Dev 1986) and in a well-documented field demonstration at Volk Air National Guard Base in 1989 (USEPA 1997). TCH for remediation was pioneered by a division of Shell Oil in 1989 (Stegemeier and Vinegar 1995), building on enhanced oil recovery experience.

(4) In the late 1990s and early 2000s, several high-profile successes occurred at sites such as Savannah River, SC, and the Visalia Pole Yard, CA. Appendix B provides additional case study information. Use of ISTR expanded significantly following these early projects.

c. Survey of in situ thermal remediation projects. At least 643 ISTR projects were completed worldwide between 1988 and 2021, based on industry surveys (Triplett et al. 2010, Horst et al. 2021). Since the early 2000s, 20 to 30 projects have been completed annually. ERH and TCH dominate applications (57.2 percent and 29.5 percent, respectively). SEE accounts for 8.3 percent, though its use has declined in recent years, while smoldering (such as STAR) applications have increased. ERH and TCH have also expanded into fractured bedrock settings (CDM 2018).

d. Appropriateness of aggressive source removal. ISTR methods often require significant capital investment. While the long-term benefits can be substantial, their value remains debated, particularly regarding the degree of “source” removal needed to achieve strict remediation goals. Some practitioners advocate containment, while others support mass removal (ITRC 2002). This EM does not address the policy debate but focuses on the technical application of ISTR.

e. Advantages of in situ thermal remediation. Soil permeability limits techniques that rely on liquid flow. Permeability contrasts affect heat-based methods that rely on conduction less. Although thermal conductivity varies by an order of magnitude, even low-conductivity soils permit heat penetration and contaminant mobilization. Heating increases vapor pressure and dissolves separate-phase liquids better. It accelerates both abiotic and biotic degradation processes. Heating promotes the removal of persistent contaminants.

f. Limitations of in situ thermal remediation. ISTR methods are not designed for most inorganic contaminants, with limited exceptions (such as mercury). These methods are less effective for low-volatile organics such as pesticides, polycyclic aromatic hydrocarbons (PAHs), dioxins, and PCBs. ISTR may also be impractical in high groundwater flux settings, in areas with critical structures, or where safety risks exist, like unexploded ordnance (UXO). Large-scale applications can be constrained by cost. Financial considerations are further discussed in Chapter 2.

1–7. Scope

a. General content. This EM provides guidance on selecting and implementing ISTR technologies. It identifies principles and considerations for government staff to apply when evaluating ISTR at a site. Since each site presents unique challenges, the

EM does not prescribe a single approach. Instead, it outlines decision points and evaluation criteria to support effective selection and implementation.

(1) Specifically, this EM describes ISTR technologies and the science and engineering principles that support them. It does not provide detailed design guidance or comprehensive information on managing waste streams (vapor phase or wastewater treatment). It does provide the following listed items.

(a) Data requirements for evaluating ISTR, including site characterization and bench- or pilot-scale testing.

(b) Data needs to monitor ISTR performance.

(c) Guidance on screening the applicability of ISTR technologies based on site-specific conditions.

(d) Considerations for reviewing ISTR designs and tools for modeling performance.

(2) In addition, this EM addresses these areas.

(a) Major construction and operations and maintenance (O&M) activities.

(b) Regulatory considerations, contracting, safety, performance, and patent or licensing issues.

(c) Summaries of ISTR applications where data are available.

(3) A flowchart is provided to support technology selection. Readers are encouraged to consult ISTR vendors during the selection process to promote use of current information.

b. Other information sources. This EM was prepared to meet the needs of USACE as well as other federal and state agencies. It was developed with input from the U.S. Environmental Protection Agency (USEPA), the Navy, the Interstate Technology and Regulatory Council (ITRC), and the private sector. The electronic version includes links to relevant resources and a linked subject index.

Chapter 2

Underlying Physical Principles and Technology Descriptions

2-1. Fundamental principles

Organic chemicals released to the subsurface may exist in four phases: the solid soil matrix, the gas phase, the aqueous phase, and a NAPL phase. Application of heat can mobilize NAPL contaminants from the soil matrix, allowing recovery through groundwater extraction or vapor collection systems. This section provides an overview of multiphase flow and multicomponent mass transfer in the subsurface and the influence of elevated temperature on contaminant removal.

a. *Chemical principles.* The following concepts provide a basis for understanding the changes that occur under ISTR.

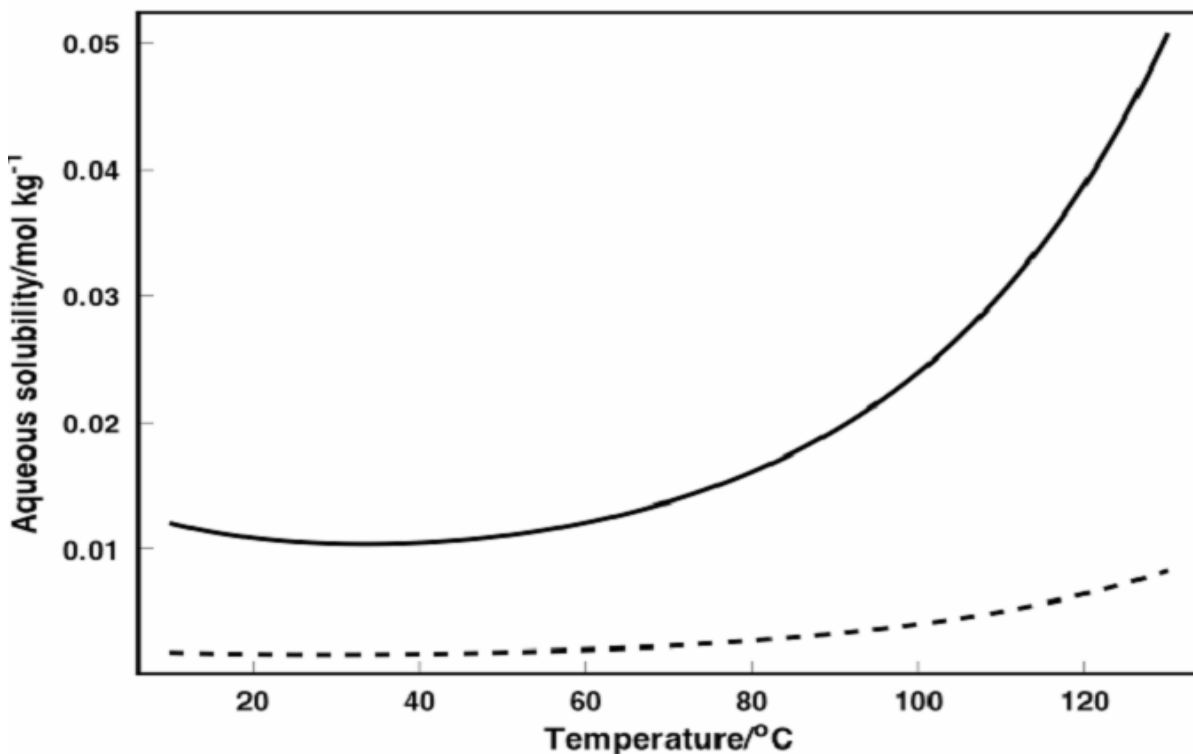


Figure 2-1. Aqueous solubility of trichloroethylene (solid line) and tetrachloroethylene (dashed line) versus temperature (Knauss et al. 2000; reprinted with permission by Elsevier Limited, copyright 2000, all rights reserved)

(1) *Aqueous solubility.* Data on hydrocarbon solubility at ISTR-relevant temperatures is limited. The solubilities of trichloroethene (TCE) and perchloroethylene (PCE) as functions of temperature are shown in Figure 2-1. Both compounds exhibit exponential increases in solubility with temperature, but only at temperatures above the boiling point of water. Experimental studies have also reported a local solubility minimum at 30 °C to 50 °C (86 °F to 122 °F) for TCE and PCE (Imhoff et al. 1997, Knauss et al. 2000, Heron et al. 1998a/1998b).

(a) The temperature dependence for larger molecules such as naphthalene is stronger. Figure 2-2 shows the aqueous solubility of naphthalene between 20 °C (68 °F) and 140 °C (284 °F). Solubility increases about 45-fold (from 31 mg/L to 1,350 mg/L) when heating from 25 °C to 100 °C (75 °F to 212 °F). In mixtures such as creosote, naphthalene solubility can increase 5- to 10-fold at ISTR-relevant temperatures (Davis 2003). These increases help explain the improved removal efficiency of dissolved PAHs observed during field-scale steam remediation at wood-treating sites such as the Visalia Pole Yard and Wyckoff-Eagle Harbor.

(b) In addition, even when aqueous solubility does not change substantially, heating can enhance mass transfer. For example, the dissolution rate of PCE DNAPL increased five-fold despite little change in solubility (Imhoff et al. 1997). For systems with mass-transfer limitations, heating may therefore substantially increase dissolved-phase removal.

(c) Overall, increased solubility enhances dissolution. For low-volatility PAHs, the aqueous phase can represent a major removal pathway. At the site in Skokie, Illinois, 22 percent of hydrocarbons removed during SEE were recovered in the dissolved phase.

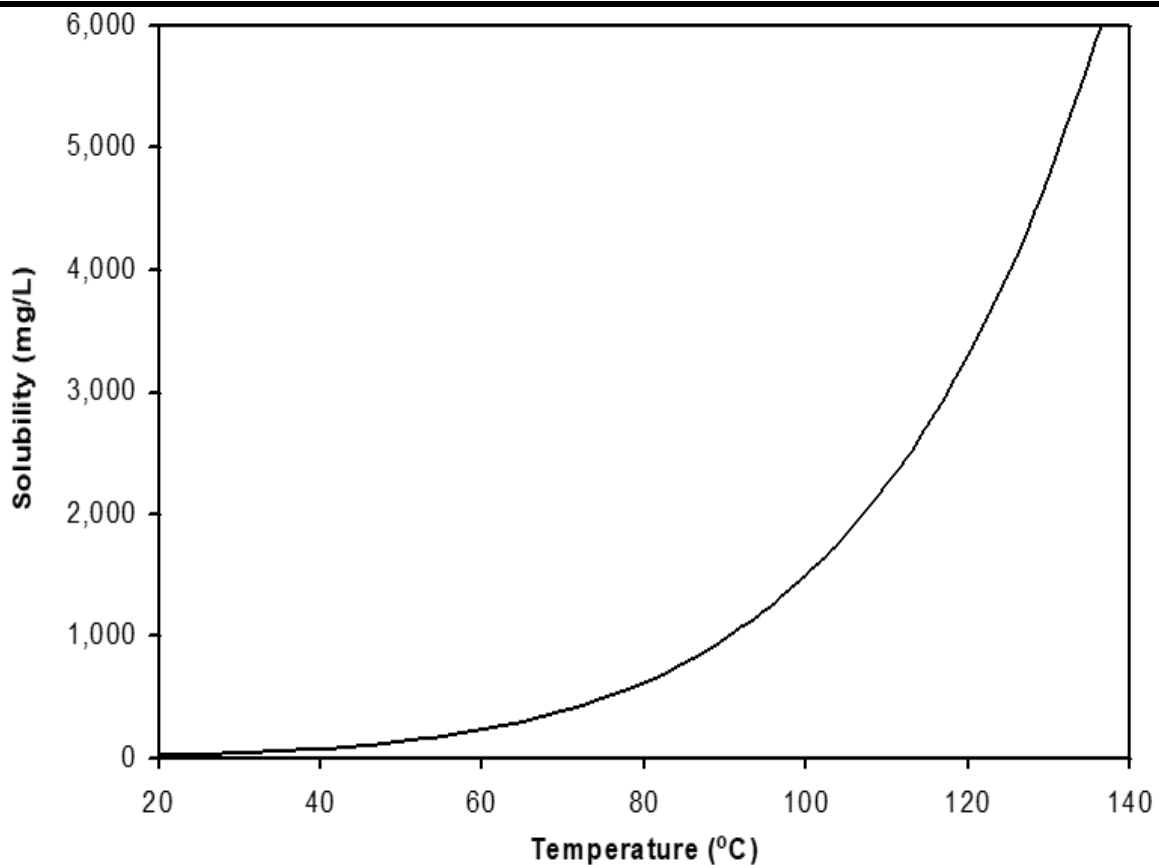


Figure 2–2. Calculated aqueous solubility of naphthalene versus temperature (Reid et al. 1987)

(2) *Sorption*. Soil/water sorption coefficients influence aqueous-phase transport of contaminants. These coefficients generally decrease with increasing temperature, increasing the ability of hot fluids to mobilize contaminants. Effects vary by contamination, soil type, and moisture content. For example, the soil/water sorption coefficient for TCE may decrease by 50 percent between 20 °C (68 °F) and 90 °C (194 °F), while soil/gas sorption in dry soil may decrease by an order of magnitude over the same range (Heron et al. 1998a).

(3) *Vapor phase.* Volatilization is governed by vapor pressure, the pressure exerted by a compound's gas phase in equilibrium with its liquid or solid. Vapor pressure increases with temperature (Figure 2–3), and boiling occurs when vapor pressure exceeds atmospheric pressure. Volatilization can also occur below a compound's boiling point through processes such as steam distillation, in that the presence of steam lowers the effective boiling point.

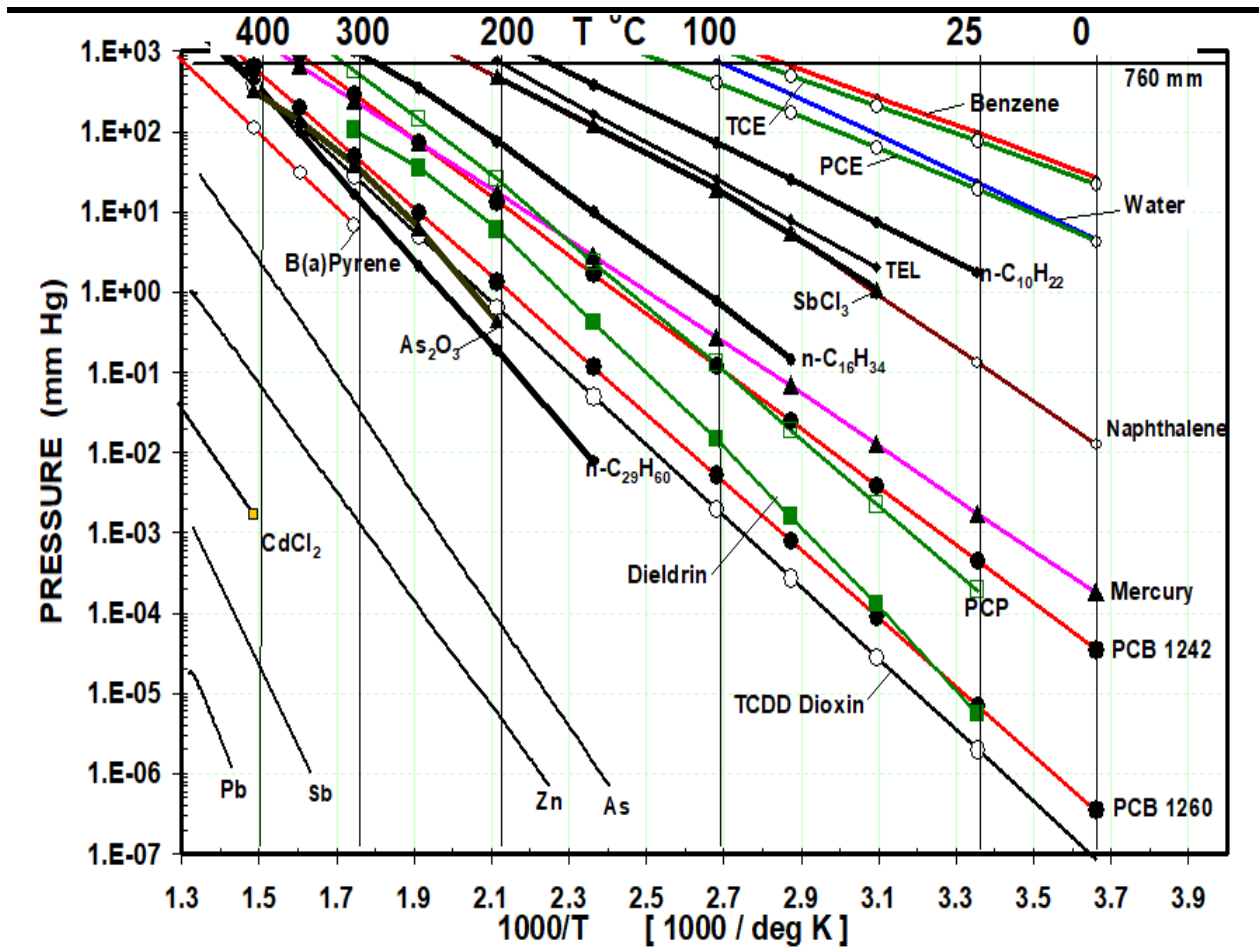


Figure 2–3. Vapor pressure of selected compounds versus temperature; atmospheric pressure is 760 mmHg (Stegemeier and Vinegar 2001; reprinted by permission from CRC Press, copyright 2001)

(a) Since vapor-phase concentration strongly depends on vapor pressure, heating increases mass transport by raising vapor concentration even below the boiling point.

(b) Figure 2–3 and Figure 2–4 illustrate these relationships. Figure 2–3 shows vapor pressure of selected compounds as a function of temperature. Figure 2–4 presents predicted vapor-phase concentrations of TCE and PCE across a range of temperatures, with aqueous solubilities at room temperature noted. The Antoine equation is commonly used to estimate vapor pressure of pure liquids, and a database of Antoine coefficients is available online (Yaws et al. 2009).

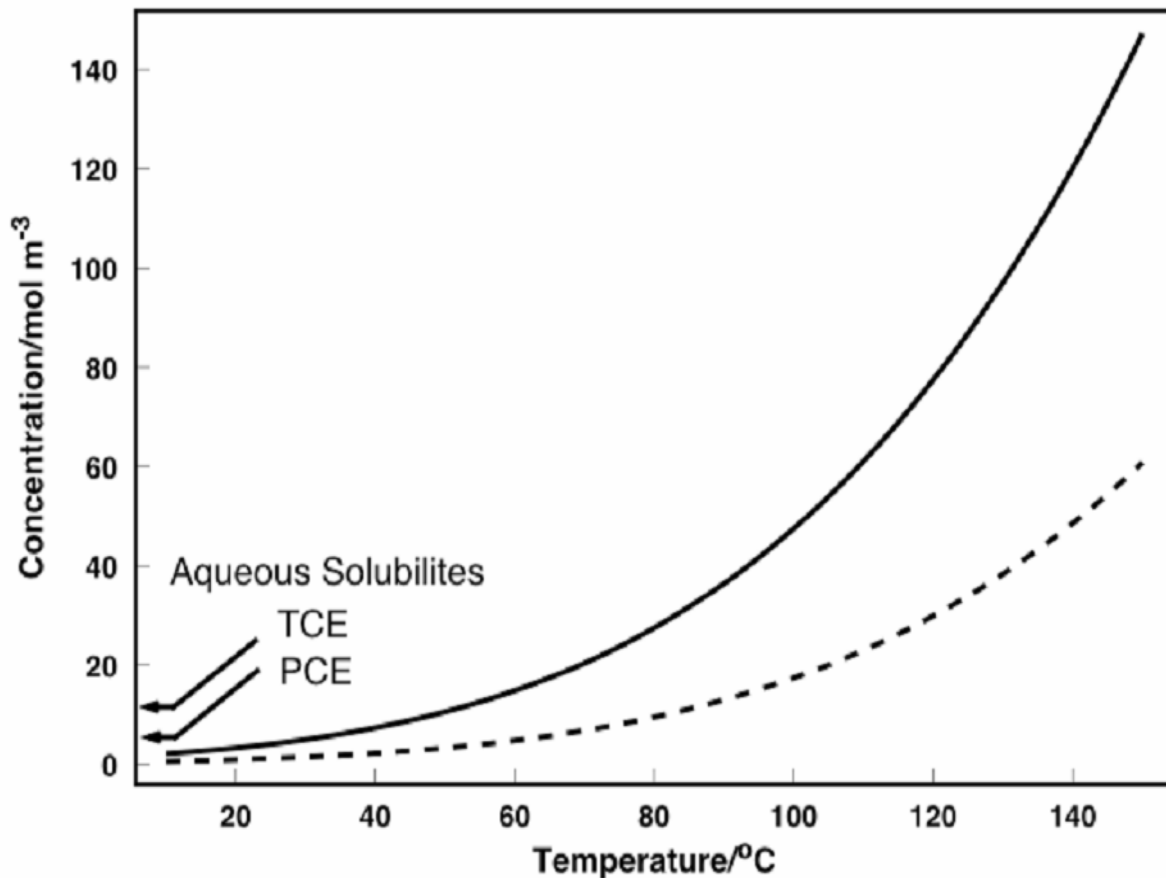


Figure 2–4. Vapor-phase concentrations of trichloroethylene (solid line) and tetrachloroethylene (dashed line) versus temperature. Calculated with the Clapeyron equation assuming ideal gas behavior. Arrows on the ordinate axis show aqueous solubilities at 25 °C (77 °F).

(4) *Gas mixtures.* Four fundamental gas laws describe the composition of mixtures.

(a) *Dalton's Law.* The pressure of a gas mixture equals the sum of the partial pressures of each individual gas.

(b) *Raoult's Law.* The equilibrium gas-phase partial pressure of a compound equals the product of its pure-component vapor pressure and its mole fraction in the NAPL phase.

(c) *Henry's Law.* The equilibrium gas-phase partial pressure of a compound equals its aqueous-phase mole fraction multiplied by Henry's Law constant (see Figure 2–5).

(d) *Ideal Gas Law.* The mole fraction of a compound in the gas phase equals the ratio of its partial pressure to total pressure.

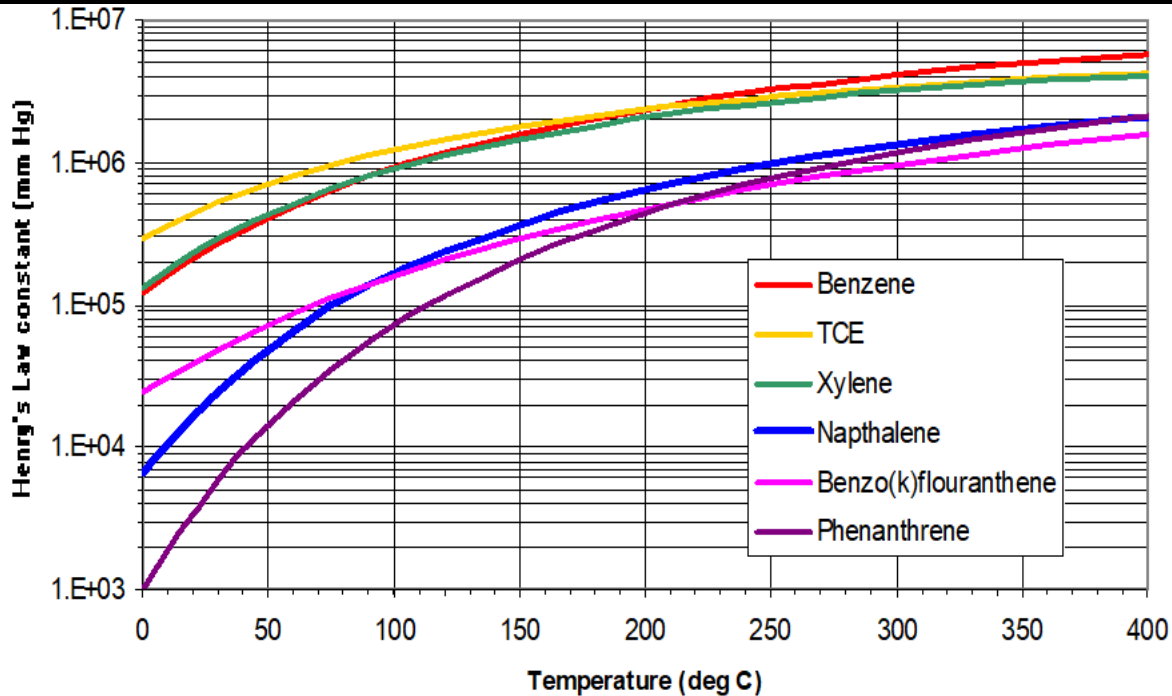


Figure 2-5. Henry's Law constants versus temperature for selected compounds (USEPA 1984)

(e) *Application to thermal treatment.* These principles show that hydrocarbon concentrations in vapor extracted from a thermal treatment zone increase with temperature. The relative proportion of each component in the vapor depends on its volatility (vapor pressure) and its liquid-phase concentration.

(5) *Hydrolysis and related processes.*

(a) Hydrolysis occurs when compounds decompose into simpler compounds while dissolving in, or reacting with, water. In the presence of oxygen or naturally occurring oxides, oxidation can alter or decompose contaminants. The potential for both hydrolysis and oxidation increases with temperature. Organic contaminants are also subject to pyrolysis, or high-temperature decomposition with or without water or oxygen.

(b) During ISTR, these processes are often undifferentiated because of overlapping conditions and byproducts. Under steam and liquid water conditions, contaminant destruction often relies on the recharge of oxygenated groundwater into the treatment zone, a process known as hydrous pyrolysis and oxidation. Thermal destruction at these temperatures is slow but can be significant, accounting for up to 17 percent of contaminant loss during steam injection at a creosote-contaminated site (DOE 2000). Hydrolysis rates vary by compound and temperature (Table 2-1). Hydrolysis rates for halogenated alkenes (such as TCE and PCE) are very slow, even at steam temperatures.

(c) Hydrolysis rates of halogenated alkanes, such as trichloroethane (TCA) and carbon tetrachloride, are rapid. These compounds are typically destroyed as soon as they dissolve.

Table 2-1
Rate of hydrolysis by compound and temperature¹

Compound	Half-life at 25 °C (years)	Activation Energy (kJ/mol) ²	Hydrolysis Product	Half-Life (°C)		
				80 Days	100 Days	120 Days
chloroform	1,850	123	mineralizes	294	31	4
carbon tetrachloride	41	115	mineralizes	11	1.3	0.2
1,1-dichloroethane	61	110	Vinyl Chloride	22	3	0.5
1,1-dichloroethene (DCE)	1.2×10^8	130	insignificant	1×10^7	1×10^6	1×10^5
1,2-DCE	2.1×10^{10}	130	insignificant	2×10^9	2×10^8	2×10^7
1,1,2-TCA	139	121	DCE	25	3	0.4
1,1,1-TCA	1.1	116	mineralizes or 1,1-DCE	0.3	0.03	0.005
TCE	1.3×10^6	127	insignificant	2×10^5	2×10^4	1,960
1,1,2,2 tetrachloroethane	0.4	92	TCE	0.4	0.1	0.02
1,1,1,2 tetrachloroethane	47	95	TCE	44	8	1.6
PCE	9.9×10^8	123	insignificant	2×10^8	2×10^7	2×10^6
1,2-dibromoethane	2.5	92	mineralizes	3	0.5	0.1
methylene chloride	1.6	119	mineralizes	0.3	0.04	0.01
1,2-dichloroethane	5.9	104	ethylene glycol	3	0.5	0.1

Notes:

¹ Weintraub et al. (1986), Barbash and Reinhard (1989), Jeffers et al. (1989).

² kJ/mol means Kilojoules per Mole.

b. Thermal principles.

(1) *Heat transport (conduction, advection, and convection).* Energy transport in the subsurface occurs by heat conduction in the porous matrix and by heat carried in moving fluids. In the absence of fluid movement, energy flow can be described by Equation 2-1.

$$q''_x = -k(dT/dx) \quad \text{Equation 2-1}$$

where:

q''_x = heat energy flux in the x direction ($W \cdot m^{-2}$)

k = thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)

dT/dx = temperature gradient in the x direction ($K \cdot m^{-1}$)

(a) The terms “convection” and “advection” are often used interchangeably, but convection includes both diffusion and advection. Diffusion of heat in fluids is usually minor compared to conduction and advection.

(b) In general, convection is the most effective transport mechanism in permeable materials such as sand and gravel, while conduction dominates in low-permeability materials such as silt and clay (Figure 2–6).

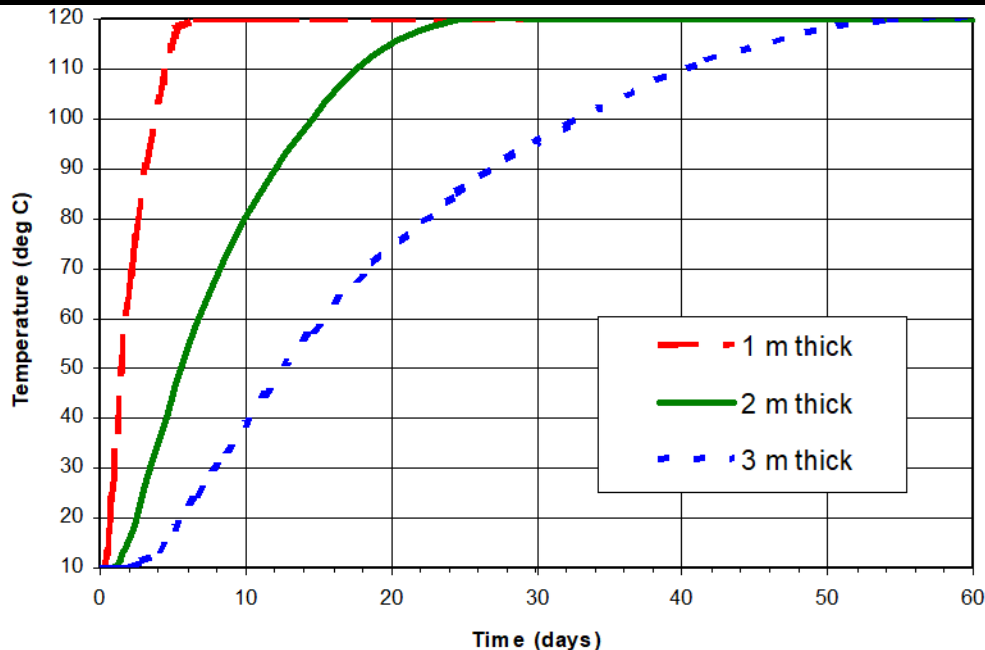


Figure 2–6. Conductive heating of impermeable layers with thicknesses of 1, 2, and 3 meters from both sides. Steam temperature above and below the layer is 120 °C (248 °F), ambient temperature is 10 °C (50 °F), and soil diffusivity is $5.82 \times 10^{-7} \text{ m}^2/\text{s}$.

(2) *Thermal conductivity and thermal diffusivity.*

(a) Thermal conductivity is a measure of a material’s ability to conduct heat.

(b) Thermal diffusivity is the ratio of thermal conductivity to heat capacity, reflecting a material’s ability to conduct heat relative to its ability to store it.

(c) Materials with high conductivity transfer heat quickly, while materials with high diffusivity heat up rapidly when exposed to a heat source. Typical conductivity values are shown in Table 2–2.

1. *Temperature dependence.* Thermal conductivity of solids and fluids varies with temperature; representative values should be selected for the range of interest (Figure 2–7). In porous media, bulk conductivity reflects both conduction and convection within pore fluids, with convection increasing at higher temperatures. Reference values for soils are provided by Johansen (1977) and Sundberg (1988), and for fluids by Poling et al. (2001).

2. *Bulk thermal conductivity equation.* The bulk thermal conductivity (k_{bulk}) of a soil combines particle and pore-fluid conductivity and can be seen in Equation 2–2.

$$k_{\text{bulk}} = k_{\text{particle}}(1 - n) + k_{\text{fluid}}(n) \quad \text{Equation 2–2}$$

where:

n = soil porosity (unitless)

Table 2–2
Thermal properties of representative materials and fluids¹

Material	Thermal Conductivity (W/m K)	Heat Capacity (KJ/m ³ K)	Diffusivity (m ² /s)	Density (g/cm ³)
Quartz	8.79	2,008	4.38×10^{-6}	2.66
Clay minerals	2.93	2,008	1.46×10^{-6}	2.65
Organic matter	0.25	2,510	9.96×10^{-8}	1.30
Silty sand (dry)	1.23	1,906	9.76×10^{-7}	1.52
Silty sand (wet)	1.41	4,359	5.82×10^{-7}	1.80
Silt (dry)	0.96	1,078	1.29×10^{-6}	1.44
Silt (wet)	1.26	5,030	4.77×10^{-7}	1.90
Water	0.57	4,184	1.36×10^{-7}	1.00
Air	0.0218	1.3	1.68×10^{-5}	0.0013
Engine oil	0.15	1,669	7.71×10^{-8}	0.89

Note:

¹ Incropera and DeWitt (1996), De Vries (1963).

(3) *Heat capacity.* The specific heat of a material ($\text{kJ}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$) is the energy required to raise the temperature of a unit mass by one degree (Figure 2–7). The product of specific heat and density is the volumetric heat capacity ($\text{kJ}\cdot\text{m}^{-3}\cdot\text{K}^{-1}$). This measures a material’s ability to store heat. Heat capacity of soils and fluids changes with temperature, but the variability among soils is generally small compared to other parameters such as permeability. Like thermal conductivity, the bulk heat capacity of a soil is the combined heat capacity of the soil particles and pore fluid.

(4) *Heat of vaporization.* The heat of vaporization ($\text{kJ}\cdot\text{kg}^{-1}$) is the energy required to convert a unit mass of liquid to gas. At the boiling point, this energy input does not raise the liquid temperature. The total heat required to vaporize a liquid from ambient temperature is equal to the sum of two elements.

(a) One is the energy required to heat the liquid to its boiling point (specific heat \times mass \times temperature rise).

(b) The second is the energy required to vaporize the liquid (heat of vaporization × mass).

(5) *Thermodynamics of non-aqueous phase liquid/water boiling.*

(a) The boiling temperature of a liquid mixture is the temperature at which its total vapor pressure equals atmospheric pressure. Since total vapor pressure is the sum of the partial pressures of mixture components, the mixture can boil at a lower temperature than the boiling point of any individual component (Lupis 1983). This process, known as co-distillation or steam distillation (Davis 1998a), allows the removal of many contaminants with boiling points above 100 °C (212 °F) at steam temperatures.

(b) Table 2–3 presents selected NAPL compounds and their steam co-distillation boiling points. Bench-scale experiments during ERH treatment of chlorinated DNAPLs (Hegele and Mumford 2014, Munholland et al. 2016) showed that uniform heating and vapor extraction are critical to prevent contaminant mobilization and redistribution into cooler zones, below low-permeability layers, or outside the treatment zone.

(6) *Thermodynamics of steam stripping via in situ steam generation.* Steam stripping occurs when contaminants partition from the soil, water, or NAPL phases into the vapor phase and are carried away by steam flow. Removal of the vaporized contaminants prevents equilibrium, allowing vaporization to continue at high rates. The contaminants condense with steam at the condensation front. When concentrations exceed solubility, NAPL or solid residues may be deposited near the steam front, forming a contaminant bank.

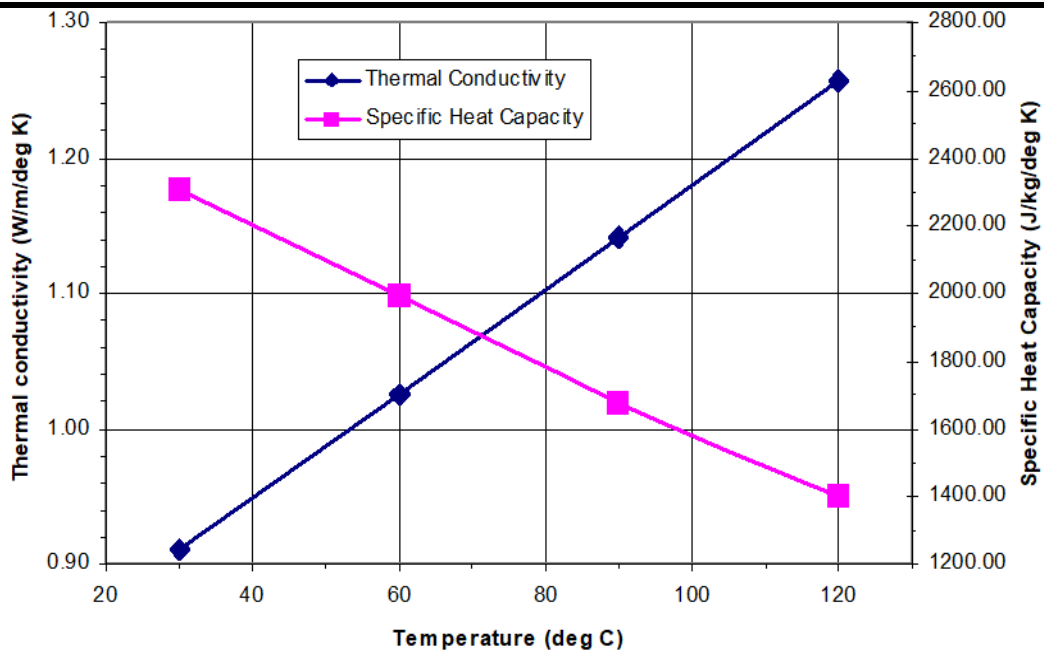


Figure 2–7. Thermal conductivity and specific heat capacity of dry silty sand versus temperature (USEPA 2002)

Table 2-3
Selected non-aqueous phase liquid compounds and steam co-distillation boiling points¹

NAPL Mixture	Component Boiling Points (°C)	Co-Distillation Point (Eutectic Point) (°C)
Benzene Water	80.1 100	69.4
Carbon Tetrachloride Water	76.8 100	66.8
Chlorobenzene Water	132 100	56.3
Chloroform Water	61.2 100	56.3
1,2 Dichloroethane Water	83.5 100	72.0
Dichloromethane Water	40.1 100	< 39.9
1,4 Dioxane Water	101.3 100	87.8
Ethylbenzene Water	136.2 100	92.0
Hexane Water	69.0 100	61.6
Styrene Water	145.2 100	93.9
Tetrachloroethene Water	121 100	88.5
Toluene Water	110.6 100	85.0
1,1,2-Trichloroethane Water	113.7 100	86.0
Trichloroethene Water	87.1 100	73.1
Xylene Water	139.1 100	94.5

Note:

¹ Lide (1999).

c. Hydrogeological principles.

(1) Fluid flow fundamentals and effects of elevated temperature.

(a) The rate of liquid flow in a saturated porous medium is proportional to the hydraulic gradient. For one-dimensional flow, see Equation 2–3.

$$Q/A = -K(dh/dL) \quad \text{Equation 2–3}$$

where:

Q/A = volumetric flow rate of water per unit of surface area [$L \cdot T^{-1}$]

K = hydraulic conductivity [$L \cdot T^{-1}$]

dh/dL = hydraulic gradient [$L \cdot L^{-1}$]

(b) Darcy's Law is obeyed for liquid flow in fully saturated soils; however, the hydraulic gradient in partially saturated soil is affected by capillary pressure. Darcy's Law can also be used to describe gas flow in soils; however, adjustments must be made for pressure-induced fluid-density changes.

1. *Hydraulic conductivity.*

a) In saturated porous media, K depends on liquid density, viscosity, and soil characteristics (see Equation 2–4), such as grain size (Hubbert 1956).

$$K = k\rho g/\eta \quad \text{Equation 2–4}$$

where:

ρ = density of the liquid [$M \cdot L^{-3}$]

η = dynamic viscosity of the liquid [$M \cdot L^{-1} \cdot T$]

g = gravitational constant [$L \cdot T^{-2}$]

k = intrinsic permeability of the porous matrix [L^2] (see Table 2–2)

b) Laboratory testing has not shown significant variations of intrinsic permeability of sands with temperature (Sageev et al. 1980). Saturated hydraulic conductivity values are not applicable under partially saturated conditions, for example, in the vadose zone, or when various combinations of air, steam, liquid water, or NAPL are present. In general, the permeability of granular soil is not significantly affected by the application of heat; however, ISTR techniques can improve the permeability of fine-grained materials, either by hydraulic fracturing from in situ steam generation or by desiccation resulting from drying at temperatures above the boiling point of groundwater.

2. *Viscosity.* Viscosity decreases with temperature (Figure 2–8). Most liquid organic chemicals exhibit ~1 percent viscosity reduction per 1 °C (33 °F) increase (Davis 1997, Poling et al. 2001). Lower viscosities improve NAPL recovery. Gas viscosities, one to two orders of magnitude lower than liquids, increase ~30 percent per 100 °C (212 °F) rise (Davis 1997).

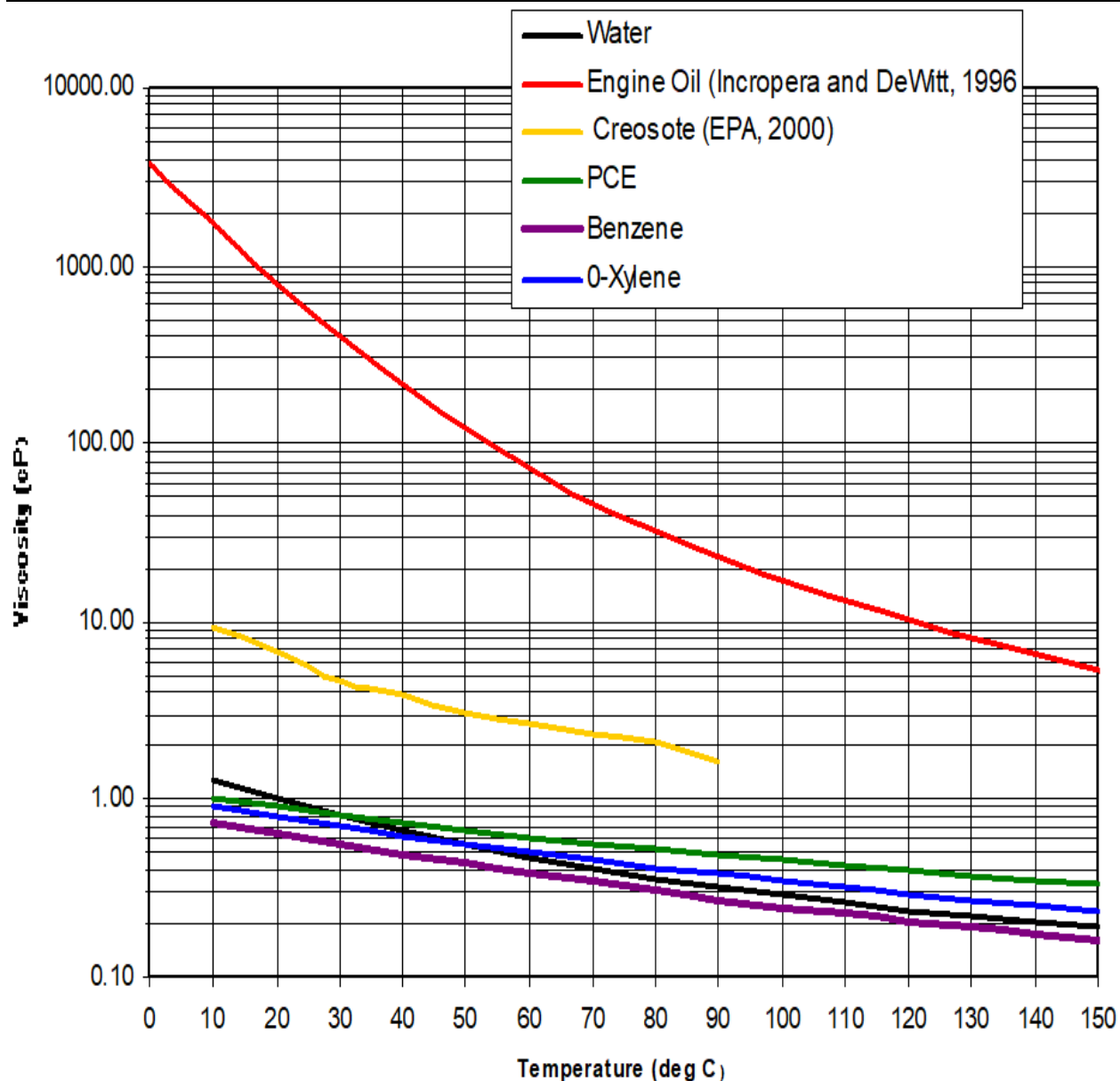


Figure 2–8. Viscosity versus temperature for liquids (Incropera and DeWitt 1996, USEPA 2000, Poling et al. 2001)

3. *Density*. Density also decreases with temperature (Figure 2–9). Hydrocarbon densities typically decrease ~10 percent per 100 °C (212 °F) rise (Davis 1997). Water density decreases ~4 percent between 0 °C (32 °F) and 100 °C (212 °F). Although modest, these shifts can influence contaminant migration. DNAPLs with densities near that of water (for example, creosote, halogenated hydrocarbons, and oil/grease mixtures) may behave as light non-aqueous phase liquids (LNAPLs) at elevated temperatures.

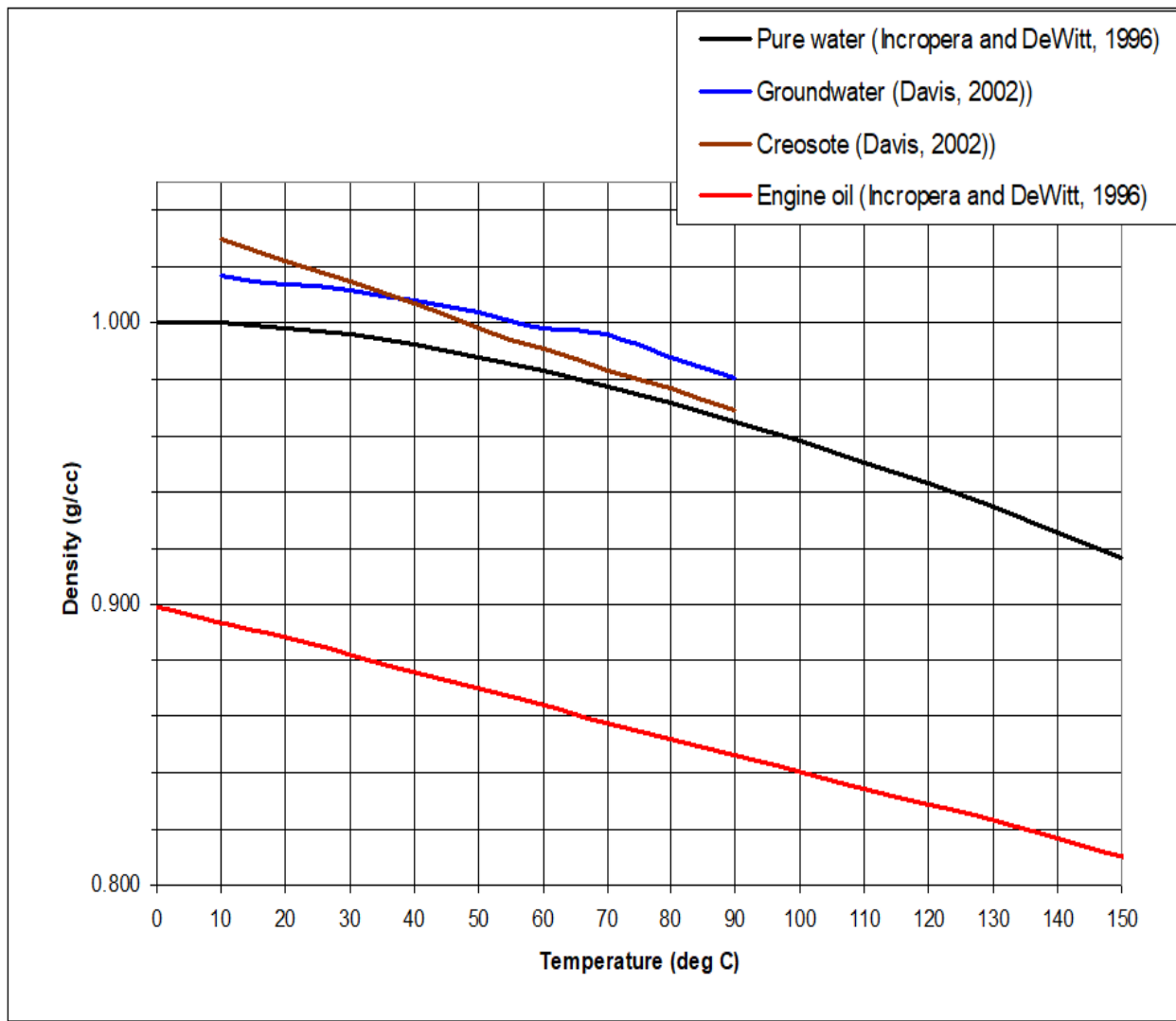


Figure 2-9. Density versus temperature for liquids (Incropera and DeWitt 1996, Davis 2002)

(2) *Multiphase flow.* The simultaneous flow of gas, water, and NAPL in porous media strongly influences ISTR performance. Figure 2-10 shows conceptual fluid movement during steam injection.

(a) *Residual saturation.* Residual saturation is the fraction of a fluid retained in porous media after displacement. In ISTR, residual NAPL is what is left after recovery well drainage or displacement by steam, air, or groundwater. Typical residual NAPL saturations in sands at ambient conditions are 14 percent to 30 percent (Wilson et al. 1990). Recovery then proceeds mainly via dissolved or vapor phases. Residual saturation decreases with increasing temperature (Sinnokrot 1969, Sanyal 1972, Davis 1994). For example, PCE residual saturation decreases linearly by ~67 percent as the temperature is increased from 20 °C to 80 °C (68 °F to 176 °F) (She and Sleep 1998).

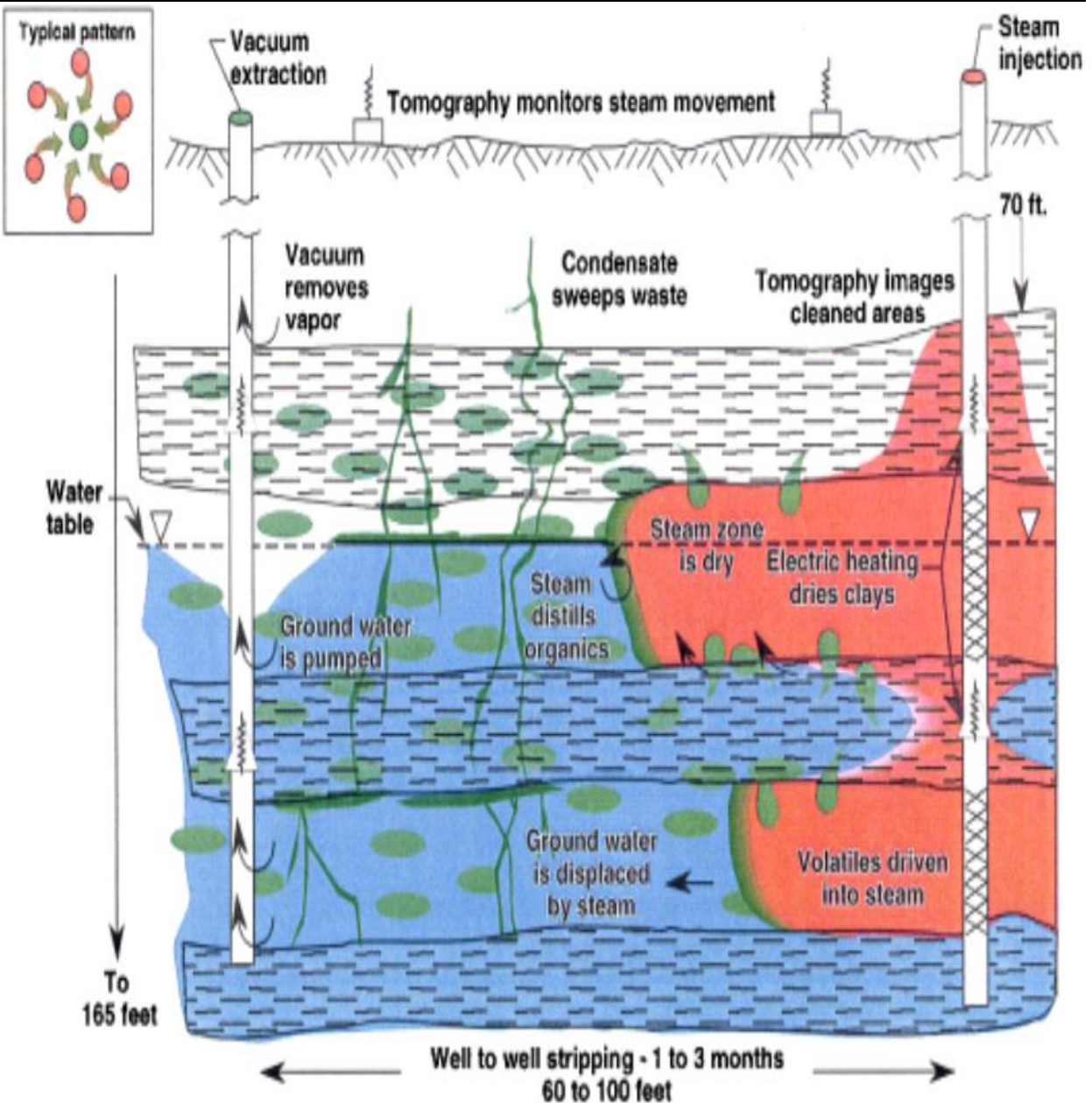


Figure 2-10. Conceptual diagram of multiphase flow at a dynamic underground stripping project (Lawrence Livermore National Laboratory 1994)

(b) *Interfacial tension and capillary pressure.* In porous media, immiscible fluids exhibit pressure differences across the meniscus, driven by interfacial tension. This capillary pressure retains immiscible fluids in pore spaces. NAPL recovery can be enhanced by lowering interfacial tensions. Air/water interfacial tension decreases with temperature, but oil/water interfacial tension shows little change (Davis 1994, Davis 1997, and Davis 2003).

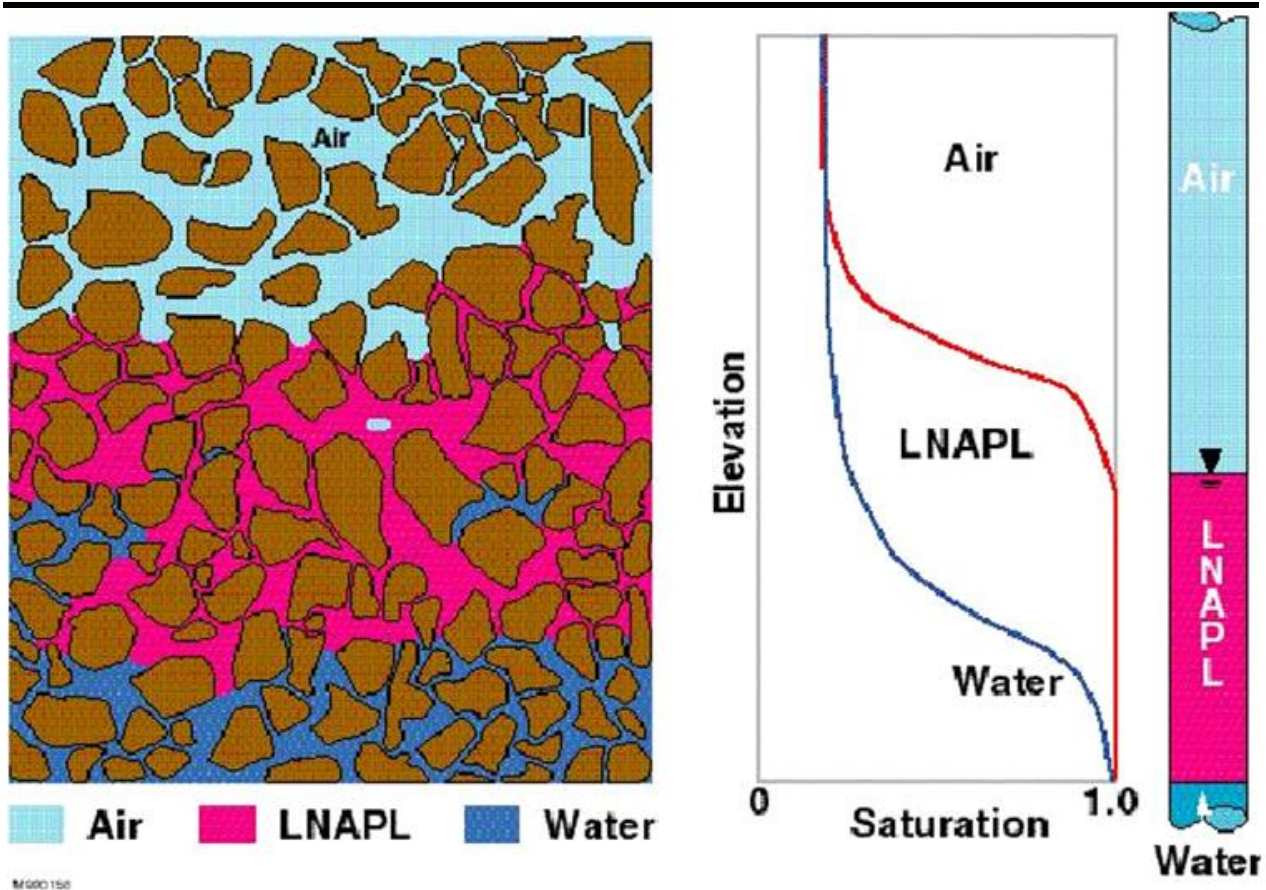


Figure 2-11. Light non-aqueous phase liquid in saturation versus elevation and well level (courtesy of Dr. Ralph Baker, TerraTherm, Incorporated, reprinted with permission)

(c) *Relative permeability.*

- Equation 2-5 shows the relationship between partially and fully saturated hydraulic conductivity.

$$k_r = K/K_s \quad \text{Equation 2-5}$$

where:

- k_r = relative permeability [unitless]
- K = partially saturated hydraulic conductivity [$L \cdot T^{-1}$]
- K_s = fully saturated hydraulic conductivity [$L \cdot T^{-1}$]

- Relative permeability is a function of the phase saturation, or fraction of the pore space occupied by the phase. As shown in Figure 2-13, relative permeability approaches 0 at residual saturation and increases with increasing saturation, approaching 1.0 as saturation approaches 1.0 (Parker et al. 1987).

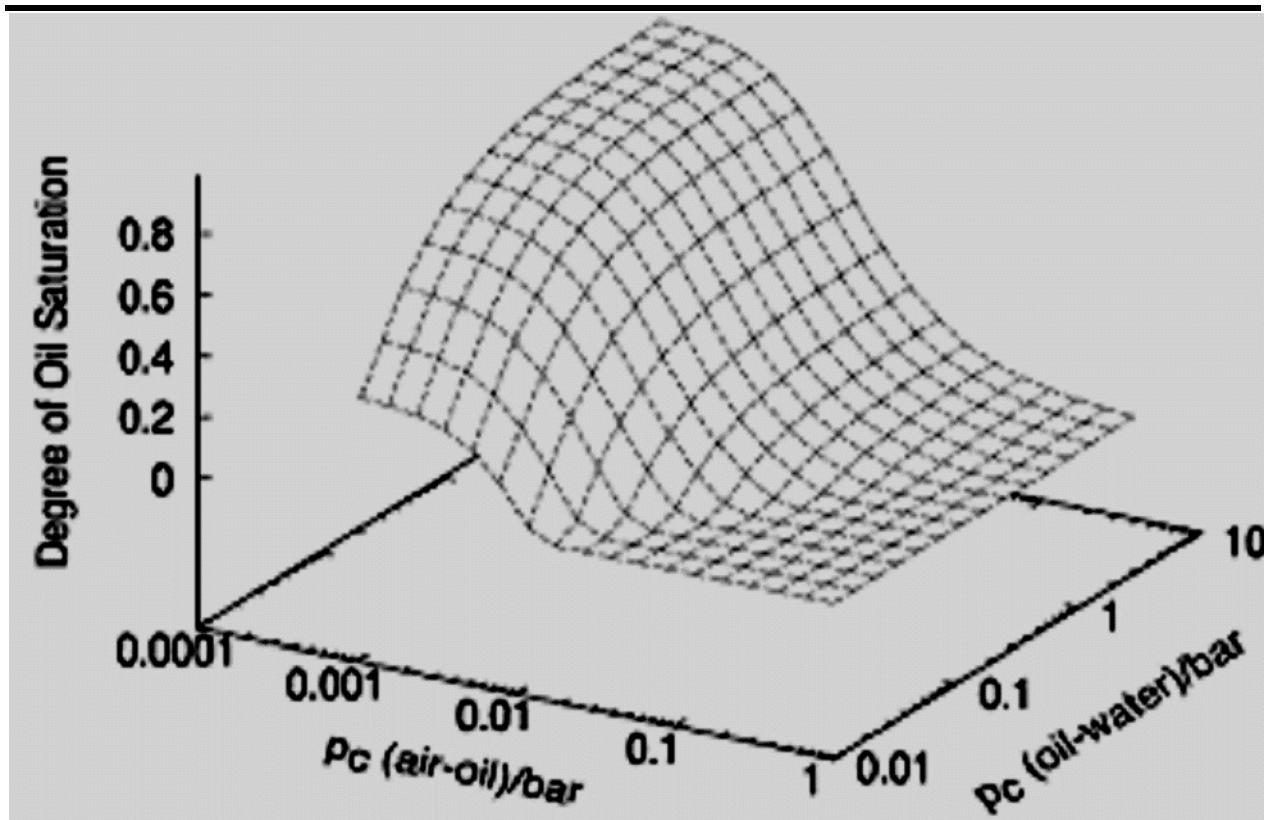


Figure 2–12. Oil saturation as a function of air/non-aqueous phase liquid and non-aqueous phase liquid/water capillary pressures. Total saturation is determined by air/non-aqueous phase liquid capillary pressure, and water saturation by oil/water capillary pressure (Lenhard and Parker 1987; reprinted with permission by Elsevier Limited, copyright 1987).

(3) *Fluid and energy transport.*

(a) *Effect of fluid transport on energy transport.* Energy is conveyed in the subsurface by advection, convection, and fluid-phase changes (steam condensation). Hot fluids transfer heat to soil particles according to the soil's heat capacity. When gases condense, however, the latent heat of vaporization is also released, delivering much more energy than sensible heat alone.

(b) *Flow of condensate from steam zones.* A key feature of ISTR energy transport is the lateral flow of hot condensates away from the steam zone. Non-condensable gas injection (used in AS) typically forms a conical gas zone extending upward (USEPA 1997). In contrast, steam injection (via wells or by in situ electrical or conductive heating) will create a broader, laterally extensive gas-saturated zone because of condensate flow. The condensate transfers heat along its path toward extraction wells or away from the heated zone, producing near-horizontal warm zones that can reach steam temperatures with less energy input. For vertical wells and electrode arrays installed at similar depths, this effect elongates the steam zone laterally. System designs can take advantage of this by optimizing horizontal steam propagation to increase well spacing (see Chapter 6).

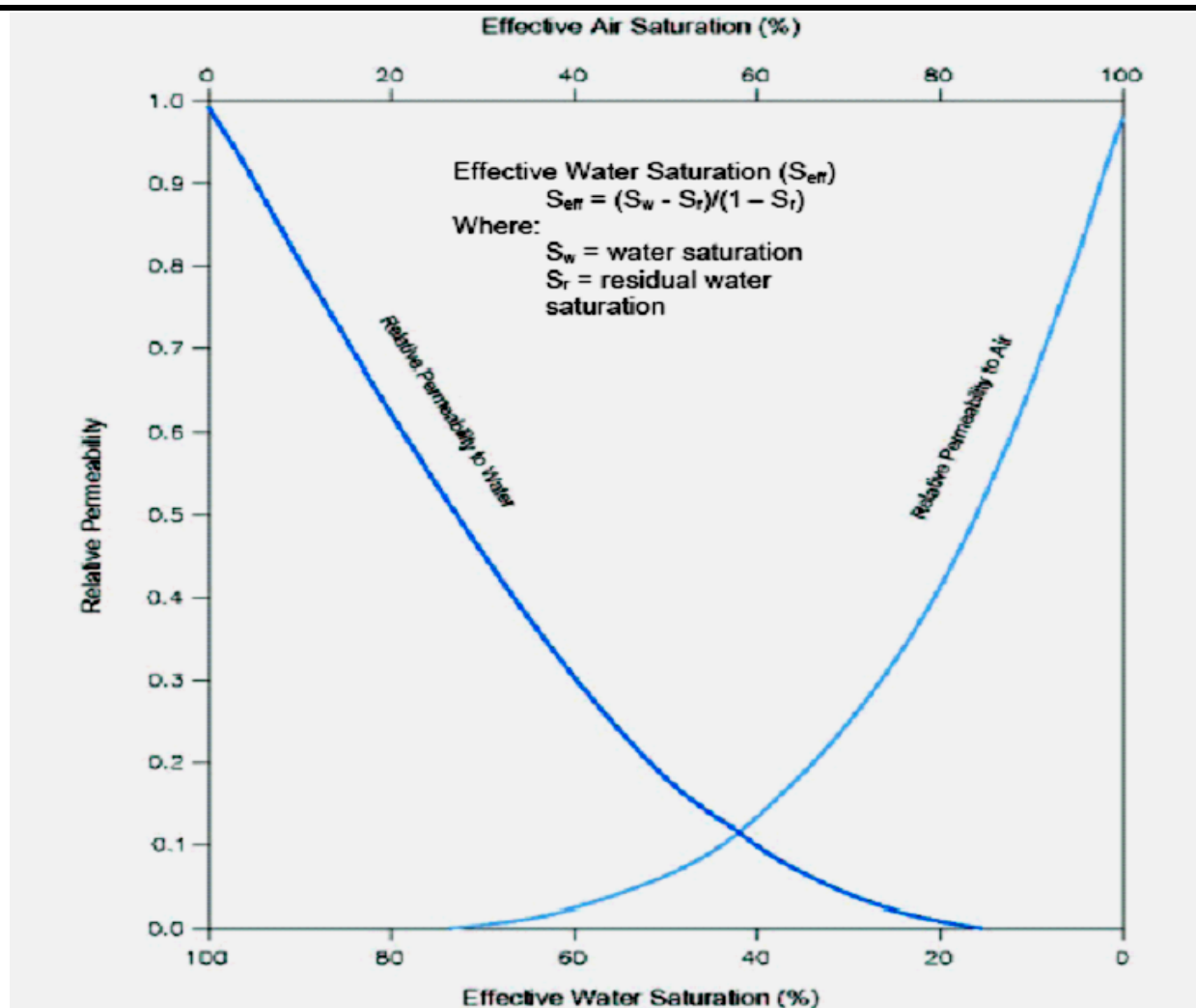


Figure 2-13. Relationship of relative permeability in soil, partially saturated with air and water, and saturation. Increasing water saturation raises relative permeability to water while decreasing relative permeability to air.

(4) *Biological processes at elevated temperatures.*

(a) Natural attenuation mechanisms (dispersion, dilution, sorption, volatilization, abiotic degradation, and biodegradation) often stabilize or reduce groundwater plumes. Of these, biodegradation is most significant because it reduces contaminant mass. While in situ biodegradation contributes little to short-term NAPL removal, it can complement thermal remediation during and after treatment, reducing downgradient plume mass.

(b) Thermal remediation can both inhibit and enhance in situ biodegradation, depending on conditions. Research shows biodegradation rates often accelerate with rising temperature up to $\sim 40^\circ\text{C}$ ($\sim 104^\circ\text{F}$) (Horst et al. 2018). Existing data indicates that soils are not sterilized permanently; rather, thermal treatment alters the microbial consortia present at a site.

(5) *Temperature tolerance of microorganisms.* Microbial occurrence and abundance depend on interactions of nutrients with physical and chemical factors such as temperature, reduction-oxidation (redox), and potential of hydrogen (pH). Biodegradation of hydrocarbons in contaminated aquifers requires both nutrient availability and tolerance of these conditions. Temperature is one of the most important determinants of microbial activity. Bacteria occupy a wide range of environments and are classified by their optimal growth temperatures (Table 2–4).

Table 2–4
Optimum growth ranges for common groups of microorganisms

Bacterial Classification	Optimum Growth Temperature
Psychrophiles	< 0 °C (< 32 °F) to < 20 °C (< 68 °F)
Mesophiles	20 °C (68 °F) to 45 °C (113 °F)
Thermophiles	45 °C (113 °F) to 90 °C (194 °F)
Extreme Thermophiles	90 °C (194 °F) to 110 °C (230 °F)

(a) *Thermophiles and extreme thermophiles.* These organisms adapt via stable enzyme systems, high proportions of saturated membrane lipids, and elevated guanine-cytosine content in nucleic acids. These increase DNA melting points (Atlas and Bartha 1993). These adaptations allow growth at temperatures that inhibit most microorganisms.

(b) *Mesophiles versus thermophiles.* Generally, microbial metabolic activity increases with temperature until enzymes denature. Mesophiles degrade hydrocarbons most efficiently at ~30 °C to 40 °C (~86 °F to 104 °F) (Bossert and Bartha 1984). Thermophiles extend this capacity up to ~70 °C (~158 °F), including degradation of PAHs and high molecular weight hydrocarbons (Huesemann et al. 2002). Although thermophiles grow more slowly than mesophiles at their respective optima, their enzymatic activity at higher temperatures can drive faster degradation reactions without diverting energy into biomass production.

(6) *Bioavailability at elevated temperatures.*

(a) Rising subsurface temperatures can enhance biodegradation by increasing contaminant bioavailability in addition to accelerating microbial metabolism. Many persistent PAHs strongly sorb to soil or sediment due to their hydrophobicity, limiting microbial access. Although specially adapted bacteria may degrade NAPLs directly (Wattiau 2002), most contaminants must first partition into the dissolved phase. Higher temperatures increase the solubility of PAHs and chlorinated solvents, accelerating dissolution and increasing availability to microorganisms (Hulscher and Cornelissen 1996, Imhoff et al. 1997, Bonten et al. 1999, Jayaweera et al. 2002).

(b) Elevated temperatures increase the solubility of TCE and PCE, enhancing the mass available in the dissolved phase. Studies also show that PAHs dissolved up to 60 °C (140 °F) can be degraded by thermophiles at rates up to eight times faster than mesophiles at lower temperatures (Viamajala et al. 2007).

(7) *Microorganism population changes and degradation potential.* The combined effects of higher metabolic rates and increased bioavailability enhance in situ biodegradation during and after ISTR. However, once subsurface temperatures exceed the tolerance of mesophiles, active degradation may temporarily decline. Many microorganisms survive unfavorable conditions by forming spores or cysts, allowing them to rapidly reactivate once circumstances improve. For example, bacterial cells in bench-scale tests of creosote-contaminated soil became metabolically active soon after steam injection (Richardson et al. 2002).

(a) Studies show that thermophilic degradation of PAHs and non-volatile hydrocarbons increases at temperatures typical of zones adjacent to active ISTR treatment (Huesemann et al. 2002). This shift from mesophilic to thermophilic dominance reduces microbial diversity but sustains biodegradation. As the treated zone cools, microbial consortia transition back toward mesophiles. The long-term impacts of these community shifts on biodegradation rates remain poorly quantified and are an ongoing research priority.

(b) Limited field data suggest that in situ biodegradation rates may increase following thermal treatment as sites cool and downgradient where heated groundwater carries higher contaminant concentrations. A detailed Environmental Protection Agency (EPA) review is available at <https://clu-in.org/download/techdrct/dettmer.pdf> (Dettmer 2002).

(8) *Reduction-oxidation theory of biodegradation.* Post-treatment monitoring can use natural attenuation protocols to evaluate in situ biodegradation. Most biodegradation is mediated by microbial enzymes that drive oxidation (reduction or redox reactions). In these reactions, organic contaminants act as electron donors, transferring electrons to acceptors such as oxygen (O₂), nitrate (NO₃), Fe³⁺, Mn⁴⁺, sulfate (SO₄), or carbon dioxide (CO₂). In reductive dechlorination, contaminants can also serve as electron acceptors.

(a) Groundwater redox conditions evolve as oxidants are consumed. O₂ is used first, followed by NO₃, manganese/iron oxides, SO₄, and finally CO₂ under methanogenic conditions. This progression, from aerobic through denitrifying, iron- and SO₄-reducing, to methanogenic, depends on organic carbon availability, nutrients, and favorable temperatures (Table 2–5).

Table 2–5
Reduction-oxidation processes that consume organic matter and reduce inorganic compounds in groundwater²

Process	Equation ¹
- Aerobic Respiration	$\text{CH}_2\text{O} + \text{O} = \text{CO}_2 + \text{H}_2\text{O}$
- Denitrification	$\text{CH}_2\text{O} + \frac{4}{5}\text{NO}_3^- = \frac{2}{5}\text{N}_2(\text{g}) + \text{HCO}_3^- + \frac{1}{5}\text{H}^+ + \frac{2}{5}\text{H}_2\text{O}$
- Manganese Reduction	$\text{CH}_2\text{O} + 2\text{MnO}_2(\text{s}) + 3\text{H}^+ = 2\text{Mn}^{2+} + \text{HCO}_3^- + 2\text{H}_2\text{O}$
- Iron (III) Reduction	$\text{CH}_2\text{O} + 4\text{Fe}(\text{OH})_3(\text{s}) + 7\text{H}^+ = 4\text{Fe}^{2+} + \text{HCO}_3^- + 10\text{H}_2\text{O}$
- Sulfate Reduction	$\text{CH}_2\text{O} + \frac{1}{2}\text{SO}_4^{2-} = \frac{1}{2}\text{HS}^- + \text{HCO}_3^- + \frac{1}{2}\text{H}^+$
- Methane Fermentation	$\text{CH}_2\text{O} + \frac{1}{2}\text{H}_2\text{O} = \frac{1}{2}\text{CH}_4 + \frac{1}{2}\text{HCO}_3^- + \frac{1}{2}\text{H}^+$

Notes:

¹ CH₂O represents organic matter; other organic compounds can also be oxidized and substituted in the equations.

² Freeze and Cherry (1979).

(b) Biodegradation may be evaluated using both primary and secondary field evidence. Primary evidence includes plume stability based on historical concentration trends. Secondary evidence includes geochemical indicators such as changes in O₂, NO₃, SO₄, sulfide, methane, and redox potential.

(c) For example, O₂ depletion indicates aerobic respiration, while elevated NO₃-reduction products indicate denitrification. Low SO₄ or elevated sulfide suggests SO₄ reduction, while methane generation indicates strongly reducing, methanogenic conditions.

(d) Negative redox potentials confirm anaerobic microbial activity, indicating that dissolved O₂ has been depleted and that microbes are scavenging mineral-bound O₂ sources.

(e) Several EPA (USEPA 1999a) and Department of Defense (Navy 1998a) guidance documents provide additional detail on redox processes and monitored natural attenuation. These should be consulted during ISTR design and monitoring.

2–2. Technology descriptions

This EM discusses three primary classes of ISTR technologies: conductive heating, ERH, and SEE. Due to increasing application, in situ smoldering is also described. Information presented here includes input from experienced vendors, suppliers, and practitioners. References to trade names or commercial products are for illustrative purposes only and do not constitute endorsement or recommendation. Each technology has differing ranges of applicability based on the type of contaminant, soil and groundwater conditions, treatment efficiency, and cost. While some technologies can reach higher temperatures, they may not be the most efficient option for all sites. Table 2–6 summarizes the approximate upper-bound operating temperatures to support preliminary technology screening.

**Table 2-6
Nominal upper bound temperatures for in situ thermal remediation technologies**

Class of In Situ Thermal Remediation Technology	Nominal Upper Bound Temperature Range
- Conductive Heating	750 °C to 800 °C (1,400 °F to 1,500 °F)
- Electrical Resistivity Heating	100 °C (212 °F) ¹
- Steam Injection	170 °C (300 °F) ¹

Note:

¹ Temperatures are dependent on depth below the water table. Increased depth corresponds to increased local pressure, and as a result, increased boiling point of water at local pressures. With water boiling at higher temperatures, higher treatment temperatures can be achieved.

a. Thermal conductive heating.

(1) *General description.* TCH applies heat to the subsurface through conductive transfer using electrically or fuel-powered heater wells. Both heat and vacuum are applied simultaneously to remediate soils and groundwater contaminated with a wide range of organic compounds. Arrays of vertical or horizontal heaters deliver heat and capture vapors.

(a) Heater types.

1. Vendor heater designs vary and may include resistive rods, wires, or coils; electromagnetic induction heaters; or gas-fired systems that circulate heated air. Examples of such vendors are listed here.

a) *TerraTherm, Incorporated, A Cascade Company.* In situ thermal desorption (ISTD), using electrically powered resistive rod heaters.

b) *TRS Group, Incorporated.* FlexHeater® thermal conduction heating service, using electrically powered resistive wires, coils, or rods (TRS Group 2021).

c) *GEO Remco.* Gas Thermal Remediation (GTR™), using natural gas, propane, or liquid fuel. Combustion units at the wellhead circulate hot air through the heater casing, with blowers facilitating air circulation.

d) *McMillan-McGee Corporation.* McMillan-McGee Corporation's TCH technology, Inductive Thermal Dynamic Stripping Process (IT-DSP™), generates heat through using electromagnetic induction coils integrated into the heater casing for efficient direct heating.

2. Additional information on vendor technologies is available through the following vendor websites.

a) *TerraTherm, Incorporated, A Cascade Company.* Information about this vendor technology can be located at <https://terratherm.com/>.

b) *TRS Group, Incorporated.* Information about this vendor technology can be found at <https://www.thermalrs.com/>.

c) *GEO Remco.* This vendor technology can be located at <https://www.georemco.com/>.

d) *McMillan-McGee Corporation.* Information about this technology can be located at <https://www.mcmillan-mcgee.com/>.

(b) *In situ thermal desorption technology.* Each ISTD heater contains a heating element operating at approximately 750 °C to 800 °C (1,400 °F to 1,500 °F). Heat transfers primarily by conduction. Figure 2–14 illustrates both vertical “thermal wells” and horizontal “thermal blankets” used for shallow contamination at < 0.4 m (< 1.3 ft). Other applications of surface heating are described by Stegemeier and Vinegar (1995).

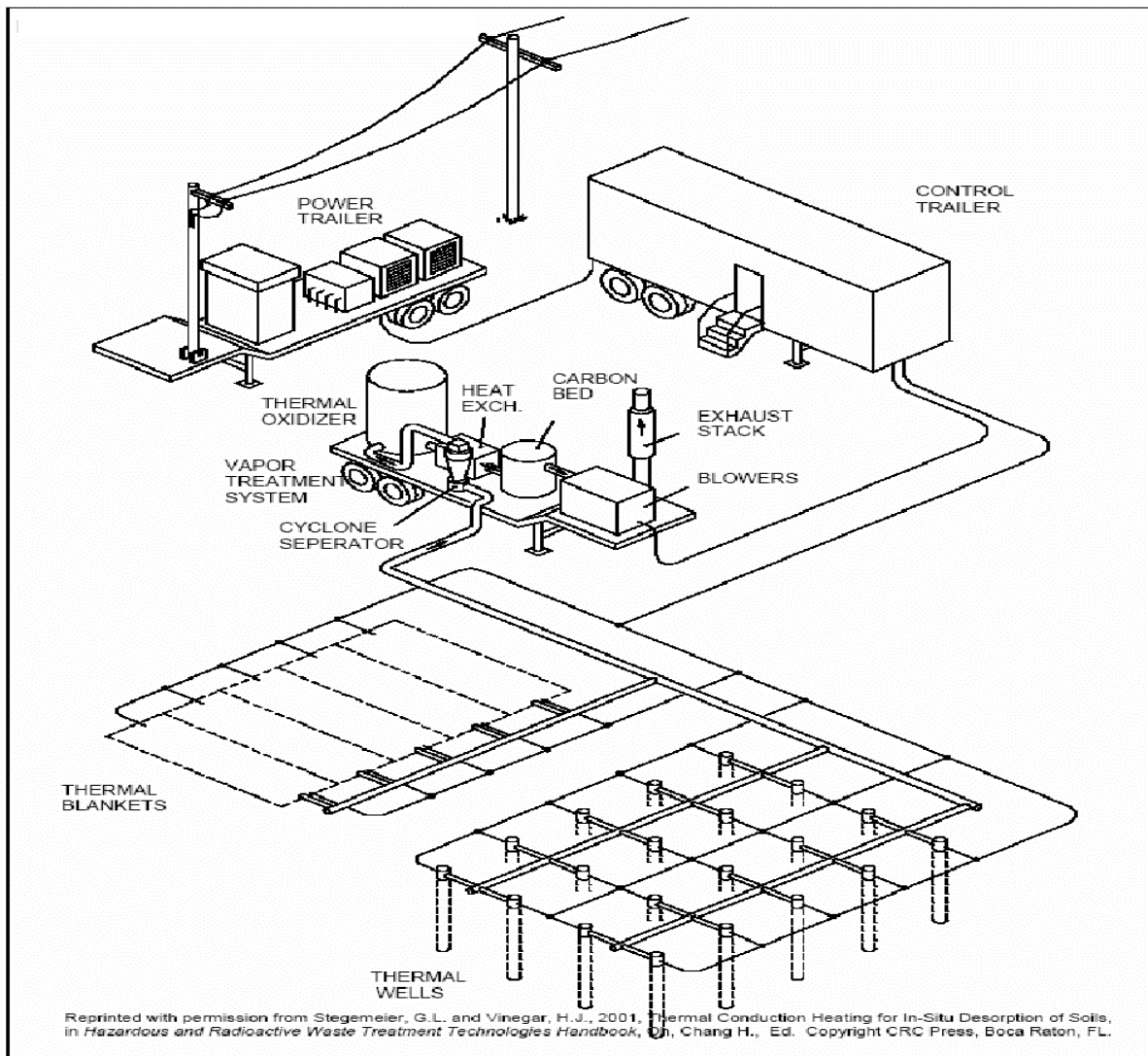


Figure 2–14. In situ thermal desorption system schematic

(c) *Contaminant treatment.* Heating volatilizes, distills, or destroys contaminants through evaporation, steam distillation, boiling, oxidation, and pyrolysis. Vaporized water and contaminants, along with some volatilized inorganics, are drawn into co-located heater-vacuum wells.

(d) *Well field layout.* Figure 2–15 shows a typical heater-vacuum well and a representative well field layout. Heaters are commonly arranged in triangular patterns that form hexagonal “six-spots” with a central heater-vacuum well, resulting in a 2:1 heater-to-heater vacuum ratio. Variations may be used depending on site needs.

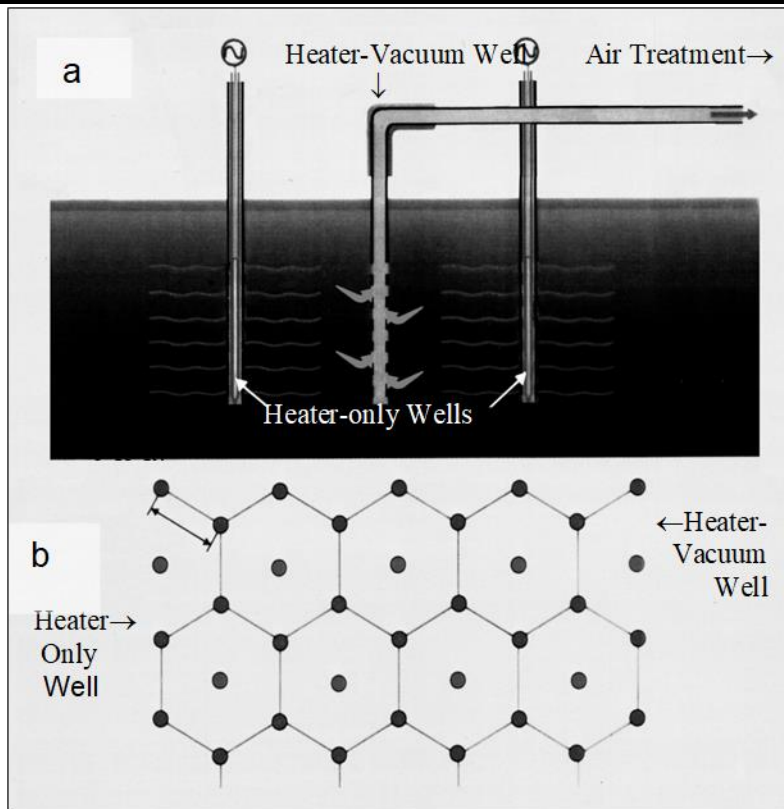


Figure 2–15. Schematic of in situ thermal desorption well field. Diagram (a) is a cross section showing one heater-vacuum well and two heater-only wells in a larger pattern. Diagram (b) is a plan view with heater-vacuum wells at the center of each hexagon and well spacing of 1.82 to 4.57 meters (6 to 15 feet).

(e) *Conductive heating.* The conductive heating process is relatively uniform in its vertical and horizontal sweep. This is because the energy (in watts) per linear foot input into the soil by thermal conduction heaters is uniform over each heater’s length (unless heater design is intentionally varied) as well as from heater to heater. Additionally, the thermal conductivity values vary over a very narrow range (\pm a factor of 2, or a factor of 4 overall) over a wide range of soil types, leading to a relatively predictable rate of heat-front propagation into the formation around each heater. As neighboring heat fronts overlap, the entire treatment zone is expected to achieve the target temperature that varies depending on the contaminant.

(2) *In situ and aboveground treatment.* During TCH, transport of vaporized contaminants is enhanced by increased bulk permeability caused by drying and shrinkage of superheated soil (above the boiling point of water) around each thermal well. Closely spaced vapor flow paths may develop even in silts and clays, allowing capture of vaporized contaminants and steam by nearby heater-vacuum wells.

(a) *In situ treatment.* Contaminants in the heated soil can theoretically be removed or destroyed with efficiencies approaching 100 percent. Even the coolest portions of the treatment zone can be heated to the boiling points of the compounds of concern (COCs) and maintained at those temperatures, such as $> 500\text{ }^{\circ}\text{C}$ ($> 932\text{ }^{\circ}\text{F}$) for high-boiling compounds, for extended periods.

1. Convection of air and water vapor enhances removal through evaporation, steam distillation, and oxidation. Laboratory and field data confirm that high temperatures combined with long residence times achieve high removal efficiency for persistent contaminants such as PCBs and polychlorinated dibenzodioxins and dibenzofurans (PCDD/Fs).

2. Projects using ISTD technologies have met target COC concentrations (often below detection limits) from initial soil concentrations of 1,000 to 20,000 parts per million (ppm). For chlorinated solvents, TCH can achieve steam distillation in cooler interwell zones while soils near thermal wells become superheated.

(b) *Aboveground treatment.* Extracted vapors and condensate are treated by an aboveground air quality control (AQC) system (see Figure 2–16). In some cases, simpler AQC systems (carbon beds without thermal oxidizers) are sufficient.

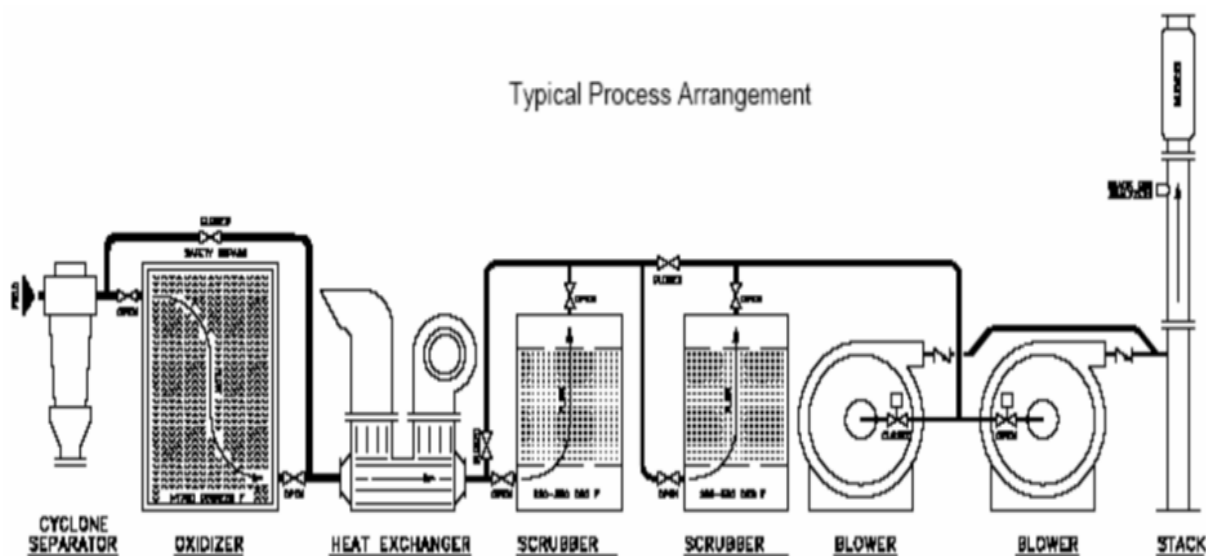


Figure 2–16. Air quality control components used with conductive heating, including a cyclone separator, thermal oxidizer, heat exchanger, scrubber beds (granular activated carbon), discharge blowers, and a continuous emission monitoring system

(3) *Technology status.* Between 1995 and 1999, several ISTD pilot and research demonstrations and four full-scale remediation projects were conducted (see Chapter 7 and Appendix B). ISTD proved effective for PCBs, chlorinated solvents (Vinegar et al. 1999), coal tar, and petroleum hydrocarbons. Additional projects are ongoing. Pilot- and bench-scale studies have also demonstrated the potential of TCH for PAHs and explosive residues, including 2,4,6-trinitrotoluene, 2,4-dinitrotoluene, hexahydro-1,3,5-trinitro-1,3,5-triazine, and nitroglycerin.

b. Electrical resistivity heating.

(1) *General principles.* ERH is a remediation technology that heats saturated or unsaturated soil by passing electrical current through it, typically to the boiling point of water. Heating is achieved by the soil's natural resistance to current flow rather than by the electrodes themselves. ERH is most often applied using three-phase alternating current, though six-phase designs have also been demonstrated. The technology has been proven effective for removing volatile and some semi-volatile contaminants from soil and groundwater (USEPA 1999d).

(a) Current flows preferentially through the most conductive soil or groundwater zones (areas with high-chloride concentrations from reductive dehalogenation). Array design and power supply sizing must account for the range of soil resistivities in the treatment zone to achieve uniform heating. High-resistivity sites are best heated with low current and high voltage, while low-resistivity sites are best heated with high current and low voltage. Thermal conduction supplements electrical heating so that, barring thermal sinks, a relatively uniform treatment temperature is achieved.

(b) ERH accelerates volatile organic compound (VOC) remediation through three mechanisms.

1. Heating the subsurface above the boiling points of most VOCs, causing volatilization for removal via vapor recovery (VR) wells.
2. Vaporizing pore water in all soil types, regardless of permeability. The resulting steam promotes removal of VOC vapors from low-permeability zones to VR wells.
3. Increasing intrinsic biological activity and chemical reaction rates as temperatures rise (see paragraph 2–1).

(c) Three-phase heating is the most common approach, though six-phase systems split line current into six phases. Both are addressed here under the general term ERH.

(d) A depiction of six-phase alternating current is shown in Figure 2–17. In a hexagonal six-phase heating array, the electrodes are configured with a central neutral electrode surrounded by six charged electrodes (Figure 2–18). The electrodes are charged 60° out of phase from each other. The voltage of all phases is constantly changing with respect to neutral; however, the average voltage difference between two adjacent electrodes (between electrodes 1 and 2, or between 1 and 6) is less than the voltage difference between electrodes that are two apart (between electrodes 1 and 3,

and between electrodes 4 and 6). Electrodes that are separated by two phase numbers are completely out of phase with each other and have the maximum average voltage difference. The average voltage ratios of these three possibilities are 1:1.7 to 1:2.

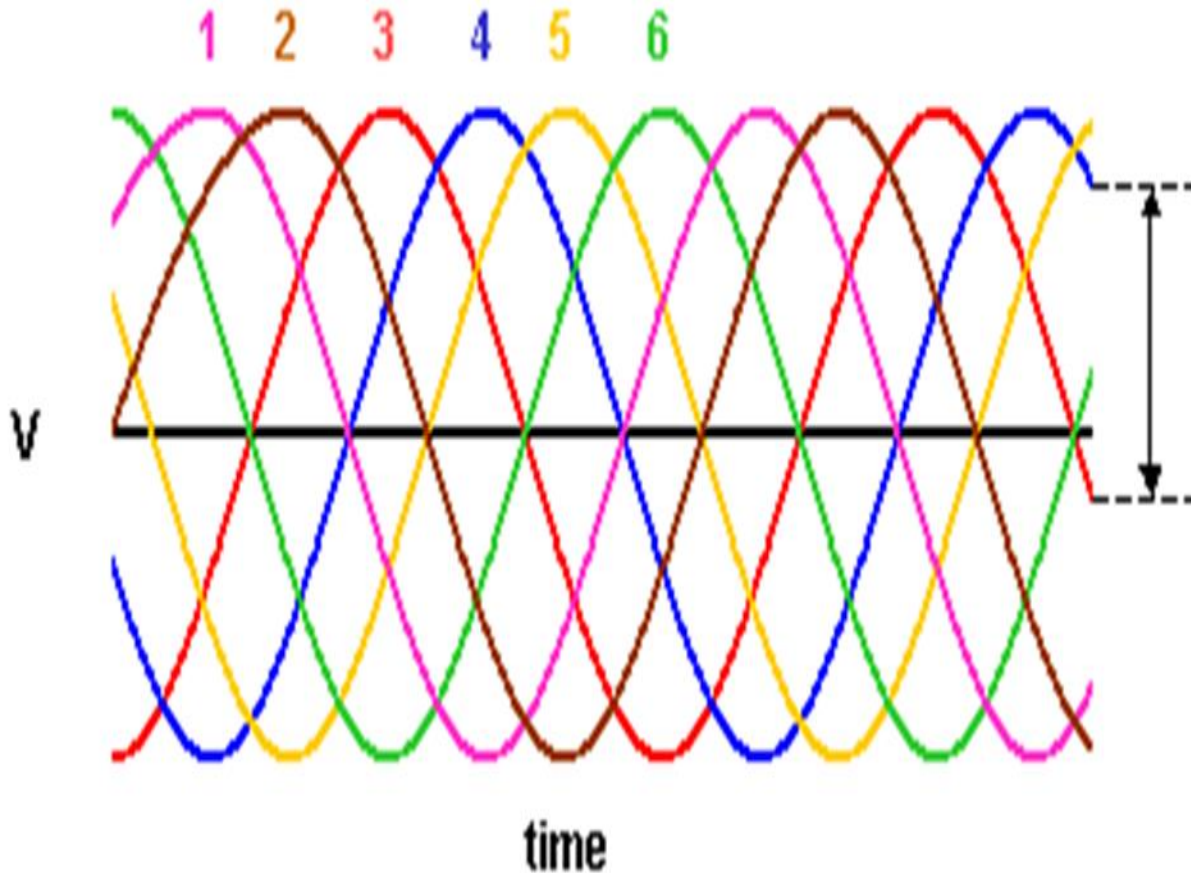


Figure 2-17. Sine curves of voltage versus time depicting six-phase alternating current

(e) When applied to a circular treatment region, the geometry of the six-phase electrode layout and the out-of-phase charging result in a uniform voltage potential between the electrodes, as illustrated in Figure 2-18. The ratio of distances in a hexagon directly correlates with the ratio of voltages in a six-phase AC system. However, this ideal distance-to-voltage correlation only occurs within a single six-phase heating array, not in situations where there are adjacent six-phase configurations. A single six-phase array can treat a circular area up to a diameter of about 18.3 m (60 ft).

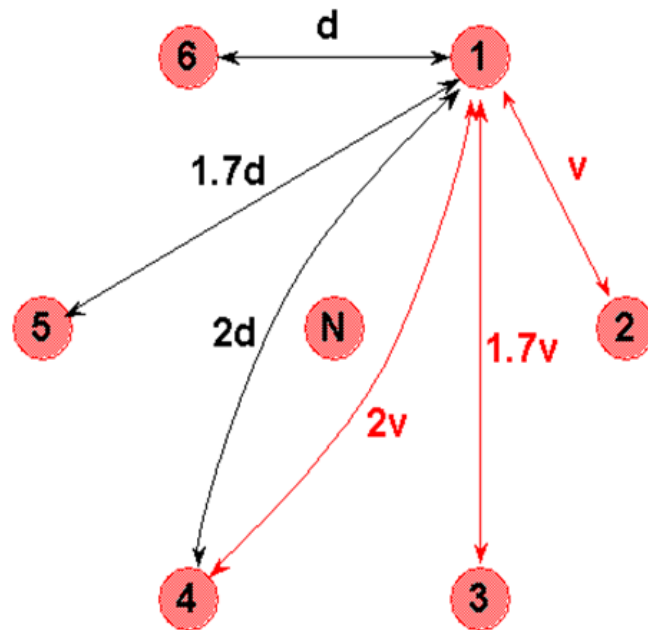


Figure 2–18. Voltage potential between any two electrodes in a six-phase heating array is proportional to their distance, and current flows uniformly within the array

(f) Three-phase heating provides a simple method to implement uniform voltage potential between electrodes, especially in treating irregularly shaped areas. An example site is illustrated below, showing the optimum phasing for three-phase heating (Figure 2–19) and for six-phase heating (Figure 2–20).

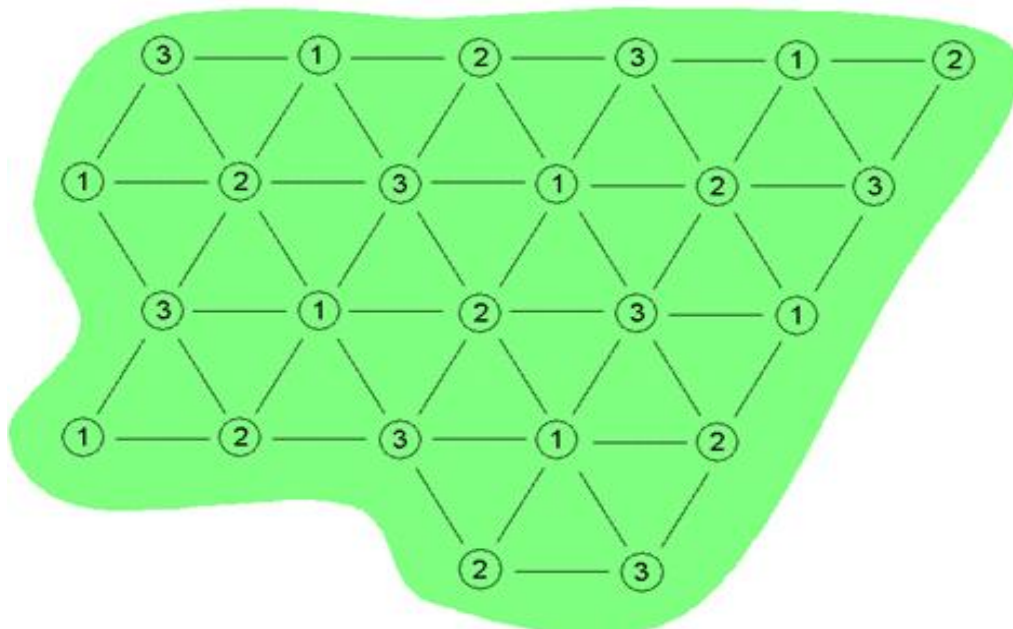


Figure 2–19. Three-phase heating pattern

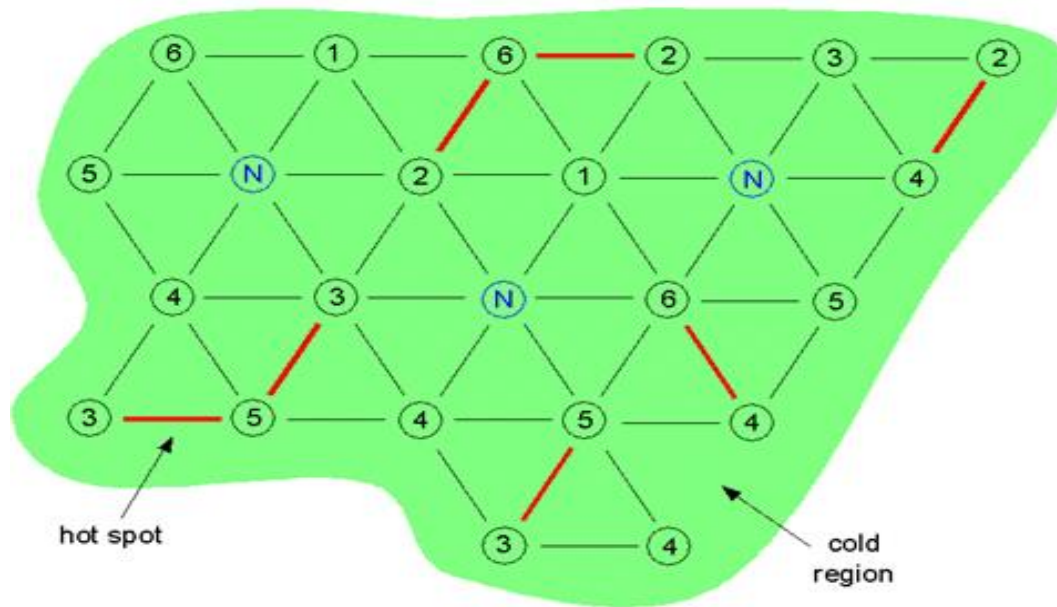


Figure 2-20. Six-phase heating pattern

(g) When using three-phase heating (Figure 2-19), the current flow and heating pattern (shown as thin black lines) are relatively simple, uniform, and regular. The electrodes can be easily “mapped” over the region to be treated. Three-phase heating is balanced electrically, with similar numbers of electrodes connected to all three phases.

(h) The optimum configuration of six-phase heating to treat the same region is shown in Figure 2-20, consisting of three complete arrays and seven peripheral electrodes.

1. If an electrode is adjacent to another electrode that has a phase number differing by one, normal electrical current and heating occur. Normal electrical conduction and heating occur when an adjacent electrode differs by one phase number from the electrode, or the adjacent electrode is neutral (labeled “N” above). If the adjacent electrodes differ by more than one phase number, an excess current occurs, leading to the formation of a hot spot, as shown between the electrodes labeled as phases “3” and “5” above. Similarly, if adjacent electrodes are in the same phase, no current flow or heating occurs, as shown in the “cold region” above.

2. Vendors of poly-phase ERH have created electrical controls to switch configurations or sequences for applying voltages, aimed at addressing hot spots and cold areas within the six-phase geometry.

(2) *Treatment system components and layout.*

(a) *Components.* The components required to implement ERH include the following items listed here.

1. Electrodes.
2. VR wells (separate, co-located, or above the electrodes).
3. A steam and vapor collection system, including piping, blower, and condenser.
4. A vapor treatment system.
5. A vapor barrier and insulative cover depending on the depth to the top of the treatment.
6. An ERH power control unit (PCU) to condition power for application to the subsurface.
7. Data acquisition systems.
8. A computer control system with a modem for continuous remote monitoring and control of power.

(b) *Schematic.* A typical ERH schematic is shown in Figure 2–21.

(c) *Electrodes.* The ERH electrodes conduct electrical energy into the subsurface and can be designed to allow independent control of the energy input to discrete depth intervals.

1. Electrodes are typically constructed using either galvanized steel pipe or copper plate to treat distinct zones in the subsurface, such that multiple electrodes can be installed within the same boring. Electrodes constructed using galvanized steel pipes are installed in the subsurface in a manner like installing groundwater monitoring wells.

2. In electrically conductive intervals, the surrounding borehole annulus is packed with a conductive material, such as graphite or steel shot, to increase the effective diameter of the electrode. In portions of the subsurface where ERH is not desired, the electrode construction materials are insulated, and the surrounding annulus is filled with relatively non-electrically conductive materials such as sand, bentonite, or cement. Electrode design and construction is discussed in paragraph 6–3a.

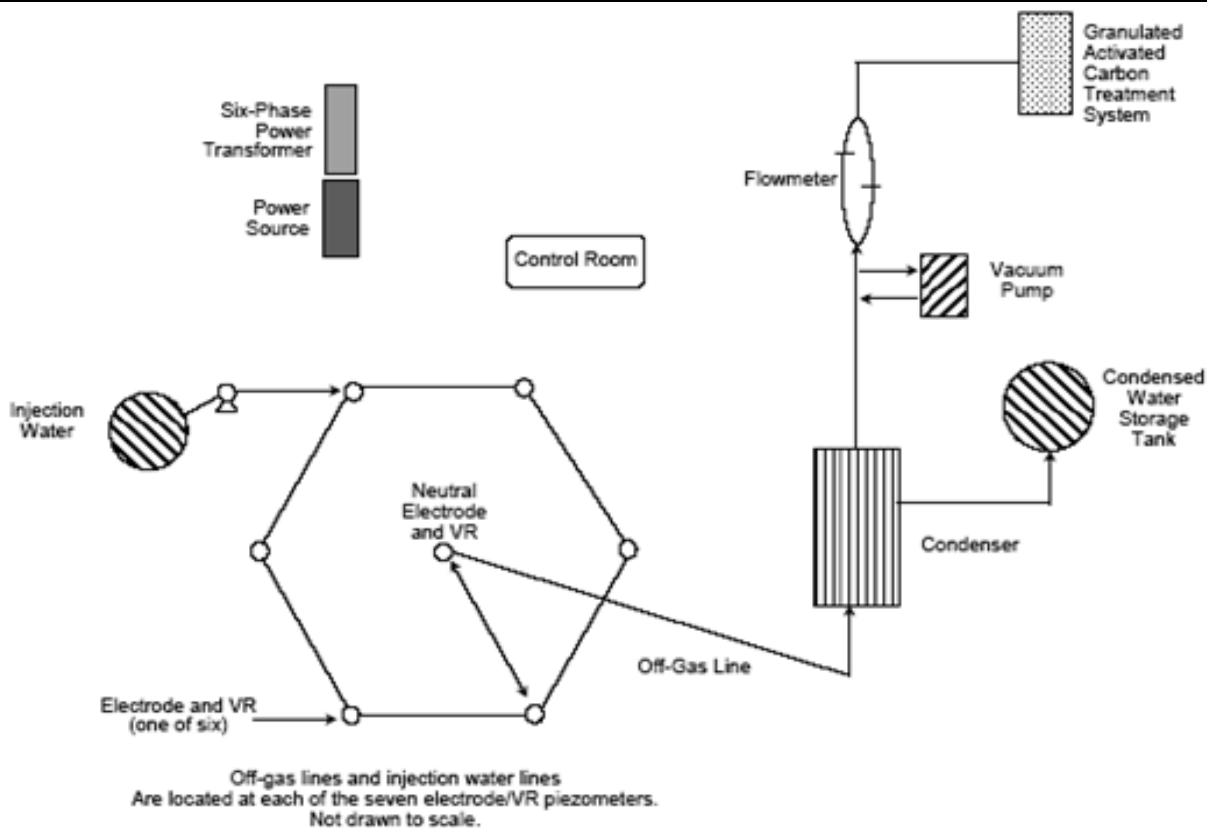


Figure 2–21. Schematic of a six-phase electrical resistance heating treatment system

(d) *Heating discrete depth intervals.* Electrodes provide the opportunity to heat discrete subsurface depth intervals. In applications with layered sequences, it may be desirable to treat discrete layers separately or to create thermal barriers. ERH allows this flexibility by placing electrically conductive materials at discrete intervals within the same borehole in which the electrode is constructed. Based on the current state of the technology and experience, the practical minimum thickness of a discrete zone is 2.43 m (8 ft) because of electrical fanning and thermal conduction.

(e) *Vapor recovery.* VR is accomplished using conventional vapor extraction techniques with shallow wells installed either vertically or horizontally. The wells may extend into the water table, depending on site conditions. Once steam and volatile contaminants have been collected by the VR system, the steam is then condensed, and the vapor is cooled to ambient temperatures. Conventional vapor treatment techniques are used to destroy the vapors (adsorb). However, due to the temperatures resulting from the application of ERH, the materials used for constructing the wells and headers must be able to withstand temperatures of approximately 100 °C (212 °F). VR wells and materials are discussed in paragraph 6–3.

(f) *Power control unit.* An ERH PCU is used to convert standard three-phase electrical power to six separate electrical phases (if desired) and to adjust the utility voltage to the appropriate level for subsurface heating.

1. The PCU includes isolation transformers that force ERH current to flow between the electrodes only, preventing ERH current from flowing to a distant electrical sink. Isolation transformers are so named because there is no conductive path between the isolated circuit and the rest of the electrical grid; the energy is transmitted via a magnetic field. Since there is no electrical path through the isolation transformer, electricity cannot leave the ERH field and move away from the site; the current cannot find a return path to complete the circuit.

2. Resistance by the subsurface environment to this flow of electrical current uniformly heats the soil and groundwater between the electrodes. Since electrically conductive intervals can be installed at different depth intervals, and the application of energy to the different parts of the electrode field can be controlled, it is possible to heat separate subsurface zones either independently or in unison.

(g) Automation and remote monitoring. The ERH process is typically automated, with an on-site computer equipped with a modem and appropriate software for remote access and monitoring. Multiple applications can be monitored and controlled remotely from the remediation site or sites, connected via dial-up modem. Site visits are required for periodic checks of the equipment, maintenance of mechanical equipment, monitoring, manual adjustments to the electrode configurations, and troubleshooting equipment malfunctions.

(h) Water addition. The only additive normally required for ERH is a drip source of potable water that is applied to soil immediately surrounding the operational electrodes. This water addition, normally incorporated in low-permeability environments, prevents the soil adjacent to the electrodes from drying out and becoming non-conductive. Most aquifers contain sufficient recharge capacity to keep the electrodes moist and conductive throughout the heating process, and water addition to the deeper sections of the electrodes is typically not required.

(i) Contaminant volatilization. As the subsurface is resistively heated, contaminants are volatilized, and soil moisture and groundwater are converted to steam. The production of steam during ERH operations effectively provides for the in situ steam stripping of VOC contaminants from the soil matrix. By raising subsurface temperatures above the boiling point of the mixture of targeted contaminants and groundwater, ERH significantly enhances the speed and effectiveness of physical contaminant removal. On its own, ERH does not necessarily remove contaminants from the subsurface; rather, it provides the physical conditions that result in the chemical, physical, and biological reactions for their removal from the subsurface.

(j) Groundwater and moisture effects. The process of in situ steam generation converts groundwater to steam, and VR removes the steam from the subsurface. This has the same effect as groundwater pumping. The net result is a slight drawdown of the water table and some measure of hydraulic control. Within the vadose zone, some decrease of soil moisture may occur if the site is covered (preventing rainfall percolation); however, the reduction of moisture observed under ERH applications has

not significantly enhanced the vapor permeability of the soil and, to date, has not been observed to adversely affect soil geotechnical characteristics.

(k) *Interim sampling and assessment.* After the initial heat-up to steam temperature, contaminant concentrations in the recovered soil vapors decrease. In a remedial cleanup, when these concentrations decrease by approximately 80 percent from peak concentrations, ERH is typically stopped, and interim groundwater or soil sampling is performed. The analytical results are then evaluated to determine if additional treatment is required. Natural attenuation processes (most importantly intrinsic biodegradation) are also commonly assessed at this time to determine if remediation goals can be attained under post-thermal treatment conditions. Based on the results of interim sampling, heating can be continued, or post-remedial sampling can be conducted to document that the remedial action objectives (RAOs) for soil and groundwater have been met.

(3) *In situ and aboveground treatment.* During heating, pore water increases in volume 1,700-fold as it is converted to steam. This has the potential to create fissures in clayey and silty soils, facilitating vapor transport. The steam forms very slowly, so the formation of fissures is on a very small scale. The high temperatures and application of adequate vacuum and vapor control should prevent downward migration of liquid contaminants via these small fractures. The possibility of such migration may need to be considered in assessing the application of the technology at a subset of sites.

(a) In situ treatment by ERH involves removal of compounds primarily through increases in vapor pressure, as well as increased intrinsic biodegradation and an increased rate of hydrolysis resulting from temperature increases.

(b) Aboveground treatment typically involves treating vapors, condensate, and entrained water. Vapor treatment involves reducing the moisture content, typically through conventional “knockout” pot arrangements. Next, this treatment is followed by appropriate treatment prior to atmospheric discharge, like granular activated carbon (GAC), combustion, thermal oxidation, etc.

1. Treatment of condensate and entrained water involves condensation and cooling through a cooling tower. The cooling tower is analogous to an air stripper, with the vapor fed to the vapor-stream treatment equipment.

2. Typically, the condensate and entrained water make multiple passes through the cooling tower, significantly reducing concentrations of volatile constituents. The treated water is then disposed of as appropriate for the site (for example, off-site treatment and disposal, discharge to the local publicly owned treatment works, or National Pollutant Discharge Elimination System permitted discharge).

(4) *Technology status.* ERH is currently widely applied at various sites at both pilot and full scale. Several vendors offer ERH services and have the personnel and equipment to address multiple sites concurrently. Appendix B provides summaries of projects to date.

c. *Steam enhanced extraction.*

(1) *General.* Steam injection for hazardous waste site remediation has its background in the petroleum industry, where it has been used for enhanced recovery of crude oil from reservoirs. In the oil industry, two modes of steam injection were developed: steam soak and steam drive. The steam soak approach involved injecting steam into a production well, holding the steam in the well and formation for a period, and then releasing the pressure to resume production from the well. This had the effect of heating up the formation in the vicinity of the well, reducing the viscosity of the oil, and modifying pressures in the oil reservoir to enhance production. Since the collapse of pressure propagated from the well to the formation, there is a net increase in the pressure gradient from the formation to the well.

(a) The steam drive approach involves the use of steam injection wells to “drive” the oil in the reservoir to production wells as an “oil bank” ahead of the injected steam front. For this purpose, on the order of one pore volume of steam is injected into the aquifer to drive the oil to the production wells. Since peak oil production rates may not be observed for years after the start of injection in a steam drive application, steam soaks have been generally favored over steam drives for enhanced oil recovery. The petroleum industry has sought to use steam injections to increase oil production through modifying subsurface pressures, decreasing viscosity, and mobilizing oil from locations that may not have been accessible through gravity drainage.

(b) For environmental applications, the analogous oil production technique is steam drive technology. The major difference between petroleum experience and environmental restoration is that the petroleum industry deals with deep, confined conditions, whereas environmental remediation projects typically involve shallower, unconfined conditions.

1. As such, there are differences in injection pressures and the scale of the application, as well as application goals. The use of steam in the oil industry was typically for the reduction of viscosity, to induce a pressure gradient and increase the mobility of light oils, typically involving the injection of in the order of one pore volume of steam.

2. In environmental restoration projects, steam injection is used to create a pressure gradient for recovery of fluids, to reduce viscosity, to manipulate formation pressures, and to increase the vapor pressure for vapor as well as liquid recovery. In environmental remediation applications, more than one pore volume of injected steam may be required to attain the desired cleanup criteria. Since environmental remediation applications are typically shallow and under unconfined conditions, injected pressures and hence steam temperatures are usually lower than those used in the petroleum industry.

(c) Figure 2–22 presents simplified steam injection in a pool of VOCs in the subsurface. SEE has been successfully injected above and below the water table (Newmark and Aines 1995, Smith et al. 1998, SteamTech Environmental Services, Inc. 1999, Heron et al. 2000). The initial injection of steam heats the wellbore and the formation immediately surrounding the injection zone of the well. The steam condenses, transferring latent heat to the wellbore, groundwater, and surrounding formation matrix. As steam injection continues, the hot water (condensate) moves into the formation, pushing the cold (ambient temperature) formation water in advance of this front. When the material surrounding the steam injection point has absorbed sufficient heat from the condensate, steam begins to enter the formation, pushing ahead of it the cold formation water and hot (condensate) water.

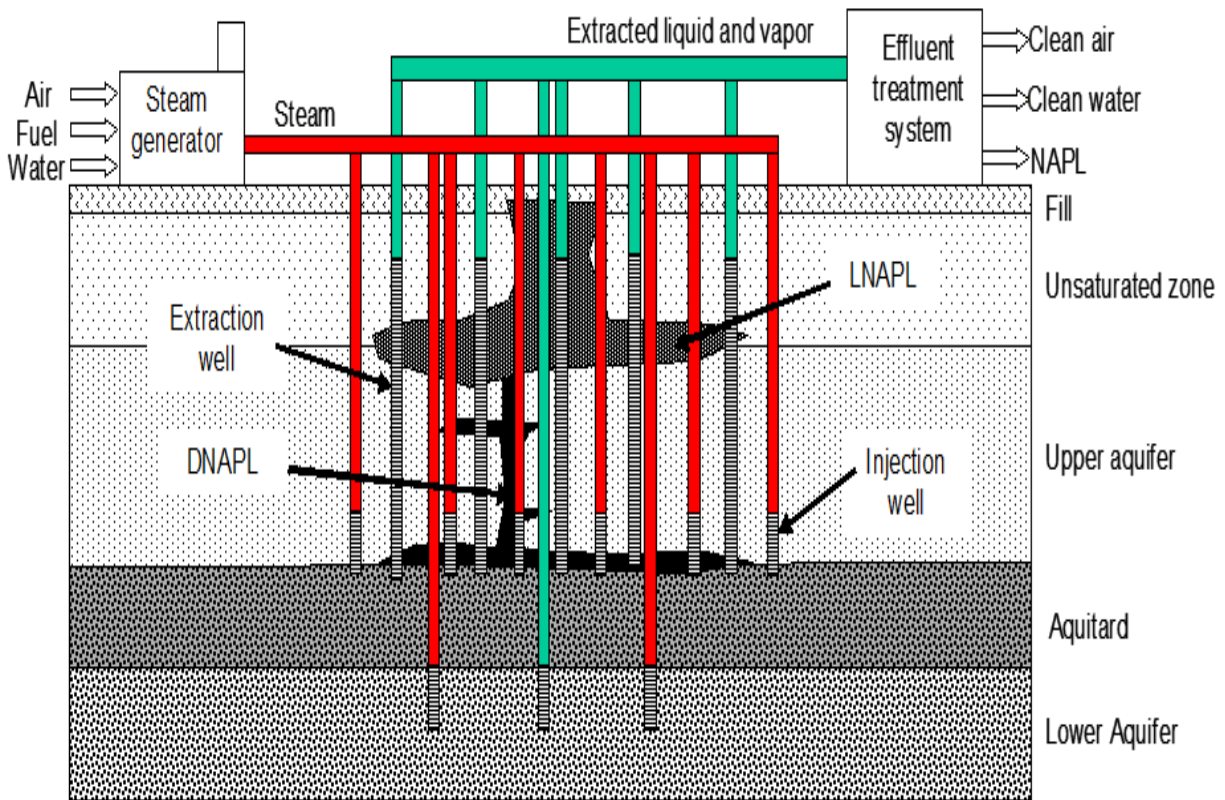


Figure 2–22. Sketch of a steam injection remediation system for a site with dense and light non-aqueous phase liquids and multiple contamination zones

(d) From Figure 2–23, the first fluid to encounter the COCs is the cold-water bank that flushes mobile compounds in groundwater. The hot water that follows reduces the viscosity of the NAPL, displacing the COCs by viscous forces, potentially reducing residual saturation, and may enhance intrinsic biodegradation of the compounds in groundwater. When the steam front reaches the zone being remediated, additional removal occurs through volatilization, evaporation, or steam distillation of volatile and semi-volatile compounds (Stewart and Udell 1988).

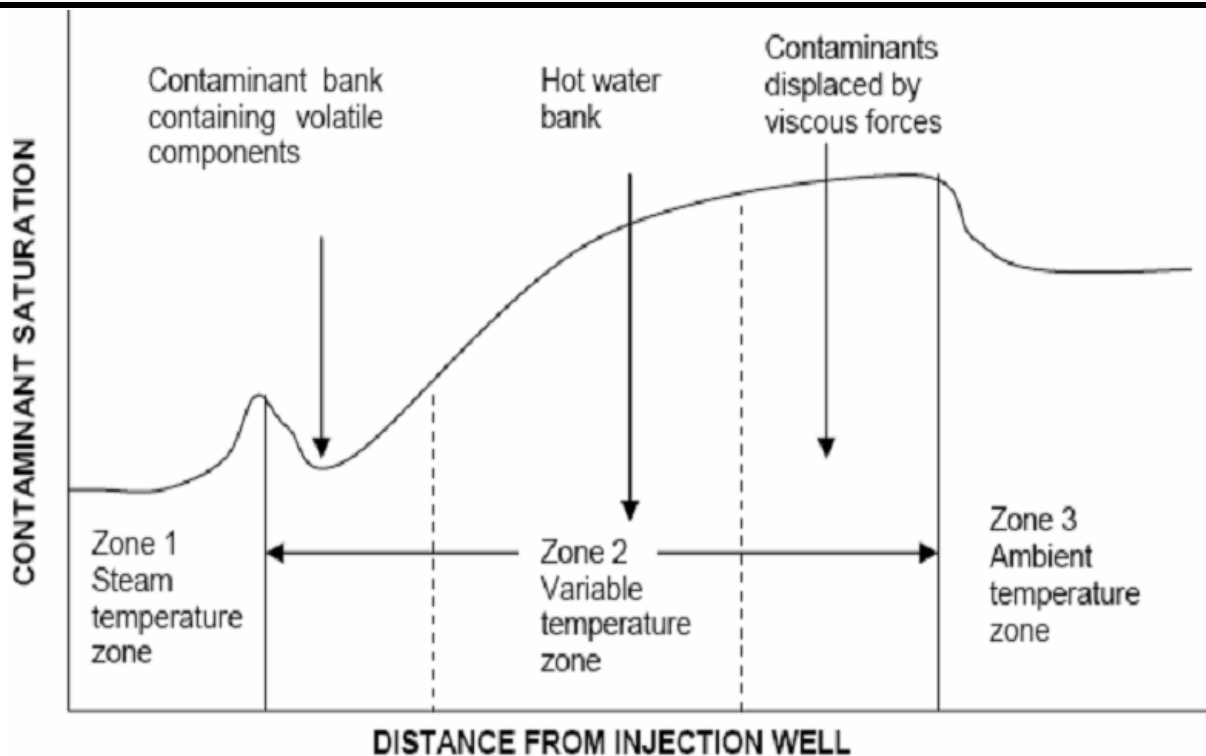


Figure 2–23. Temperature zones that form during a steam flood (Wu 1977; copyright, Society of Petroleum Engineers, used with permission)

(e) In some cases, where the NAPL saturation is high and the steam injection rate is modest, a bank of NAPL or highly concentrated contaminants can be formed in front of the steam zone.

1. An NAPL bank forms where fluids flowing from the steam zone have displaced the contaminants, or those volatilized from the steam zone were then deposited by condensation at the steam front. The residual compounds volatilized by steam are also added to the bank of compounds being mobilized and condensed in advance of the steam front.

2. Studies at the University of Stuttgart (Schmidt et al. 1998) and the University of California at Berkeley have indicated that the formation of NAPL banks can be eliminated by co-injection of air. Other practitioners use preheating of the highly contaminated zones by ERH prior to steam injection to minimize the chance of NAPL bank formation. By heating part of the treatment zone prior to injection of steam, the formation of a cool bank of condensate is prevented.

(f) After the target zone is heated to near steam temperature, mass removal has been increased by inducing pressure cycling between the injection and extraction wells (Udell et al. 1991).

(g) Experimental work has shown that liquid-phase compounds with boiling points less than that of water can be completely removed from porous media, except for a small amount absorbed into the formation matrix (Hunt et al. 1988). Steam is considered effective for liquid hydrocarbons having boiling points up to 175 °C (~350 °F) and can remove 96.8 to 99.9 percent of #2 fuel oil and jet fuel, given enough pore volumes of injected steam (Hadim et al. 1993). Applications of greater volumes (for example, greater than one pore volume) of steam can result in further reduction in concentration in groundwater and the aquifer matrix.

(h) One-dimensional laboratory experiments have shown that compounds, or mixtures of compounds with boiling points of up to 300 °C (572 °F), were removed by continuing steam injection past its breakthrough point (one pore volume) (Udell and McCarter 1996). Continuing steam injection to 100 pore volumes reduced concentrations of compounds with boiling points of 450 °C (842 °F) by at least one order of magnitude. Injecting 100 pore volumes may not be economically feasible at many sites, but what this illustrates is that, with greater effort, further concentration reductions may be realized.

(2) *In situ and aboveground treatment.* When the pollutants represent a mixture of volatile and semi-volatile compounds, such as is the case for mineral spirits, gasoline, or other fuels, the compounds with lower boiling points vaporize first, followed by the lower boiling point compounds. As a result, there is a corresponding “dispersion” of the constituents of the mixture in the bank of condensed compounds moving through the formation in advance of the injected steam front. This may be critical in the choice of vapor control technology. For example, if internal combustion engines are to be used to destroy gasoline vapors, a higher octane mixture is handled in the earlier stages of the project than in the later stages. The initial higher octane fuel mixture, if not adjusted through blending with lower octane fuel, may damage these engines.

(a) In environmental applications, the pressure of the injected steam may increase pore pressure. This increase may also serve to inhibit the volatilization of many compounds. Cycling of steam injection and vacuum extraction after steam breakthrough can enhance the recovery of hydrocarbon by creating a thermodynamically unstable condition, in which vaporization is encouraged as pore fluids boil (Udell et al. 1991). Pressure cycling using steam in a cyclic mode is known as “huff and puff” in the oil industry. However, in the oil industry, the goal has been to use the “collapse” of the formation pressures around the well during a steam soak to create a higher pressure gradient around the well to promote the flow of oil.

(b) For sites contaminated by volatiles, the goal of cyclic steam injection is to create temperature and pressure changes that promote volatilization of VOCs, so the contaminants boil out and are recovered by vacuum extraction. After steam breakthrough, the steam injection is discontinued while maintaining vapor and groundwater recovery. This reduces the effective air pressure in the formation, resulting in rapid evaporation of water and contaminants, as the formation releases energy by boiling to reach equilibrium at a lower pressure and temperature.

(c) For sites contaminated with semi-volatile or non-volatile chemicals, such as creosote, pressure cycling is used both to enhance vaporization of the lighter contaminant fractions and to induce mixing of injected steam and air with contaminated groundwater. Pressure cycling may stimulate dissolution of NAPL phases into groundwater. It may also promote degradation reactions that occur under aerobic conditions at elevated temperatures, such as hydrous pyrolysis oxidation (HPO) or biological degradation. At creosote sites, pressure cycling may also enhance liquid-phase NAPL displacement and removal by mechanisms like enhanced oil recovery.

(d) Steam breakthrough at all extraction wells is not required for cyclical operation. This technique has been applied under a range of conditions at a remediation site (Smith et al. 2000). For example, at one location, a void from an abandoned catch basin prevented steam breakthroughs at a nearby recovery well. As injected steam exited the soil into the void, the resulting pressure drop cooled the steam. The steam generators in use could not pressurize the void, so steam breakthrough was not observed at the well.

(e) Even so, cyclic operation significantly improved VOC removal and enhanced heating of the area. At another location at the same site, cyclic operations led to the production of a “solvent bank” from a recovery well where steam breakthrough had not previously been observed.

(f) Other steam injection projects have also used pressure cycling to enhance mass removal, including the following sites.

1. Solvent Services, San Jose, CA (Udell and Stewart 1989).
2. Lawrence Livermore National Laboratory (LLNL) Gas Pad (Newmark and Aines 1995).
3. Visalia Pole Yard, Visalia, CA (Davis 1998b).
4. Alameda Point, Alameda, CA (Udell et al. 2001).
5. Portsmouth Gaseous Diffusion Plant, Piketon, OH (SteamTech Environmental Services, Inc. 1999, Heron et al. 2000).
6. Savannah River Site, Aiken, SC (Integrated Water Resources 2002).
7. Edwards Air Force Base Site 61, Edwards, CA (Earth Tech Inc. and SteamTech Environmental Services, Inc. 2003).
8. Loring Quarry Site, Limestone, ME (Davis 2003).
9. Pinellas Science, Technology, and Research Center, Largo, FL (Heron et al. 2005).

(g) At some sites, air is injected to create conditions for direct oxidation. After steam breakthrough, hot air is injected or drawn into the formation by the VR system. Many compounds are more susceptible to oxidation at higher concentrations. This provides a means of in situ destruction of residual compounds that may not be easily removed through steam injection.

(h) In summary, there are four main removal mechanisms employed in steam injections, allowing for the recovery of pollutants.

1. Physical displacement of NAPL as the steam migrates from injection to extraction wells (the contaminants are mobilized owing to reduction in viscosity and interfacial tension and mobilized via hydrodynamic forces).
2. Vaporization and extraction as a vapor phase (boiling of the NAPL or volatilization of dissolved/adsorbed contaminants).
3. Solubilization and condensation of contaminants with subsequent removal in the dissolved state by the groundwater extraction system.
4. In situ destruction is attributable to either chemical or biological reactions.

(i) At the field scale, the mechanisms listed above may occur simultaneously and often cannot be identified individually. However, simple monitoring and sampling can help to identify the dominant mechanisms and to optimize the mass removal and remedial results. This optimization involves adjusting the steam injection strategy, deciding on the duration of pressure cycling, determining whether to co-inject air or O₂, and adjusting the groundwater and vapor extraction rates.

(3) *Technology status.* In 1991, the application for the first patent for steam injection for environmental restoration was submitted (Udell et al. 1991). It was first applied in the field at the Solvent Services, Inc., site in San Jose, California, in 1988. This involved a demonstration using a single recovery well surrounded by six injection wells and was used to remove a wide variety of compounds. In general, the following statements can be made for the status of steam injection for remedial purposes.

(a) For gasoline and chlorinated solvents such as TCE and PCE, both pilot tests and full-scale remediation in porous media have shown great promise for increasing mass removal compared to traditional techniques and for achieving very low concentrations in soil and groundwater.

(b) For oils such as JP-4, kerosene, and motor oil, removal of the bulk of the mass is possible. However, the evidence gathered so far indicates that the treatment is less effective for the heavier components of the oil, due to their lower volatility and fluid mobility. Therefore, while the oil's mobile fractions can be removed and the groundwater quality greatly improved, the soil concentrations of total petroleum hydrocarbon (TPH) may still be above background concentrations following treatment (for example, Alameda Point, CA).

(c) For wood-treating chemicals such as creosote and pentachlorophenol (PCP), laboratory studies show that partial to complete NAPL removal is possible and that the lower boiling point compounds such as naphthalene and PCP can be effectively treated using more steam and longer treatment time than used for chlorinated solvents. Field evidence from Visalia Pole Yard indicates that mass removal can be highly effective, and that it is possible over several years of treatment to lower the groundwater concentrations of the risk-driving chemicals (in this case PCP and naphthalene), thereby significantly reducing the impact to down-gradient water recipients.

(d) Fractured rock studies conducted in 2002 indicate that NAPL sources can be eliminated in relatively weathered rock settings such as Edwards AFB, CA, and that it is possible to accelerate mass removal from sparsely fractured, complex sites such as the Loring Quarry site, Maine (Davis 2003). However, so far steam injection in fractured rock settings has only been tested at these two locations in the United States, and conclusions regarding remedial endpoints are still not available.

(e) Concerns about the formation of an NAPL bank and possible downward migration of contaminants have so far been eliminated either by co-injection of air with the steam or by preheating part of the treatment zone prior to steam injection. Soils have been preheated using ERH techniques. This increases project costs to some degree, and the economic impact of this should be assessed.

(f) Steam injection equipment is readily available and can be rented or purchased based on the duration of the project.

(g) Extraction and treatment systems for vapor and water are relatively straightforward for sites with chlorinated solvents and complex for wood-treating sites, where high naphthalene concentrations, the presence of polar compounds such as PCP, the presence of dioxins and furans, and the presence of heavy metals such as chromium and arsenic in the extracted fluids complicate treatment and separation.

(h) Several new areas have been explored for steam injections as a remedial technique. These include the use of air and O₂ to enhance in situ destruction reactions (biological or chemical, such as HPO), the use of single-well treatment schemes for small sites (such as Beale AFB, CA) (ESTCP 2005), and innovative pressure cycling modes for difficult fractured rock sites.

d. *Smoldering.*

(1) *General description of treatment process and layout.* Smoldering is a flameless form of combustion that involves the reaction of organic material (fuel) and oxidant, producing mostly heat, CO₂, and water (ESTCP 2019). The concept of using smoldering in environmental remediation was initially developed in the late 2000s, with the first pilot test reportedly completed around 2010 (Horst et al. 2021).

(a) In situ environmental remediation applications using smoldering essentially involve three key components. First, an initial energy delivery into the subsurface provides heat to start the combustion reaction. Second, the combustion reaction is fueled by (and simultaneously destroys) contaminants that are present in the subsurface due to historical releases or disposal practices. Third, oxidants are added into the subsurface via injection of air or other gases to sustain the combustion reaction. In situ smoldering is typically targeted for treating contaminants such as heavy fuel oils, creosote, and coal tar that are present in the subsurface as NAPLs (Horst et al. 2021). Savron Solutions, Inc. holds the patent and the rights to commercial application of in situ smoldering, known as STAR (see <https://www.savronsolutions.com/star/>).

(b) The combustion reaction that occurs during in situ smoldering is intended to be a self-sustaining process in that heat energy does not need to be continually added into the subsurface once ignition is confirmed. For the combustion reaction to self-sustain, it must generate sufficient heat energy in the subsurface and have access to oxidant at a sufficient rate of flux (Grant et al. 2016). The ability to meet these requirements is largely dependent on the type of contaminants, concentration of contaminants, type of soil, and groundwater conditions.

(c) Since the combustion reaction uses contaminants as a fuel source, there must be a sufficient number of contaminants in the subsurface soils to sustain combustion. The in situ smoldering process relies on a combustion front propagating itself through the contaminated soils. The combustion process must generate enough heat to ignite the contaminated soil along the front while simultaneously overcoming the heat losses that occur in the subsurface. The lower concentration limit of contaminants that typically sustain combustion is cited as 3,000 to 5,000 milligrams per kilogram (mg/kg) of TPHs (Grant et al. 2016); however, this lower limit varies based on several factors. Lab-scale bench testing is commonly completed to confirm if contaminated soils have sufficient fuels to sustain combustion.

(d) Contaminant type is also an important consideration for in situ smoldering. Low volatility contaminants like coal tar, creosote, and heavy fuel oils are best suited for in situ smoldering because these compounds do not significantly transfer from the solid or liquid phase to the gaseous phase as they are heated.

1. By contrast, high-volatile contaminants such as light petroleum hydrocarbons (gasoline) and chlorinated solvents volatilize when heated. Since the in situ smoldering combustion reaction occurs when the fuel is in a solid or liquid phase, high-volatile contaminants typically do not lead to a self-sustaining combustion reaction (Grant et al. 2016).

2. Addition of a supplemental fuel source such as emulsified vegetable oil can be injected to sustain the smoldering front or fill fuel gaps where contaminant concentrations are lower or are comprised of higher volatility compounds (Salman et al. 2015).

(e) The soils that are best suited for in situ smoldering are silty sands or coarser materials such as gravel. The porosity of these types of soils allows enough oxidant (air) to be injected into the subsurface to sustain the combustion reaction.

1. Finer soils such as silts and clays are generally not amenable to in situ smoldering because enough air cannot be delivered to sustain combustion. When in situ smoldering is completed below the water table, the combination of air injection and heat from combustion must be sufficient to keep groundwater from flowing through the contamination zone being treated and drive off the residual pore water present within the contamination zone.

2. If this does not occur, the groundwater acts like a heat sink that stops combustion. In practice, very coarse materials that can convey large volumes of groundwater have created difficulties in keeping groundwater out of the contaminant zone (Grant et al. 2016).

(f) In-well heaters are used to provide the initial energy to ignite the contaminated soils. The in-well heaters are installed in steel wells (referred to as ignition points) drilled into the zone of contamination. The ignition point wells are also simultaneously used to inject air or other gases into the subsurface. In-well heaters are typically electrically powered; during the first in situ smoldering pilot test, the heaters used were 4.1 kilowatts and 9 kilowatts, respectively (Scholes et al. 2015). Heaters can be portable and used at multiple different ignition points at the same site. Smoldering can be considered an energy-efficient method of treatment relative to other thermal treatment approaches, as the energy source is the contaminant itself, and any energy required to initiate the combustion front is temporary.

(g) Thermocouples are used to measure subsurface temperatures to confirm that a self-sustaining combustion front is propagating through the contaminated soil. Thermocouples are installed at multiple depths and distances proceeding out from the ignition point.

(h) The air handling equipment that is needed during an in situ smoldering implementation is like traditional air sparge and SVE equipment. Atmospheric air is typically injected through the ignition point well into the subsurface. Variations of the smoldering technology can use air enriched with O₂ for injection. This increases the amount of oxidants delivered into the subsurface while using less overall airflow to deliver the oxidant. SVE wells are installed throughout the target treatment zone (TTZ) to capture contaminants that volatilize from the subsurface. In addition to contaminant capture, the vapor extraction system accomplishes a second goal of capturing and testing subsurface soil vapor for combustion gases, such as carbon monoxide (CO), CO₂, and O₂ that indicate if combustion is occurring.

(2) *In situ and aboveground treatment.*

(a) The combustion reaction that occurs during in situ smoldering is expected to result in near-complete destruction of organic compounds in the subsurface, provided

the combustion front reaches the contaminated zones and the compounds are not volatilized before combustion (Grant et al. 2016). Subsurface temperatures have been observed from several hundred to approximately 1,000 °C (1,832 °F), with the highest values occurring along the combustion front as it propagates through soil.

(b) As the front advances, soils ahead are heated by convection and conduction. This heating allows volatile constituents to be driven off before combustion and captured through the VR system. However, volatilization and recovery are not major removal mechanisms for coal tars or heavy molecular-weight NAPLs; combustion has been estimated to account for 98 to 99 percent of mass destruction (Scholes et al. 2015).

(c) Case studies illustrate this balance per Savron Solutions, Inc. website (see <https://www.savronsolutions.com/case-studies/>). At one petroleum hydrocarbon site, smoldering achieved 90 percent mass reduction, with about 20 percent destroyed in situ by combustion and the remainder recovered and treated aboveground. At a coal tar site, treatment of 150,000 pounds of material followed the traditional pattern of 98 to 99 percent in situ destruction and 1 to 2 percent recovery via SVE.

(d) Due to site heterogeneity and technology limitations, complete (100 percent) removal of contaminants is unlikely. Fringe soils with contamination below the threshold for sustaining combustion, or isolated pockets not identified in the conceptual site model (CSM), may not be fully treated.

1. *Soil impacts.* The temperatures generated during smoldering can boil off pore water and destroy natural organic matter. This creates the theoretical potential for subsidence under certain geologic or hydrogeologic conditions, although no field cases had been observed as of 2016. Geotechnical assessment is recommended where soils contain significant natural organic matter (Grant et al. 2016).

2. *Combustion front behavior.* The combustion front in self-sustaining smoldering is typically less than 2 feet thick and advances a few feet per day. Field experience shows the front can travel across small gaps where either contaminant concentrations are low or there is restricted air flow (Grant et al. 2016). Challenges include propagation from higher to lower permeability units due to preferential airflow and sustaining combustion in zones with high water content that limits O₂ transport (Vidonish et al. 2016).

3. *Aboveground treatment.* Equipment is like AS and SVE. A compressor supplies air to the subsurface, and blowers extract soil vapors for treatment. Off-gas is treated with vapor-phase activated carbon or thermal oxidizers. Additional details on air sparge are provided in EM 200-1-19.

(3) *Technology status.*

(a) Between 2010 and 2020, at least 12 in situ smoldering projects were completed; about 85 percent were pilot tests (Horst et al. 2021). As of 2021, vendor availability is limited. Savron Solution, Inc. markets the STAR process as the primary implementation of this technology.

(b) Bench-scale and pilot testing are recommended before full-scale application. Bench-scale tests determine whether site soils and contaminants can sustain combustion, while pilot tests refine design parameters such as air delivery, well spacing, and ignition points.

(c) Research is also underway to evaluate smoldering for contaminants that cannot serve as a fuel source, such as light petroleum hydrocarbons (gasoline) and per- and polyfluoroalkyl substances. In these cases, the concept is to introduce a surrogate fuel to enable self-sustaining combustion, with the expectation that non-combusting contaminants are destroyed by the resulting heat (Grant et al. 2016; ESTCP 2019).

2–3. Unavoidable and potential effects

The use of ISTR can produce detrimental impacts within the treated area and, in some cases, in surrounding zones. These impacts must be evaluated on a site-specific basis. At many sites, the potential effects of ISTR are minor compared to the ongoing risks posed by contamination. In other cases, engineering controls, mitigation, or adjustments to the thermal approach may be needed to manage these effects. If economics or logistics are significantly affected, ISTR may not be an appropriate technology.

a. Ecological impacts. Heat applied to soil alters the biological community within the treatment zone and may affect adjacent soils through thermal conduction. Both microorganisms and higher organisms can be directly impacted.

(1) *Microbiological impacts.*

(a) Microbial populations shift toward mesophiles and thermophiles during and after ISTR. Ambient species are greatly reduced in the treated volume, and this effect (though less intense) extends outward as surrounding soils warm.

(b) Soil drying during TCH and ERH suppresses microbial activity in heated zones but can enhance microbial activity outside them. Localized sterilization may occur under the high temperatures associated with TCH, or organisms may enter inactive states.

(2) *Impacts on higher organisms.*

(a) Multicellular organisms such as worms and insects are typically killed or displaced when soil temperatures exceed their tolerance. Burrowing mammals are forced from the treatment zone, and noise or site activity may further deter wildlife from the vicinity. Predators, dependent on these lower species, may also be affected.

(b) If threatened or endangered species are present, biological surveys and possible relocation measures may be required. However, field experience shows varied responses. For example, during steam injection and later ERH applications in Skokie, Illinois, small mammals/birds were attracted to the warmth of the treatment area during winter.

(3) *Vegetation and habitat impact.*

(a) Heat and site construction activities destroy vegetation within and adjacent to the treatment zone. Restoration efforts may require revegetation to address ecological or aesthetic concerns. In some cases, engineering controls may be needed to protect sensitive habitats.

(b) Conversely, vegetation has often flourished at the margins of ISTR projects and within treated areas after completion. Weed control at the treatment fringe may be necessary during long-term applications.

(4) *Aquatic habitat.*

(a) ISTR applications near surface water bodies are challenging because of heat losses and potential disruption of aquatic ecosystems. Many benthic and free-swimming species are highly sensitive to temperature changes. Conductive heat loss to surface water, or discharge of heated groundwater, may reduce or eliminate some species while favoring others.

(b) Engineering controls may be necessary to minimize these effects. Options include adjusting injection and extraction layouts to emphasize extraction near protected water bodies, installing clay barriers with low permeability and thermal conductivity, or, in extreme cases, refrigerating soil adjacent to water bodies. Alternatively, a surface water feature such as a stream could be temporarily relocated to prevent ecological impacts.

b. *Physical impacts.* ISTR alters the physical characteristics of soil, groundwater, and buried objects. Potential impacts and remedies are summarized below.

(1) *Soil impacts.* The drying that may occur with ERH and TCH may affect the engineering properties of the soils. During the application of ERH methods, the reduction in moisture content appears to be restricted to depths at or around the water table.

(a) In cases where the soils are expansive, the drying has the potential to cause shrinkage and desiccation, affecting nearby or overlying structures. Dewatering associated with thermal remediation may result in consolidation of the soils, resulting in some subsidence and potential foundation damage. Soils may require rewetting following ISTR. Some engineering properties may not be the same following rewetting. Injection of steam at pressures that approach the overburden pressure potentially could fracture the soils, possibly causing ground heaving, structural damage, and steam

breakout in unexpected places. Changes in moisture content may affect the bearing strength of soils, threatening foundation stability.

(b) Moisture content was measured in soil prior to and after ERH treatment at a site containing clay soils in the metropolitan Chicago area, where ERH was used to remove TCE DNAPL from a dense glacial clay till. The minimum measured moisture content was reduced from a range of 10 to 11 percent to 8 to 9 percent, but the maximum measured moisture content was higher in the set of post-treatment samples compared to the pretreatment set of samples. The post-treatment samples with the lowest moisture contents were measured in the 1.5 m to 2.7 m (5 ft to 9 ft) depth interval. Monitoring during remediation showed that this depth interval was in the vicinity of the water table and was in fact dewatered as part of the remediation.

(c) While hardly a comprehensive study, this data appears to indicate that only soils at or near the water table experience a reduction in moisture content. Soils in the saturated zone showed less variability in moisture content compared to the samples obtained from the water table and above in the post-treatment sampling. Soil in the vadose zone does not appear to experience significant moisture loss since steam continues to rise from the water table throughout the treatment period. However, the post-remediation moisture content values show a greater variability than the pre-remediation values. Therefore, if soil shrinkage were to occur, it would happen in a zone experiencing dewatering in the vicinity of the water table. The project manager needs to evaluate potential shrinkage at the depth of the water table and capillary fringe, including impacts to foundations also found in the vicinity of the water table.

(2) *Groundwater and non-aqueous phase liquid impacts.*

(a) Hydraulic control is essential to prevent contaminant migration during ISTR. Regulators and the public require assurance that DNAPLs do not remobilize. Groundwater concentrations must be monitored downgradient to confirm contaminants remain contained.

(b) ISTR can also reduce water availability for nearby users, requiring reinjection of treated water to sustain supply. Heated groundwater may persist downgradient, affecting water quality and geochemical conditions. Elevated temperatures can increase solubility of some materials or cause precipitation of others.

(c) NAPLs change physically at elevated temperatures, often becoming more mobile. If recovery systems are not designed to capture this movement, contaminants may migrate into adjacent soils, deeper zones, or surface water. System designs should anticipate and control this risk.

(3) *Impacts on buried objects and utilities.*

(a) Buried utilities may be damaged by heat or electrical currents. Plastic piping, electrical lines, and communication cables are especially vulnerable. Utilities can also act as conduits for steam or vapor, creating safety hazards. All ISTR sites must be surveyed for utilities, and rerouting may be required before treatment.

(b) Utilities may also create localized cooling zones. For example, during an ERH project in Chicago, water infiltrated a sub-grade loading dock through roof drains and downspouts despite storm sewer redirection. The pooled water cooled near-surface soils, condensed vapors, and created local VOC accumulation zones.

(4) *Vapor intrusion*. Rising temperatures increase DNAPL volatility and mobility, raising the risk of contaminated vapors migrating into nearby buildings. Uncontrolled vapor intrusion into basements or occupied spaces is a growing concern. Appropriately sized extraction and control systems are essential to prevent this outcome.

Chapter 3

Site Characterization for In Situ Thermal Remediation Technology Screening and Design

3–1. Introduction

This chapter describes the site characterization data necessary for screening and designing remediation systems using the three ISTR technologies that are the subject of this EM. ISTR techniques can be used for a range of applications where providing heat accelerates physical, chemical, and biological reactions to affect remediation. The most common applications of ISTR technologies to date are for source treatment, where NAPLs are encountered. As a result, this is the perspective used in this EM.

a. ISTR methods (such as ERH) have also been used to enhance biodegradation in Alaska and to reduce aqueous phase concentrations to facilitate the sale of a commercial property in Washington State. It is also believed that in situ thermally enhanced hydrolysis represented a significant destruction mechanism for a methylene chloride cleanup in Waukegan, IL. Also, ISTR methods are used for in situ destruction through oxidation and hydrolysis pyrolysis oxidation.

b. This EM does not focus on describing, or prescribing, the most appropriate investigative techniques, but instead presents the data requirements for designing and implementing the three ISTR methods. The project engineer/manager must then determine the most appropriate means to obtain the required information based on project objectives, site constraints, and budget.

3–2. Data collection requirements to support remedy choice and design

a. To adequately characterize a site for remediation, a CSM should be developed that explains the distribution of the contaminants in the subsurface (defining treatment area and depth). The basic elements of the conceptual model are the nature and extent of the plume, the extent of the source zone, and locations of known or suspected NAPL.

b. In developing a CSM, an understanding of geological history is also important to help explain the distribution of the contaminants in the subsurface. For example, in glaciated terrains, multiple advances and retreats of glaciers leave behind separate till units (that may or may not be readily differentiable). At many locations in the Chicago area, till units may be separated by an inter-till layer, typically containing sand and

gravel ranging from 7.5 cm (3 in.) to 0.61 m (2 ft) thick. Since these inter-till layers may be thin, they may be missed or ignored in the logging of the boreholes. However, inter-till layers have been observed to be zones of accumulation and migration of NAPL.

c. The development of the CSM also involves groundwater flow, subsurface stratigraphy (boundaries between till units and inter-till deposits), joints and fractures in tills, mineralogy, and manmade influences (groundwater pumping, artificial conduits, or barriers such as building footings, subsurface fill, abandoned foundations, fill material, proof-rolled soil surfaces, caissons, sheet piling, and subsurface utilities). Environmental and cultural resources also need to be included in the development of the CSM to ensure that there are no “surprises” requiring remedy redesign or a total change in remedial approach.

3–3. Site physical properties and site conditions

As with other in situ technologies, when evaluating the application of ISTR technologies, one should acquire and evaluate information regarding the physical properties and conditions of the site.

a. *Information needs.* Physical site information needs to include the following items.

- (1) Description of the site and setting, including a scaled site plan.
- (2) Stratigraphic features.
- (3) Hydrogeological and hydraulic parameters.
- (4) Accessibility of the area to be treated.
- (5) NAPL volume estimates.
- (6) Evaluation of contaminant mobility to determine cost-effectiveness of ISTR.

b. *Description of site including site plan.* To adequately design a remediation system, one of the most basic needs is for scalable maps of the site. The maps should have surveyed locations of site features, including utilities (above and below ground), surface features (paved surfaces, creeks, rivers, overhead lines), natural subsurface features such as bedrock faulting and joint orientation, neighboring facilities, and locations of buried features (underground storage tanks, subsurface vaults, abandoned foundations, pipelines, etc.). These maps are used to present and interpret data from the site characterization and to lay out the remedial design. Further, the survey information needs to be field checked for accuracy prior to or during the design phase.

c. *Stratigraphic features.* Stratigraphic features are typically depicted in boring logs or geological cross sections.

(1) Information from these sources should include soil type, rock type, observations on fractures and joints, mineral infilling of fractures and joints, depth to groundwater, location of perched zones, piezometric information, contaminant distribution, and stratigraphic boundaries. Some information may be collected or confirmed as part of the installation process. Information on stratigraphic boundaries should also carry with it an understanding of geological history.

(2) For settings where there have been multiple glacial advances and retreats, the stratigraphic boundaries between the till zones may have associated with it thin layers of ablation material from the glaciers or glacio-fluvial or glacio-lacustrine deposits. These may provide zones for NAPL accumulation, and may also provide zones to focus treatment, providing zones of elevated permeability for steam injection in an otherwise clayey sediment.

d. Hydrogeologic and hydraulic parameters.

(1) When heating the subsurface, it is important to recognize that the specific heat capacity of water ($4.21 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{°C}^{-1}$) is more than four times that of the soil or rock matrix (about $1.0 \text{ kJ}\cdot\text{kg}^{-1}\cdot\text{°C}^{-1}$). Since heating water is costly, minimizing groundwater flux into the treatment zone is critical for controlling remediation costs.

(2) Groundwater velocity is a key factor in ISTR system design. A good understanding of groundwater velocity and flow, as well as more detailed hydrogeologic information such as well yield and distance-drawdown relationships from pump tests, can inform both technology selection and system design.

(a) Hydraulic conductivity. Hydraulic conductivity is a particularly important input for steam injection because it controls injection and recovery rates. Soil permeability is less critical for TCH and ERH, but it remains important for designing effective VR systems. When soil is completely dried during TCH, even tight soil develops enough permeability for contaminant removal.

(b) Groundwater flow. Groundwater velocity and direction strongly influence heat distribution and recovery system effectiveness. High velocities may increase heat loss and require additional engineering controls, while very low velocities may limit steam or heat propagation.

e. Site accessibility. Site accessibility can determine the ease or difficulty of implementing an in situ remediation technique that affects cost and feasibility. These accessibility issues include obstacles to drilling, such as low overhead clearance because of ceilings, obstructions, power lines, or steep slopes that do not allow conventional drilling rigs that are used as part of the installation of ISTR systems to safely operate.

(1) *Construction constraints.* Constraints on construction must be considered early. Restrictions may apply to access, noise, dust, odors, or work hours, and personal protective equipment may be required. In winter, ISTR operations can melt snow,

creating runoff hazards on adjacent traveled ways. Preventive measures must be taken to avoid creating unsafe conditions.

(2) *Operational constraints.* Long-term system operation may be limited by available workspace, access for maintenance crews, or proximity to sensitive receptors such as residences or businesses. These factors should be evaluated during planning to avoid costly interruptions once heating begins.

f. Non-aqueous phase liquid location and volume estimates. Each of the ISTR technologies may be implemented in a modular fashion, and as a result, it may be only necessary to know the extent of the zone to be treated relative to the dimensions of the module of the technology to be used.

(1) For instance, if using ERH, the distance between electrodes is typically 2.6 m to 6.1 m (8.5 ft to 20 ft).

(a) At several ERH sites, because of site conditions and the compounds being treated, the spacing has been considerably closer: 2.74 m (9 ft) at Lowry Air Force Base North Pit, Denver, Colorado (Beyke and Crownover 2006); 4 m to 6 m (13 ft to 20 ft) at Inhabited Residential Apartment Building; and ~1.5 m to 3 m (~5 ft to 10 ft) at International Chemical and Nuclear Corporation Pharmaceutical, Portland, Oregon. Therefore, the lateral extent of the area containing NAPL need only be defined to a level of accuracy of ± 2.6 m to 6.1 m (± 8.5 ft to 20 ft).

(b) In many cases where the extent of the NAPL is uncertain, it may be less expensive to simply expand the array of heater wells/electrodes/wells to account for the uncertainty rather than to further characterize the spill. It is good practice to sample the soils from the perimeter heater wells/electrodes/wells as confirmation of adequate coverage of the treatment area.

(2) Estimating NAPL volume is typically an exercise involving broad simplifying assumptions with uncertain results. The mass of NAPL removed or recovered or destroyed typically exceeds NAPL estimates. However, NAPL volume should be estimated to at least approximate the volumes that can be expected to be recovered. These estimated volumes support these conditions.

(a) Regulatory permitting purposes to estimate organic discharges from the remediation system.

(b) Determining the most appropriate and cost-effective AQC technique.

(c) The budget for the AQC treatment.

(d) Allowing the project engineer and manager to indicate the mass to be produced to compare against the CSM.

(3) If the recovered NAPL volume greatly exceeds the calculated volume, the engineer may need to re-evaluate the CSM and assess impacts on schedule and budget. Alternate sources of NAPL may be present that were not identified in the site characterization. This may influence the length of remediation time and, hence, the budget.

(4) If the quantity is significantly less than calculated, the remediation engineer should evaluate the effectiveness of the recovery technique(s). There may be blockages in the piping and treatment equipment (such as condensate buildup in the carbon canisters) that are affecting the determination of the recovered mass. If poor recovery is taking place, it also affects the length of remediation time and, hence, the budget.

g. Evaluation of contaminant mobility. ISTR techniques have the potential to mobilize NAPL. If heating can significantly change the physical characteristics of the NAPL, the remediation engineer must verify that it can be captured. Therefore, NAPL characteristics such as specific gravity and changes in viscosity with temperature should be measured to appropriately design the recovery system.

3–4. Chemical analyses and contaminant properties

Chemical analyses required for ISTR techniques include conventional analyses for VOCs and semi-volatile organic compounds (SVOCs) (in both soil and groundwater) to define the extent of the COCs and to estimate the organic loading to the vapor treatment equipment. Additional analyses should also be made to address issues that may affect the operation or effectiveness of the remediation system.

a. Organic parameters.

(1) Concentrations of target and non-target compounds need to be evaluated to determine the loading and to properly design the treatment system. Non-target compounds may impact remediation effectiveness. For example, VOC evaporation rates are slowed if the target contaminant is dissolved into oil or grease, as described by Raoult's Law.

(2) A parameter that is typically overlooked for active in situ remediation applications is total organic carbon (TOC). The TOC content of the soil influences methods that use lower temperatures of in situ remediation (ERH and shallow SEE applications) because TOC preferentially adsorbs VOCs that may be present in the subsurface.

b. Inorganic parameters. Concentrations of major anions/cations in groundwater are important in evaluating treatment options. Calcium and iron compounds may precipitate on well screens and treatment equipment during heating, affecting maintenance and, potentially, feasibility. Anions such as carbonates can provide acid buffering capacity. This buffering capacity can be important because hydrochloric acid (HCl) may be generated from treating chlorinated hydrocarbons at the high temperatures that can be achieved using thermal conduction.

c. *Non-aqueous phase liquid characteristics.* The characteristics of the NAPL need to be known prior to selecting and designing an ISTR application. Characteristics include specific gravity, interfacial tension, viscosity, vapor pressure, and aqueous solubility, including variability with temperature. Many of these characteristics may be obtained from literature sources.

d. *Trends in dissolved phase compounds.*

(1) If the site to be remediated has historical groundwater monitoring data associated with it, the remediation engineer should evaluate concentration trends. These concentration trends can be used to evaluate whether natural attenuation is taking place, whether investigations have mobilized NAPL, and the effectiveness of a pre-existing remediation system (that may provide insight into the probability of success for the ISTR method to be implemented). Further, historical concentration trends may provide insight into the presence of NAPL (especially at sites where it may not have been physically observed) to appropriately place the ISTR system.

(2) On initial heating, concentrations of most VOCs in groundwater increase in the zone being heated until the temperature of the water reaches the eutectic point of the azeotropic mixture. As temperatures increase beyond this point, concentrations decline. Therefore, groundwater concentrations can be expected to vary over the period of the ISTR application, and it is necessary to determine if there are potential adverse effects and engineer the remediation system accordingly.

3–5. Data needs specific to each technology

a. *Thermal conductive heating.* TCH is the least sensitive of any in situ remediation technology to variations in soil type (VR may be influenced by soil type and variations in lithology) and total dissolved solids in groundwater. This is because thermal conductivity varies by only a factor of ± 2 for a wide range of common earth materials. This lack of variability in soil heat conductivity is one of the key factors in the versatility of ISTD.

(1) There is no practical limitation to the geometry of the TCH treatment zone. For example, it can be thin, irregular, or deeper than 30 m (98 ft). Nor does the presence of subsurface debris, such as concrete walls, tanks, or landfill debris (including metallic objects), impede TCH.

(a) Site characteristics do, however, influence TCH design. For example, treatment of shallow contamination requires that an insulating surface cover be installed to manage heat losses. Shallow contamination may be addressed more cost-effectively by using fewer long horizontal heaters placed in trenches than by employing numerous short vertical heaters installed in wells. Lithology does affect the choice of drilling methods, with direct-push commonly used for heater-only wells and auger methods for heater-vacuum wells. Subsurface debris may also affect drilling methods for the installation of heater wells. High permeability zones can affect the ability to achieve

superheated temperatures, if needed, and may dictate the need to employ measures to control recharge into the treatment zone.

(b) Treatment of VOCs with ISTD TCH, by contrast, is much less affected by recharge zones and can be readily performed below the water table except in highly permeable aquifers. Generally, the upper limit for hydraulic conductivity is approximately 10^{-3} centimeters per second (cm/s).

(2) The electrical load of a TCH system is comparable to what is typically available at industrial or commercial sites.

(3) The overall size of the treatment zone is an important site characteristic. As with other on-site treatment technologies, economies of scale affect treatment costs, such that large sites exhibit much lower unit costs, whereas very small sites may be more cost-effectively addressed by other means such as excavation.

(4) As with other ISTR technologies, site information needs for ISTD include these items.

(a) Concentrations and characteristics of COCs.

(b) Extent of contamination (lateral and vertical).

(c) Approximate location, nature, and extent of free product or “neat” contaminant.

(d) Concentrations of non-target contaminants that may contribute to the loading on off-gas treatment equipment, such as GAC.

(5) As a result of the high temperatures achieved using ISTD TCH, inorganic groundwater chemistry can have significant effects. That is, concentrations of anions, such as carbonates, can provide in situ buffering capacity, where the in situ destruction of chlorinated hydrocarbons has the potential to produce HCl. If there is insufficient buffering capacity, the lowered pH must be considered in the selection of piping and treatment equipment materials and possibly in the treatment processes.

(6) Since ISTD TCH can be used to treat a wide variety of organic (and some inorganic) contaminants in a range of settings, the data needs vary depending on the remedial context. Four general categories of applications include the following.

(a) Vadose zone VOCs.

(b) Vadose zone SVOCs (may include VOCs).

(c) Saturated zone VOCs.

(d) Saturated zone SVOCs (may include VOCs).

(7) Although soils above the water table (in the vadose zone) and below it can both be treated with TCH, measures need to be taken to control the rate of water recharge into the thermal treatment zone, particularly below the water table, if the recharge rate is too high. Such measures can include dewatering with wells or trenches and installation of hydraulic barriers, such as steel sheeting, slurry walls, jet-grout walls, and freeze walls, keyed into an underlying aquitard. These actions may increase costs, impacting the project. A key information requirement for TCH, especially below the water table, is data allowing estimation of recharge rates, including permeability and hydraulic gradient, and spatial variations in the treatment zone. The results of pumping tests are particularly relevant.

(8) The contaminant category and concentration, as well as emission standards, are important as they dictate the selection and design of above-ground AQC equipment.

(9) The application of ERH is not sensitive to variations in site lithology in achieving even heating (VR may be influenced by soil type and site lithology). Some soils or zones of groundwater with total dissolved solids above background concentrations may heat preferentially to others as the treatment volume is heated up. However, as the soil tends to warm toward the limiting threshold of the boiling point of water, soil that may have lagged in the rate of temperature increase also rise in temperature to the boiling point of water. A key role of site lithology in ERH applications is the influence on how NAPL migrates and accumulates, which should be evaluated prior to implementing the remediation. Important information required for site characterization and technology screening includes the following items.

(a) The area and depth of the remediation.

(b) The contaminant characteristics (especially boiling point, water solubility, and hydrolysis rate).

(c) The contaminant percent reduction required.

(d) The TOC content of the soil.

(e) The presence of low-volatility co-contaminants such as oil and grease.

(f) The location of subsurface utilities.

(10) Other common site information can refine technology selection and design but generally does not affect cost or effectiveness significantly. This information includes the following items.

(a) Soil lithology (to identify subsurface features that may retard migration or accumulate NAPL).

(b) Soil saturation or moisture content.

(c) Presence or absence of separate phase NAPL.

(d) Soil and groundwater electrical (specific conductance of groundwater) or thermal properties (and delineation as to where these may vary).

(11) Since the treatment interval is typically uniformly heated, information regarding the precise distribution of contamination or NAPL is not required. However, it is important to have enough contaminant distribution information to allow designation of a “box” or boundary that includes the contaminant mass to be treated. The remediation boundary can be irregular, and the depth interval can vary across the site. If extensive treatment of the upper 0.6 m (2 ft) of soil is required, this adds to the cost owing to heat losses to the atmosphere. If extensive (greater than 90 percent) reduction of such shallow VOCs is required, an insulating surface blanket is often used to achieve higher temperatures. An interval of 2.4 m (8 ft) thick is the thinnest region that can be practically treated owing to both vertical fanning of the current as it travels between the electrodes and thermal conduction of heat out of the target zone.

(12) The physical and chemical characteristics of the target contaminant affect the remediation energy, time, and cost. The percentage of contaminant reduction (as measured by contaminant mass, before and after soil sampling, or groundwater sampling) is another important remediation parameter. The percentage of reduction desired might be based on a health risk assessment or on the dissolved groundwater concentration at a downgradient receptor. For most VOCs, “adding a nine” to the desired percent contaminant reduction (for example, changing from 90 percent to 99 percent or changing from 99 percent to 99.9 percent) increases the overall project cost by 10 to 20 percent.

(13) If high levels of contamination extend to within 1.2 m (4 ft) of the soil surface, subsurface utilities should be evaluated. Most utilities are not affected by ERH if they are constructed of metal, vitrified clay, or other temperature-insensitive material. ERH has been applied in regions that are traversed by metal natural gas pipelines, telephone, fiber optic cables, water, and sewer lines. Temperature-sensitive utilities include plastic water and natural gas lines and electrical cables that carry significant power.

(14) The electrical load of an ERH system is relatively small compared to most industrial and military activities but significantly larger than most remediation approaches. Utility locations, age, capacity, and rate structures are important issues to be considered. The existing utility infrastructure should be evaluated during the technology screening to determine if it has sufficient capacity to provide power for an ERH system.

b. Steam enhanced extraction.

(1) The major design data required for steam injections consists of the following.

(a) The lateral and vertical extent of the treatment zone. This is used to estimate the volume to be heated, steam needed, and overall cost.

(b) NAPL presence and COCs (density, vapor pressure, solubility). This drives the treatment strategy and effluent treatment system component selection.

(c) Target cleanup levels for different soils and groundwater. This is used to evaluate feasibility and treatment duration and to determine if polishing steps are desirable.

(d) Geological stratification (affecting steam injection strategy and number of injection intervals with depth).

(e) Horizontal and vertical permeability of target layers (this drives well spacing and screen length selection).

(f) Hydrological data (hydraulic gradients, seepage velocity, hydraulic conductivity). This affects the necessary pumping rates for maintaining hydraulic control.

(g) Obstructions to well installation (buildings, subsurface installations, etc.). This affects the choice of well design and feasibility.

(2) Small sites, located at shallow depths, may not be treated with steam injections economically, unless cheaper options such as excavation are ruled out owing to site-specific constraints such as buildings or underground lines that cannot be removed. The pressure of the injected steam is limited by the overburden pressure. This weight is directly related to the thickness of soil above the injection zone. A general guideline is that the injection pressure should not exceed 0.5 pounds per square inch gauge per foot of overburden. However, recent field demonstrations have shown that this value can be exceeded safely at shallow sites with a surface cover (Alameda Point, Pinellas Science, Technology, and Research Center) and at fractured rock sites with significant rock strength (Edwards AFB Site 61, Loring Quarry Site).

(3) In practice, the injection rates for shallow sites are restricted by the limited weight of the overburden and thereby the minimum practical injection pressures that can be attained in the field. As an example, steam was injected at 3 m (10 ft) below grade at Alameda Point, and the pressure was limited to about 8 pounds per square inch gauge. This limited the achievable steam injection rates to below 200 lb/hr per well, which in turn led to a design with the injection wells less than 9.1 m (30 ft) away from the central extraction well.

(4) Injection of steam below paved surfaces and concrete floors may allow treatment at shallower depths, provided building foundations are not negatively affected. Generally, steam is effective for treating zones deeper than 1 m to 2 m (3 ft to 6 ft), making this a highly versatile method.

(5) Given the infrastructure required for steam injections (steam generators, wells, controls, sources of high-quality water, fuel, electricity, etc.), an economy of scale needs to be realized for treatment. Small quantities may not be economically treated.

(6) Higher permeability soils are more conducive to steam injection than lower permeability soils. The lower the permeability is, the higher the injection pressures required, resulting in higher steam temperatures. Higher pressures can also result in soil instability. Higher pressure in turn limits mass flux to the vapor phase because the vapor pressure of the COCs must overcome the induced pressures in the soil resulting from the steam injection. Generally, the lower limit for hydraulic conductivity for steam penetration is $\sim 10^{-5}$ cm/s for sites deeper than 9.1 m (30 ft), with higher permeability needed for shallower sites. For sites less than 6.1 m (20 ft) deep, a practical limit for steam injection is probably $\sim 10^{-3}$ cm/s. However, if the hydraulic conductivity varies around this value, steam injection can be combined with electrical heating to overcome heat transfer limitations of the tighter zones.

(7) Steam can still be effective in treating low-permeability soils when the steam is injected into adjacent lenses/layers with higher permeability (Adams and Smith 1998). Steam has been injected into gravel-filled inter-till zones to treat clay till with a matrix hydraulic conductivity in the order of 10^{-8} cm/s. In that application, steam was injected into a dewatered thin sand and gravel zone of 10 cm to 60 cm (3.9 in. to 23.6 in.) at the stratigraphic break between two ground moraines. The steam apparently migrated laterally through the inter-till layer and vertically through the joints and fractures in the till. It is also believed to represent the vertical migration pathways for the PCE and mineral spirits that were released at the site, rapidly heating approximately 12 m (40 ft) of clay till overlying the inter-till unit.

3-6. Evaluation of biological degradation potential

a. Source removal, reduction, and recovery are achievable using ISTR methods, resulting in a reduction in mass flux to groundwater. At some sites, sufficient mass removal may occur, making the assimilative capacity of the aquifer crucial for playing an important role in attaining remediation goals. As such, depending on the remediation goal, it may be appropriate to evaluate natural attenuation. Intrinsic biodegradation is typically a significant part of this process. This evaluation can be important in the overall remediation plan. It is beyond the scope of this EM to provide background on what natural attenuation parameters to analyze for and how to interpret the data. The reader is referred to the following sources of information.

(1) American Society for Testing and Materials (ASTM) E1943-24. Standard Guide for Remediation of Ground Water by Natural Attenuation at Petroleum Release Sites. (Available at <https://www.astm.org/Standard/standards-and-publications.html>.)

(2) Committee on Intrinsic Remediation. Natural Attenuation for Groundwater Remediation (National Resource Council 2000). (Available at <https://nap.nationalacademies.org>.)

(3) EPA EC-G-2002-095. Use of Monitored Natural Attenuation at Superfund, Resource Conservation and Recovery Act (RCRA) Corrective Action and Underground Storage Tank Sites (USEPA 1999b). (Available at <https://nepis.epa.gov/Exe/ZyPDF.cgi/P100GIAB.PDF?Dockey=P100GIAB.PDF>.)

(4) Interstate Technology and Regulatory Council. Natural Attenuation of Chlorinated Solvents in Groundwater: Principles and Practices (ITRC 1999). (Available at <https://itrcweb.org/isb-principles-and-practices/>.)

(5) USEPA (EPA 600/A-95/112). Intrinsic Bioattenuation for Subsurface Restoration (USEPA 1995). (Available at <https://www.osti.gov/servlets/purl/464884>.)

(6) Air Force Center for Environmental Excellence. Technical Protocol for Implementing Intrinsic Remediation with Long Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater, Volume I (Wiedemeier 1995a) and Volume II (Wiedemeier 1995b). (Available at <https://discover.dtic.mil/>.)

(7) USEPA Office of Research and Development. Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Groundwater (Wiedemeier 1998). (Available at <https://nepis.epa.gov/Exe/ZyPDF.cgi/30003ONO.PDF?Dockkey=30003ONO.PDF>.)

b. General observations regarding the three ISTR technologies are discussed in the following paragraphs.

(1) *Thermal conductive heating.* When operated with the aim of having the entire treatment zone attain temperatures above the boiling point of water (as for treatment of SVOCs), the temperatures achieved using ISTD TCH effectively sterilize the soil in the treatment zone. When operated to accomplish in situ steam distillation of VOCs at temperatures below the boiling point of water, the sterilization effect may be somewhat lessened. In either case, however, microbiota is not permanently eradicated from the treated soil and may repopulate the soil as it cools.

(a) Evidence suggests that a large fraction of the TOC remains after ISTD, probably because very high molecular weight compounds such as humic and fulvic acids are not destroyed at such temperatures. This TOC may serve as a carbon source for re-emerging microbiota. At the same time, ISTD tends to mineralize a certain fraction of the organic nutrients into inorganic forms. These forms, being more water-soluble, are likely more bioavailable than prior to thermal treatment. This may help to explain the observation that vegetation has rapidly invaded and flourished on sites where ISTD had been conducted.

(b) Therefore, although research is currently lacking, one may expect that in situ biological degradation can resume after TCH, particularly in fringe zones surrounding the thermal treatment zone and in the associated dissolved plume, where hydrocarbons may remain following thermal treatment of the source zone. In addition to high-temperature applications, TCH may also be used in cold climates to slowly warm soils to accelerate biodegradation of organic contaminants.

(2) *Electrical resistivity heating.* Biodegradation can be incorporated into ERH remediation applications. While ERH has the potential to heat the subsurface to the boiling point of water, this does not necessarily sterilize the subsurface. At one of the earliest full-scale applications of ERH in Skokie, Illinois, cis-1,2-DCE (a daughter

compound from the biodegradation of TCE) was observed in the off-gas from the treatment area throughout the entire process (Beyke et al. 2000). During this period, concentrations of methane were also observed to increase in off-gas. Methane, based on oxidation-reduction potential (ORP) measurements in the groundwater, is believed to have been the result of the anaerobic biodegradation of organic material in the groundwater.

(a) Biodegradation was also tracked isotopically at the Skokie, Illinois location. Groundwater impacted by chlorinated aliphatic hydrocarbon will become depleted in carbon-13 (^{13}C) and enriched in chlorine-37 (^{37}Cl) during evaporation (ISTR operations), while during microbial degradation, isotopic concentrations in groundwater become enriched in both ^{13}C and ^{37}Cl (Sturchio et al. 2000).

(b) This relationship allowed researchers and the remediation engineer or project manager to track the fate of the chlorinated aliphatic hydrocarbon and determine the nature of the remediation taking place. The isotopic data from the Skokie site showed biodegradation to be taking place during and after treatment.

(3) *Steam enhanced extraction.* Biological degradation potential under steam injection can be assessed as part of a natural attenuation evaluation. The injection of steam creates a steam zone, a variable temperature zone, and an ambient temperature zone. The variable temperature zone, which may be relatively extensive in lower permeability settings, provides an environment to enhance biological activity. Biological activity may increase two- to three-fold for each 10 °C (50 °F) rise in temperature. Nutrients may be added (if necessary) to enhance bioactivity (Basile et al. 1994). At the first application of this approach in Skokie, Illinois, it is estimated that approximately 10,400 kg (23,000 lb) of TCE and 1,1,1-TCA were reductively dehalogenated (biodegraded) as part of the remediation, representing 36 percent of the mass removed or destroyed during the application period (Smith et al. 2000).

Chapter 4

Technology Screening and Feasibility Studies for In Situ Thermal Remediation

4-1. Introduction

a. To effectively select the appropriate remedial technology, it is important to define the remediation goals. As discussed in previous sections, increases in temperature greatly affect chemical properties, including chemical, biological, and physical reactions. It is these enhancements of physical, chemical, and biological reactions that ISTR methods seek to utilize to effect remediation, either through a single approach or a combination of methods.

b. Possible operations that can be performed as part of ISTR applications are listed here.

- (1) Removing, reducing, or recovering the source (the most common application).
- (2) Enhancing chemical reactions such as HPO.

- (3) Enhancing biological reactions.

4–2. Identify remedial action strategies

ISTR technologies have most commonly been applied to the removal of NAPL, and, accordingly, this EM focuses primarily on those applications. ISTR methods have also been used to enhance biological processes, volatilize aqueous-phase concentrations, and induce oxidation (for example, through cyclic injection of steam and air to promote HPO). The application of heat alters chemical, physical, and biological properties and reactions, all of which play important roles in environmental remediation.

a. Source removal/reduction/recovery. Thermal methods are typically applied for the removal, reduction, or recovery of NAPL. Many industrial organic chemicals found at hazardous waste sites (PCE, TCE, 1,1,1-TCA, benzene, ethylbenzene, toluene, and xylenes) have boiling points below 150 °C (302 °F). Where these compounds are present as NAPL, the primary removal mechanisms include enhanced volatilization, steam distillation (utilizing the azeotropic mixture eutectic point), HPO, and vapor-phase oxidation and pyrolysis. Two or more liquids heated together boil at a temperature (the eutectic point) below the boiling point of the individual components of that mixture (for example, a mixture of TCE in water has a eutectic point of 73.1 °C (163 °F), while TCE in air at standard atmospheric pressure boils at 87 °C (188.6 °F). Source removal, reduction, and recovery can also significantly reduce the mass flux of organic chemicals from the source zone such that, when coupled with natural attenuation, the aqueous phase is substantially cleaned up (Smith et al. 2000).

(1) Identification of thermal treatment areas.

(a) Determining the extent of non-aqueous phase liquid. The lateral and vertical extent of NAPL at a site is best established using multiple lines of evidence rather than a single measurement. These lines of evidence may include the following.

1. Groundwater and soil chemical data.
2. Inferences from site characterization tools such as USACE's Site Characterization and Analysis Penetrometer System and the Fugro Rapid Optical Screening Tool®.
3. Visual observations in groundwater or soil samples, where possible.
4. Direct measurement of NAPL in groundwater.
5. Comparison of concentrations to aqueous solubility data.

(b) Dividing large or complex sites into subareas. At some large or complex sites, it may be appropriate to divide the site into subareas for thermal treatment. Subarea designation allows different parts of a site to be prioritized when the entire site cannot be treated due to implementation constraints or limited funding. This approach also

supports phased implementation of thermal treatment. Subareas may be identified and prioritized based on factors such as these items.

1. The estimated relative amount of NAPL in each subarea.
2. Relative differences in NAPL mobility, if any, between subareas.
3. Proximity of each NAPL subarea to drinking water sources/risk receptors.
4. The degree of certainty regarding the presence of mobile NAPL in each subarea.
5. Expected future land use in each subarea.
6. Relative ease of access for implementation in each subarea.

(2) *Setting remedial action objectives.* Although RAOs are specific to each site and regulatory program, there are several common approaches to consider in setting RAOs for ISTR. The appropriate Office of Counsel must be consulted regarding the proper application of the laws and requirements under the various regulatory programs and patent law. There may be differences in application between the various environmental restoration programs.

(a) RAOs include general remediation goals and site-specific numerical cleanup standards that address current and potential groundwater risk pathways at a site. RAOs depend on the expected future land use of the site and the designated beneficial uses of the groundwater aquifer beneath the site. For example, when groundwater poses an actual or potential health risk and is a potential drinking water source or could affect a drinking water source, the National Contingency Plan directs EPA to restore groundwater to federal and state drinking water standards whenever possible, in a reasonable time per National Contingency Plan, 40 Code of Federal Regulations (CFR) 300.430(a)(1)(iii)(F).

(b) EPA record of decision guidance (USEPA 1999c) states that “different remediation objectives should be developed for the NAPL zone and for the portion of the aquifer outside of the NAPL zone.” This is based on the conclusion in the guidance that “in general, restoration of an aquifer contaminated with NAPLs to applicable or relevant and appropriate requirements (ARARs), such as federal and state maximum contaminant limits (MCLs) or other risk-based cleanup levels in a reasonable time frame, is not attainable in the NAPL zone unless the NAPLs can be removed.” The appropriate Office of Counsel should be consulted regarding the application of this EPA guidance to the site in question.

(c) In setting performance objectives for remediating the NAPL zone, several different approaches are possible. The performance objectives for the NAPL zone relevant to in situ treatment do not need to be numerical standards but need to be measurable. Examples of non-numerical remedial goals for ISTR include the following.

1. Remove mobile NAPL.
2. Remove NAPL “to the maximum extent technically feasible.”
3. Remove a specified amount of NAPL based on estimated quantities (such as gallons or a percentage of the estimated total NAPL; in other words, remove 90 percent of the NAPL or remove 90 percent of the most volatile fraction of the NAPL).
4. Achieve an order of magnitude reduction of NAPL.
5. Demonstrate that “significant” NAPL recovery equals real risk reduction (by removing 90 percent of NAPL, the remaining 10 percent represents only a negligible risk).
6. Achieve a net reduction in flux of contaminants to groundwater that is lower than the assimilative capacity of the aquifer, allowing natural attenuation processes to achieve water quality goals at some point of compliance.
7. Achieve specific performance standards (heating criteria or treatment time periods).
8. Use a goal structure like what has been used for SVE (achieving asymptotic recovery curves indicating that a well-designed, installed, operated, and optimized system has reached a point of diminishing returns).
9. Achieve indirect goals such as reducing time or lateral extent of follow-up actions such as pump-and-treat.
10. Conduct a “cost-effective” removal of NAPL.

(d) There are shortcomings to several of these approaches. Remedial goals based on a specific quantity of NAPL recovery are problematic because of the uncertainty associated with estimating the initial NAPL volume. It is also difficult to quantify residual risk (or risk reduction) after ISTR to demonstrate that a specific risk-reduction goal has been achieved. Demonstrating that NAPL removal has been cost-effective raises the question of what cost per gallon of NAPL recovered is cost-effective in relation to the total groundwater remediation costs, including long-term O&M.

(e) Ultimately, RAOs for ISTR must be determined on a site-specific basis and must fit into the overall, long-term cleanup strategy for the site. Due to the uncertainties currently associated with ISTR technology, RAOs may need to include contingencies if sufficient NAPL is not recovered. One contingency includes conducting follow-up actions such as pump-and-treat to contain NAPL sources that cannot be removed and that are considered a continuing threat to groundwater.

b. Other remediation strategies. As noted above, ISTR methods can be applied for different purposes beyond NAPL removal, particularly to enhance physical,

chemical, and biological processes that promote remediation. This paragraph provides examples of ISTR applications where NAPL removal is not the primary goal.

(1) *Enhance physical changes.* Physical changes include changes in state (solid to liquid to vapor). Thermal methods can be used to vaporize dissolved compounds in groundwater. This process essentially involves boiling the groundwater.

(a) At a site in Washington State, ERH was applied to reduce relatively low concentrations of chlorinated solvents in slow-moving groundwater, enabling rapid site cleanup to support property sales at a higher value than if PCE and TCE remained in the groundwater.

(b) Changing physical conditions can also alter the physical properties of specific compounds. For example, heat reduces the viscosity of many materials, facilitating their recovery. At the Yorktown Naval Facility, steam injected through horizontal stainless steel wells were used to reduce the viscosity of Navy special fuel oil, allowing recovery via a trench system. Engineering studies have also evaluated the feasibility of using steam, ERH, and TCH at several refineries to enhance recovery of lube oils currently extracted using more conventional methods.

(2) *Enhance chemical reactions.*

(a) HPO involves chemical oxidation in the presence of heat. Reactions between O₂ and common organic pollutants occur significantly faster at steam temperatures compared to ambient conditions.

1. For in situ destruction using HPO, the subsurface is typically heated with TCH or SEE. Most TCH field projects benefit from naturally occurring subsurface water to support the HPO reaction. The product stream often contains more than 50 percent water and may also contain air. In addition, steam and O₂, or O₂ alone (typically supplied as air), are injected in pulses, creating a heated, oxygenated zone in the subsurface.

2. When injection stops, pressures dissipate, steam condenses, and contaminated groundwater flows back into the heated zone for in situ treatment. Dissolved contaminants in the groundwater mix with O₂ and condensate, and in the presence of heat, oxidize rapidly to form CO₂ and chloride ions (in the case of chlorinated compounds such as PCP, TCE, or PCE). Reaction kinetics for gas-phase oxidation and pyrolysis increase dramatically above the boiling point of water. Using HPO, it is estimated that more than 68,038 kg (150,000 lbs) of wood-treating chemicals were degraded at the Visalia Pole Yard site.

(b) As discussed, chemical reactions such as hydrolysis also accelerate significantly with temperature, particularly in the cleanup of alkanes. At the time of this EM's preparation, there were no known cases of ISTR applied solely to enhance hydrolysis. However, thermally enhanced hydrolysis of methylene chloride was believed to have been a significant mechanism in the ERH remediation at Waukegan, Illinois. Similarly, a review of ERH remediation data from Skokie, Illinois, suggests

thermally enhanced hydrolysis may have played a major role in removing 1,1,1-TCA from groundwater (Beyke and Crownover 2006).

(3) *Enhance biological reactions.* The application of heat can greatly increase biological activity; estimates suggest biological activity triples with every 10 °C (50 °F) increase in temperature. When temperature limits in situ biodegradation, heat may be added using ISTR methods. For example, at Fort Richardson, Alaska, ERH was used to stimulate intrinsic biodegradation of fuels during winter months (Appendix B).

(a) Biodegradation has been observed during ERH operations, even at temperatures approaching the boiling point of water. At the Skokie, Illinois, ERH site (Beyke et al. 2000), cis-1,2-DCE (a biodegradation daughter product of TCE) was detected throughout the treatment period. Methane was also detected in off-gas samples, further evidence of biological activity.

(b) Steam injection coupled with simultaneous enhanced biodegradation (Basile et al. 1994) has been successfully applied at two Illinois sites (Adams and Smith 1998, Smith et al. 2000). At one of these sites, approximately one-third of the released chlorinated solvents were destroyed via in situ biodegradation.

4–3. Measures of success for in situ thermal remediation

If residual NAPL is present, MCLs or other cleanup standards may not be achieved in groundwater at a site for an unknown period after completion of thermal treatment. In some cases, natural degradation of the residual NAPL may be adequate to meet RAOs. At other sites, follow-up activities such as pump-and-treat or enhanced biodegradation are performed. Depending on the size of the remediation, the benefits of ISTR may be realized in as little as 18 months, or it may require years of monitoring to assess the full benefits at a site. Therefore, different measures of “success” are needed for ISTR technologies. Success can be defined by mass removal goals, but this approach has limitations, as noted above. Narrative goals like reducing the need for long-term pump-and-treat are measures of success but may not be demonstrated in the short term.

a. When applying ISTR technologies, it is important to realize that complete removal of the source area is impractical. For various compounds, reduction of source mass may be sufficient to reduce the contaminant flux to groundwater to levels that, for instance, do not represent residual NAPL, or where there is a lack of rebound, which then allows the natural assimilative capacity of the aquifer to control plume migration. This involves evaluating natural attenuation.

b. For chlorinated solvents, this may be determined by the organic carbon demand. Each 1 mg of dissolved organic carbon oxidized via reductive dechlorination consumes 5.65 mg of organic chlorine (Wiedemeier et al. 1998). This ratio can be used to determine organic carbon demand and the change in this organic carbon demand as the compounds degrade. Organic chlorine can be determined from the following relationship for TCE.

c. For example, as two moles of TCE are reduced to ethene, six moles of chlorine (shown below as Cl₂ gas) are produced (TCE: 2C₂HCl₃ + 3H₂ → 2C₂H₄ + 3Cl₂).

- (1) Molecular weights: TCE 2(12.011) + 3(35.453) + 1.01 = 131.39
Chlorine 3(35.453) = 106.359
Mass Ratio of Chlorine to TCE = 106.359:131.30 = 0.81:1

(2) Therefore, 10 mg/L of TCE is equivalent to 8.1 mg/L of organic chlorine, which in turn represents 1.43 (8.1 ÷ 5.65) mg/L of organic carbon demand.

d. Organic carbon demand is then compared to concentrations of organic carbon in groundwater. Where organic carbon exceeds the organic carbon demand and appropriate redox conditions are present, reductive dehalogenation is occurring and there is sufficient assimilative capacity in the aquifer. Conversely, where organic carbon demand exceeds available organic carbon in groundwater, the dehalogenation process may be inhibited.

e. Similarly, for fuels, where the O₂ demand is satisfied by the dissolved O₂ concentrations or other electron donor sources, the aquifer may assimilate continued flux to groundwater from the source area.

4-4. Feasibility evaluation flowchart

Once the remediation goal is established, each ISTR technology has a range of effectiveness, depending on the desired temperature range to be achieved, the soil type in which it is applied, the depth of contaminant, the setting of contaminant (such as perched on a clay layer, potential for mobilization as a result of heating), and the potential for VR. For example, the feasibility of engineering a cost-effective recovery system. ISTR technologies have seen limited testing in bedrock environments at the time of preparing this manual. As a result, the experience base does not exist to develop procedures for application in bedrock. Figure 4-1 presents a flowchart for evaluating site conditions to determine whether ISTR is potentially applicable for the site given its setting and infrastructure. Conditions to be evaluated include delineation of the source area, nature of compounds to be remediated, availability of utilities, geotechnical issues, drainage in the remediation area, and drilling access issues.

a. Selection of the appropriate technology for a given site is site-specific, dependent on varying factors such as cost (and cash flow constraints), geology, hydrogeology, community acceptance, availability of power, and depth of treatment. The technologies that are the subject of this manual have been undergoing continuous improvement as more sites are treated. Engineering solutions have been developed for issues that have been encountered, providing a knowledge base to expand the settings where the technologies may be applicable. It is recommended that several vendors be contacted once it is determined that ISTR may be applicable for a given site to evaluate the issues involved in applying the technology at said site.

b. Steam injection temperatures that can be achieved are based on the injection pressures that can be achieved. Since most environmental restoration projects are typically performed at depths of less than 30 m (100 ft), the highest temperature that can be reasonably achieved in soil using steam is approximately 170 °C (~350 °F).

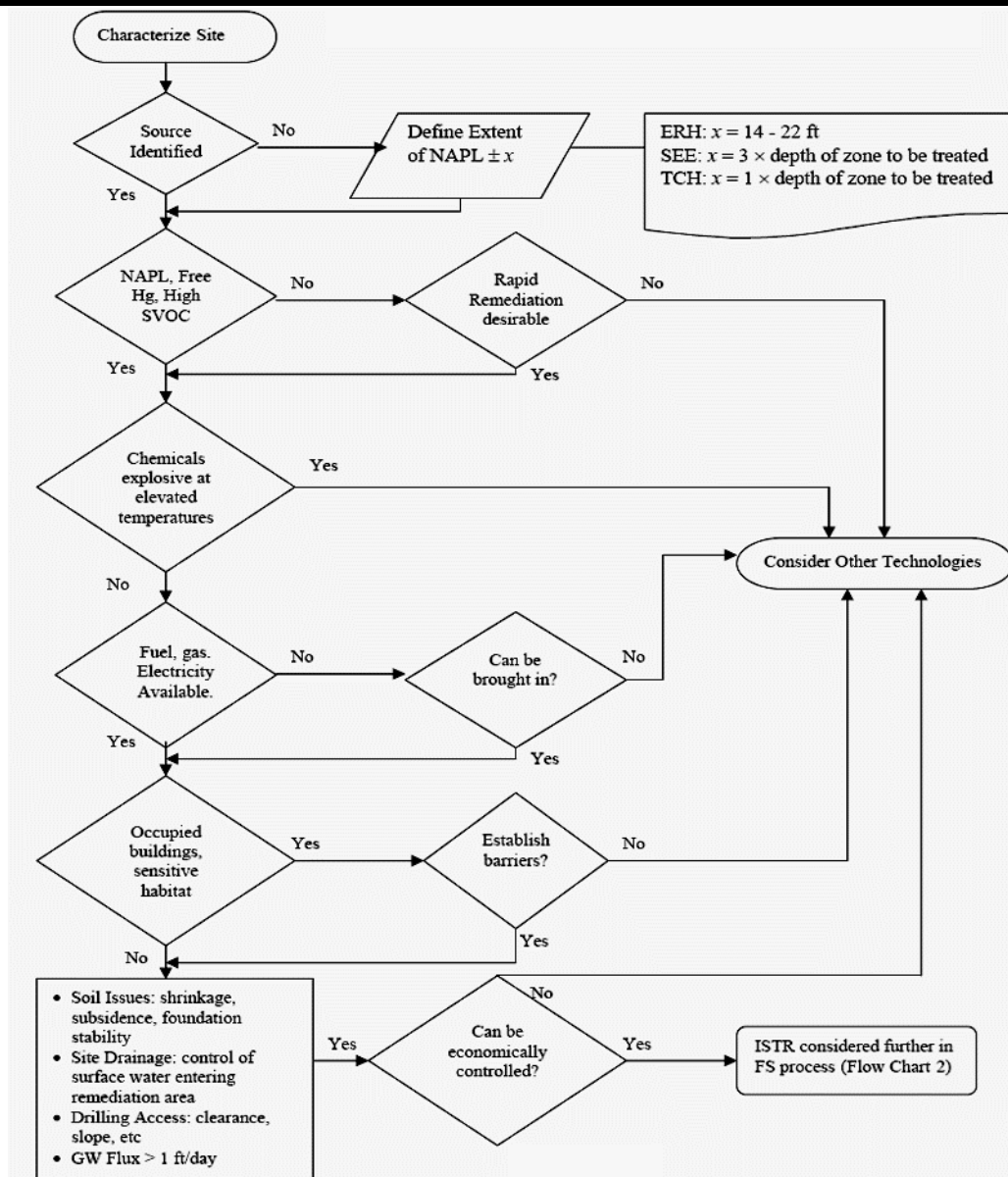


Figure 4-1. Evaluation of site characteristics

c. Thermal conductance and ERH methods heat the subsurface relatively evenly. However, steam injections are susceptible to the steam following zones of higher hydraulic conductivity. Unfortunately, contaminants in soil can migrate by diffusion into very tight layers from which they require very long times for removal again by diffusion. In highly anisotropic conditions (braided stream deposits and fractured bedrock), injected steam is susceptible to following paths of least resistance and may not heat the

desired zone. Depending on the degree of anisotropy present, zones where steam is not conveyed are heated by conduction and convection.

d. Depth of treatment is a critical issue. The spacing of heater wells, electrodes, and injection wells is based on what is known as an aspect ratio.

(1) For thermal conduction, the (heater) well spacing should not exceed the thickness of the heated zone (Stegemeier and Vinegar 2001). Well spacing, not the thickness of the heated zone, determines the time required to heat the formation. As such, this is defined as a 1:1 aspect ratio (distance between heater wells, also known as the thickness of the zone to be treated). It should be noted that most applications of TCH have involved heater well spacings of 1.8 m to 2.4 m (6 ft to 8 ft). Depending on the desired goal, the heater well spacing can also exceed the thickness of the zone targeted for treatment. If the objective of TCH is to accomplish in situ steam distillation, rather than to achieve superheated temperatures, aspect ratios of somewhat greater than 1:1 can be utilized.

(2) For ERH, the spacing of the electrodes is based on soil type, applied voltage, and electrical resistance of the soil/groundwater system to be treated. Typical spacing between electrodes is 2.6 m to 6.1 m (8.5 ft to 20 ft). Therefore, at depths greater than this, the ERH aspect ratio is less than 1:1, indicating that significant drilling is required to treat a large, deep area. For steam injections in the vadose zone, aspect ratios ranging from 3:1 to 5:1 have been used. Steam sparging aspect ratios range from 1:1 to 3:1 in the saturated zone.

4–5. Evaluation of short-term impacts of in situ thermal remediation

a. The short-term impacts of remedial action are evaluated in terms of the potential effects on human health and the environment during implementation of the action as well as site issues. The assessment of short-term impacts is primarily based on four key factors.

(1) Potential short-term risks to and protection of the community during implementation of remedial action.

(2) Potential impacts to and protection of workers during remedial action, and the effectiveness and reliability of protective measures.

(3) Potential environmental impacts of the remedial action and the effectiveness and reliability of mitigation measures during implementation.

(4) Impact on soils and foundations.

b. As with other remediation technologies, ISTR presents the potential for exposure of nearby communities to site contaminants via fugitive emissions of vapors, incomplete hydraulic control and capture of contaminated groundwater and vapors, and on- and off-site management of process waste generated by the action.

(1) Short-term risks also include dust generated during construction and noise from equipment operation and drilling. During implementation, access restrictions and engineering controls can be used to protect the public from construction and O&M-related activities at the site.

(2) During active thermal heating and cool-down, engineering controls are necessary to control potential exposure routes to the surrounding community. The controls may include groundwater and vapor extraction; on-site physical and chemical treatment of vapor, water, and air waste streams; and off-site treatment and disposal of process wastes at permitted disposal facilities.

c. Extensive performance monitoring requirements, including well-field measurement of temperature, pressure, and steam distribution; rates and effectiveness of contaminant removal; and treatment plant discharges to the air and groundwater, are important elements of the remedy. Specific monitoring activities to promote protection of the surrounding community could include monitoring of fugitive and stack emissions (treatment units and boilers), dust and opacity, noise, and groundwater.

d. Short-term impacts on workers associated with ISTR include potential exposures to construction-related risks (ranging from the risks of working around mobile equipment to trips, slips, and falls), potential worker exposure to NAPL and dissolved-phase contaminants, unique physical hazards (high temperatures and high-voltage electricity) during installation and O&M of the remedy, and fugitive air emissions. These risks and the protective measures to address them are discussed in paragraph 10–2.

e. Potential ISTR short-term impacts on the environmental receptors identified at a site are primarily fugitive emissions from treatment operations and the direct thermal effects of actively heating soil. Other potential environmental impacts are associated with construction activities, such as noise, traffic, and dust. Mitigation measures include engineering controls like those used for community protection. Sites located near surface water bodies present special concerns in terms of potential impacts and mitigation measures. Different statutory requirements exist for conducting ecological assessments at a site. Remedial actions are required to substantively comply with laws that limit or prohibit impacts on natural resources. The appropriate Office of Counsel must be consulted to determine what limitations state and federal environmental laws may place on the remedial action.

f. TCH and ERH can reduce soil moisture content. This could have the potential for soil shrinkage in expansive clays, potentially impacting foundations. Data evaluations to date have shown that under ERH applications, moisture content is reduced by approximately 50 percent in the vicinity of the water table in clay soils. Moisture content above the water table remains relatively consistent owing to the continued steaming from below during treatment. The thickness of the zone experiencing reductions in moisture content is believed to be a factor of the duration of heating and the hydraulic conductivity of the soils.

Chapter 5

Bench- and Pilot-Scale Studies

5-1. Introduction and considerations in determining testing approaches

a. The goals of a bench or pilot study typically include feasibility demonstration and evaluating and potentially optimizing process design.

b. It is therefore important to define the need for bench- or pilot-scale testing and the goals that are to be achieved. Bench-scale testing assesses the treatability of a particular compound or suite of compounds and defines potential chemical reactions (adverse or desired) when heating occurs. Pilot testing typically confirms design parameters in situations where uncertainty exists about treatment of COCs or process performance under site-specific conditions. For large and complex sites, the use of bench- or pilot-scale testing can supplement the modeling and assist the engineer or scientist in determining if ISTR is an appropriate means to remediate a site.

c. Bench-scale tests usually consist of column studies. Column tests gauge the effectiveness of the ISTR technology on specific contaminants existing at the site. ISTR has been demonstrated to be effective for most VOCs. However, if the chemicals of concern are not VOCs, or there is a mixture of chemicals of concern, column studies should be performed to evaluate the feasibility of ISTR technologies. Column studies refer to packing a column with site soil and site contaminants, applying a representative ISTR technology, and measuring effluent concentrations as a function of time. The test results usually cannot be directly scaled up to the full-scale ISTR system unless the site lithology consists of homogeneous isotropic soils.

d. Since pilot testing is expensive, it can be justified if uncertainties arise that are critical to the success of the project and can be answered by the pilot. Therefore, the pilot must be carefully designed to obtain critical data and not simply to satisfy curiosity.

(1) Pilot-scale tests are conducted at the site, the location of which is determined by the goals of the pilot test and site-specific constraints. The pilot should be of sufficient size to encompass a significant portion of the site variability, or the results from the pilot test may not be applicable to the rest of the site.

(2) A pilot test is usually designed so that the pilot test system can be incorporated into the full-scale system should a full-scale application of the ISTR be merited. This phased approach can significantly speed the overall remediation process. The size of the equipment installed for the pilot test should be carefully considered if such a phased approach is to be used so that, if the test is successful, the rest of the remediation can be conducted cost-effectively.

e. A pilot test should achieve the following goals listed here.

(1) *Mass removal.* A pilot test may be used to demonstrate that the ISTR technology can remove contaminant mass at sufficient rates and has the potential to achieve the remedial goals. It should be kept in mind that the most readily extracted

fraction of the contaminant mass is removed by advection no matter what ISTR technology is chosen for the pilot test. The removal rate is expected to decline sharply after a period when diffusion-limited mass transfer ensues (except in the case of TCH). When designing the pilot test, the test should be long enough to accurately capture the long-term contaminant removal rate.

(2) *Radius of influence.* The radius of influence of each steam injection well, ERH electrode, or thermal conduction well can be calculated theoretically. However, a pilot test should be designed to provide the vadose and saturated zone responses to the application of heating. The well-field layout in the full-scale system can be adjusted accordingly.

(3) *Subsurface characteristics.* A pilot test can provide information on the nature and variability of site-specific subsurface parameters, such as soil permeability, hydraulic conductivity, soil moisture retention, and contaminant distribution.

(4) *Design parameters.* A pilot test provides valuable information on the design parameters, such as the size of the equipment and treatment system for the full-scale application. ISTR pilot tests may be designed to meet the remedial goal at a small area of the site; for this situation, it is relatively simple to scale up the system to remediate the site. The size of the treatment system can be adjusted if inadequacies are discovered during the pilot test.

(5) *Cost estimates.* Costs for full-scale system implementation and operation can be concluded from the pilot test. Some adjustments may need to be made if the well spacing is found to be inefficient or if the treatment system size must be scaled up.

f. Performing a pilot test in a sub-area of the main portion of the plume risks impacts from influx of contamination from surrounding areas during and following treatment. This complicates the interpretation of mass removal rates and the achievable contaminant concentrations. Several published reports on pilot testing of ISTR methods have noted these complications. Also, adjustments made to the pattern of the injection and extraction wells or electrodes to carve out a small section for the pilot may limit the ability of the system to heat the entire area or may cause the spread of contaminants.

g. A pilot test work plan should be prepared before conducting pilot- or bench-scale tests. The work plan is crucial for specifying test objectives, the range of operation conditions, and parameters to be monitored, including the location, methods, and frequency of measurements to be taken. A site safety and health plan is also required to ensure the safety of all on-site workers. A schedule showing critical tasks and the various phases of the work should be included. A materials list for necessary equipment and supplies should be prepared. Consult the appropriate Office of Counsel to determine if permits should be obtained for the pilot system installation and discharge streams.

5–2. Thermal conductive heating

a. *Bench-scale studies.* Two general types of bench-scale thermal conduction studies include feasibility demonstration and process design evaluation.

(1) *Feasibility demonstration.* The principal focus of the feasibility demonstration is to confirm that the soil becomes decontaminated by TCH and to determine the extent of remediation as a function of temperature and, to a lesser extent, the duration of heating.

(a) Bench-scale feasibility may be demonstrated by placing a soil sample in a cylindrical metal tube and passing air through the sample while heating the assembly within a muffle furnace. A thermocouple inserted into the soil sample monitors that the soil is heated to the target temperature and then maintained at that temperature for the requisite amount of time (48 to 72 hours), while minimizing thermal overshoot.

(b) A typical objective is to demonstrate the extent of removal of COCs as a function of target temperatures; therefore, temperatures are selected to cover the range of interest based on the properties of the COCs. For example, 200 °C (392 °F), 250 °C (482 °F), and 300 °C (572 °F) were selected to test soil contaminated with explosive compounds such as hexahydro-1,3,5-trinitro-1,3,5-triazine, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazine, 2,4,6-trinitrotoluene, nitroglycerin, and isomers of 2,4-dinitrotoluene and 2,6-dinitrotoluene. As the compounds being tested were SVOCs, the soil undergoing testing was homogenized prior to subsamples for thermal testing being collected. Analysis of pre- versus post-treatment samples enabled assessment of the degree of contaminant removal as a function of temperature and treatment time (Baker et al. 2001).

(2) *Process design evaluation.*

(a) The principal focus of the process design evaluation is to design and optimize a cost-effective remediation program. The total remediation program consists of the in situ heating requirements, plus the AQC system for the control of well field emissions. In addition to the fundamental demonstration of the decontamination of the soil, additional issues that are addressed during a process-design evaluation program are listed below.

1. What contaminants are desorbed from the soil (as opposed to being destroyed in situ), and at what characteristic temperatures?
2. If there are chlorinated organics present in the soil, does the chlorine exit the soil matrix as a chlorinated hydrocarbon or as HCl vapor? To what extent is the gaseous HCl neutralized by the soil's buffering capacity?
3. For the contaminants desorbed from the soil matrix, can the emissions be adsorbed on activated carbon, or is a thermal oxidizer or acid gas scrubber required to reduce the emission levels to below air discharge limits?

4. For the contaminants desorbed from the soil matrix, do the hydrocarbons desorb in a way such that char (for example, coke) formation in the vacuum extraction wells is a concern? Also, should supplemental precautions, like air bleeds, be provided to clean the extraction wells in cases of excessive char deposition?

(b) In general, the cost of the process design evaluation is greater than a feasibility demonstration, with the principal differences being the additional analytical work and the time required to do two sequential studies. The only circumstance where a feasibility demonstration should be done before the process design evaluation is where the issue of achievement of treatment objectives or the appropriateness of TCH for a given COC is in question. PCBs and dioxins fall within the former category (contaminants whose treatability with TCH has been well established), and new applications of TCH, such as mercury removal, are an example of the latter.

(c) To gain insight into the process design issues, several modifications to the standard feasibility demonstration apparatus and testing procedures are instituted.

1. A custom test chamber is utilized with uniform heating and multiple temperature measurements in the soil sample.

2. The purge-gas flow rate through the test chamber is controlled at a much lower flow rate.

3. Off-gases pass through a gas cleanup train consisting of a condenser and activated carbon traps. Additional filtering through a packed bed scrubber is used when the COCs include significant concentrations of chlorinated hydrocarbons.

4. Off-gases are monitored for total hydrocarbon (THC) level, either by use of a flame ionization detector or a combustible gas detector.

5. Air sampling and impinger tubes may also be used to examine the loading of a specific COC or its vapor-phase concentration.

6. The test chamber temperatures are charted to detect short-term transients, in addition to data-logged temperature data.

(d) The data produced during the process design evaluation is analyzed using procedures appropriate for the COCs in the soil matrix. Further, this data is also used to select and design the AQC equipment. As such, each process-design evaluation effort and analytical plan is configured for the site-specific requirements of the individual remediation application.

(e) Data produced during feasibility demonstrations or process design evaluations can provide valuable input parameters for simulation modeling during design.

b. Pilot-scale studies. Thermal conduction pilot tests have been performed at several sites, including the Missouri Electric Works (MEW) Superfund site in Cape Girardeau, Missouri (Vinegar et al. 1997), and the Bay Area Defense Conversion Action

Team demonstration at the former Mare Island Naval Shipyard in Vallejo, California. The following paragraphs describe a recommended approach.

(1) *Thermal wells.* Figure 5–1 depicts a typical pilot test in which 13 thermal wells (12 heater-only wells and a central heater-vacuum well) are installed in a triangular array at a spacing of 1.83 m (6 ft). A wider interwell spacing, such as 2.13 m (7 ft), may be necessary at full scale, but a narrower spacing can save time during the pilot test, with the results being easily scalable to other spacing following the Inverse Square Law. Suitable electrical distribution equipment is required to power the thermal wells.

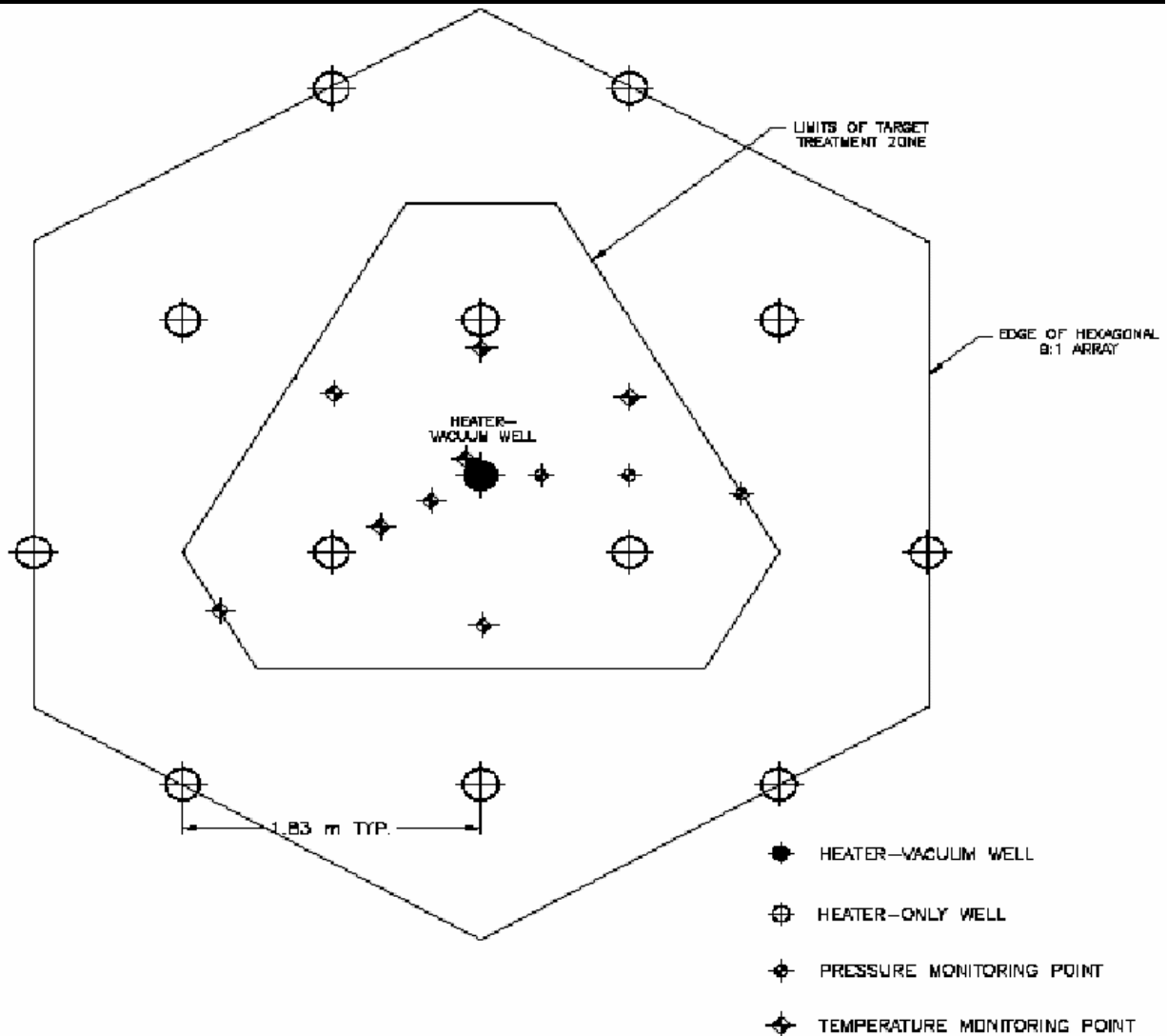


Figure 5–1. Thermal conduction pilot-test layout

(2) *Monitoring points.* Several thermocouple arrays (allowing measurement of temperature at various depths) and several discrete soil gas pressure monitoring points (PMPs) are installed to enable tracking of subsurface temperature and pressure gradients between the thermal wells. Figure 5–1 and Figure 5–2 illustrate typical locations of monitoring points relative to the positions of the thermal wells.

(3) *Surface cover.* A surface cover is typically placed over the pilot test area to serve as a vapor barrier, reduce heat loss, and seal out rainfall (Figure 5–2).

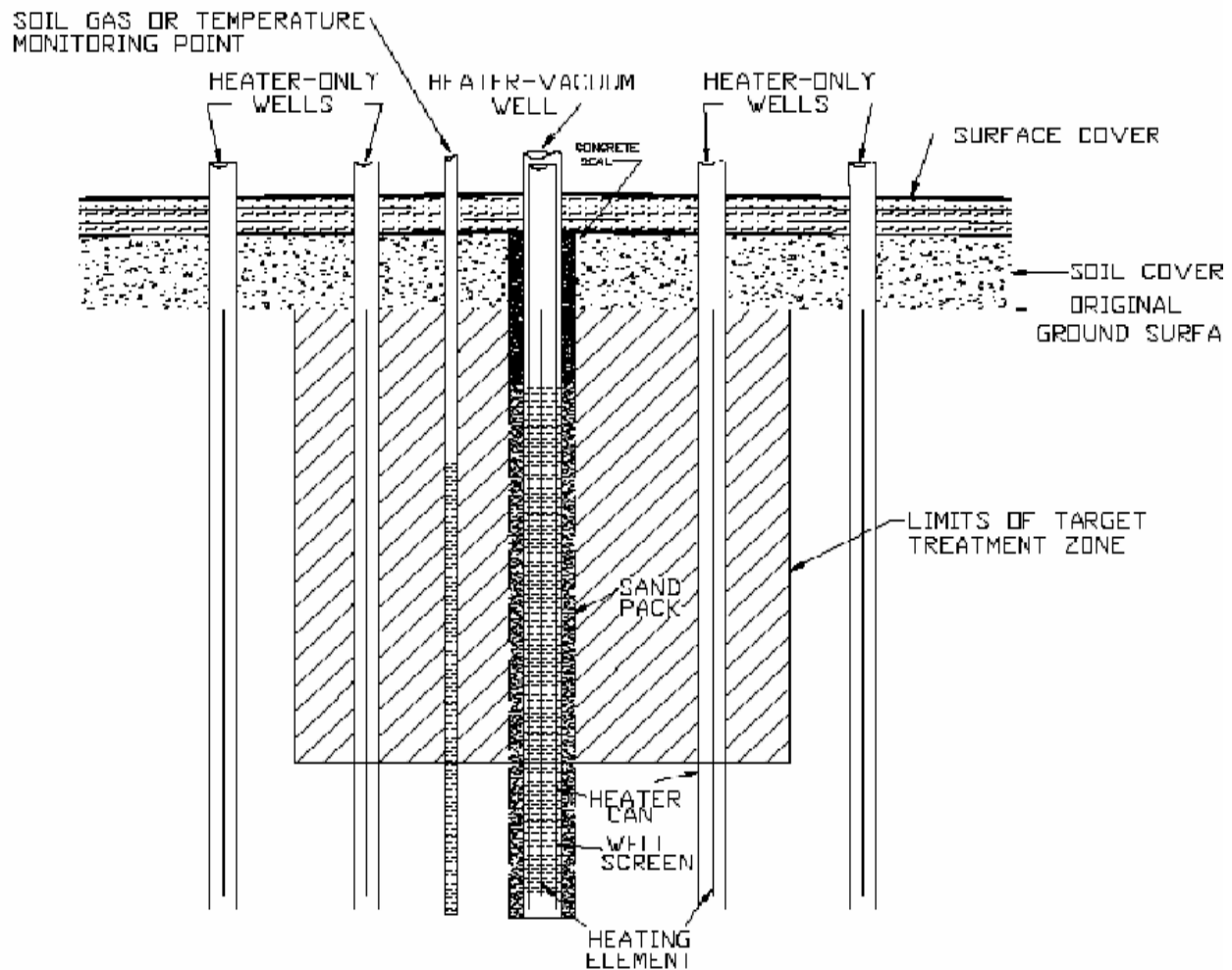


Figure 5–2. Thermal conduction pilot-test cross section

(4) *Air quality control system.* The central heater-vacuum well is connected to a vacuum extraction manifold leading to an AQC system. Depending on the COCs, examples of AQC systems are thermal oxidizers, heat exchangers, scrubbers, carbon beds, or only a carbon bed. A blower, discharge stack, and air monitoring equipment are also provided. A condenser (not depicted in Figure 5–3) is typically used in these systems.

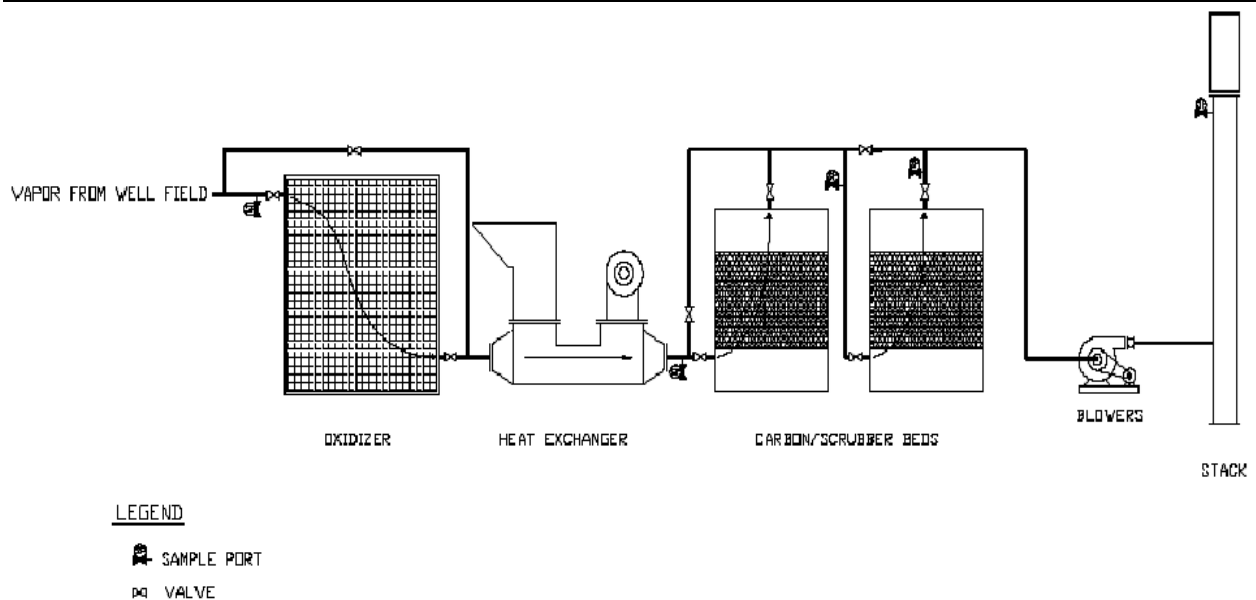


Figure 5-3. Thermal conduction pilot-test process diagram

(5) *Operation.* With the AQC system on, the thermal wells are energized, typically for a period of one to two months, as is needed to achieve target temperatures in the interwell locations within the TTZ, depicted in Figure 5-1 and Figure 5-2. Air emissions are monitored to verify compliance with standards and to evaluate performance.

(6) *Soil sampling.* Direct-push methods (hand or power augering, Geo-Probe®) are used to sample soil prior to and following treatment at representative locations within and near the TTZ. Since soil treated by ISTD tend to take weeks or months to fully cool, post-treatment sampling of hot soils is often recommended. Since the core samples are taken from a hot environment and may be kept in closed barrels that can be cooled far below their original temperature, it is unlikely that significant volatile compounds are lost from even warm cores. One method involves collecting the samples in metal liners, immediately capping them on retrieval, and cooling them with ice to ambient temperatures (Gaberell et al. 2002). Once cooled, the liners are opened and subsampled for laboratory analysis of all applicable COCs.

c. Other considerations. Other items that are commonly examined during field-scale pilot (depending on site) include the following.

- (1) Groundwater infiltration/control adequacy/appropriateness.
- (2) Subsidence.
- (3) Rate and nature of hydrocarbon off-gassing.
- (4) Water production rate.
- (5) Coking.

- (6) Site-specific thermal conductivity.

5–3. Electrical resistivity heating

a. Bench-scale studies.

(1) Bench tests are usually not done prior to ERH projects. Removal of VOCs through steam distillation is a physical process that is relatively well understood in comparison to the removal processes of most other remediation techniques. However, an ERH bench test may be warranted under the following circumstances.

(a) The treatment region consists of landfill debris or other non-soil material.

(b) The treatment region includes peat layers or buried wood debris (the effects of extremely high TOC levels are not well known at present).

(c) The target VOC is dissolved into a greater mass of oil or other low-volatility hydrocarbon (Raoult's Law effects are difficult to predict).

(d) For determining attainable concentrations, where significant groundwater flow exists, or to evaluate materials of construction (to determine corrosion potential).

(2) For best results, bench testing should be performed in triplicate. An ERH bench test usually includes the following steps.

(a) Pretest aliquots of soil are analyzed.

(b) Soil is packed into a small, sealed reactor vessel and heated, usually by placing the reactor in a muffle furnace (for the purpose of bench testing, the method of heating is not important).

(c) As the soil is heated, a very small amount of air is injected into the reactor as a carrier gas, and off-gas from the reactor is condensed.

(d) When a target condensate production is reached (typically 10 to 15 volume percent of the soil sample), heating is terminated, and the reactor is cooled to 4 °C (39 °F), and a post-test soil sample is analyzed.

b. Pilot tests. Pilot tests may be conducted using either three- or six-phase modes of heating. Typically, pilot tests have been conducted to demonstrate feasibility rather than evaluate a process design or optimization. This is because the process design is relatively straightforward using ERH. Pilot testing typically involves installing a six-phase array of electrodes to heat a selected portion of the impacted area to be treated. The major difference between a pilot- and full-scale application is the number of arrays and, hence, the capacity of the PCU and ancillary treatment equipment.

5–4. Steam enhanced extraction

Laboratory treatability studies for steam injections should be done when the contaminants are semi-volatile and, thus, some question exists about the amount of steam or energy that might be needed to achieve the desired residual concentrations of contaminants in the soil or to estimate the likely residual concentrations for a given number of steam injection pore volumes. When there is a mixture of contaminants present, it may also be beneficial to determine the physical properties of the NAPLs as a function of temperature. Brief descriptions of the laboratory experiments follow.

a. Physical properties. Density can be measured as a function of temperature using a method like ASTM D1217-20, with a water bath to control the temperature of the sample in the range from ambient temperatures to near steam temperatures. This data can be used to determine if DNAPLs, such as creosote or coal tar, become LNAPLs as the temperature increases. Since chlorinated solvents remain denser than water at temperatures below their boiling point, this testing is of less use for chlorinated NAPLs.

(1) Viscosity can be measured by a method like ASTM D1296, using a jacketed beaker to maintain the sample at the desired temperature and allowing measurements to be made ranging from ambient to steam temperatures. These data demonstrate the increased mobility of the liquid as the temperature increases. Generally, contaminants such as creosote or coal tar, which have relatively high viscosities at ambient temperatures, show significant increases in mobility as the temperature increases.

(2) Chlorinated solvents generally have relatively low viscosities at ambient temperatures, and the increased mobility with temperature is not as great. Surface and interfacial tension measurements can also be made using ASTM D971 and jacketed beakers to maintain the samples at the desired temperature. Decreases in surface and interfacial tension with temperature may reduce residual liquid saturations and allow more of the contaminants to be collected as a liquid, and, therefore, more of the high boiling point contaminants may be recovered.

b. Steam injection experiments. The laboratory setup for a one-dimensional steam injection experiment is shown in Figure 5–4.

(1) Metering pumps are used to deliver a set flow rate (50 to 100 mL•hour⁻¹ for the size soil sample used here) of water to the steam generator. The power input to the steam generator was set to produce steam at a temperature of 150 °C (302 °F). Steam is injected into the top of the soil column to produce a vertical downward flow through the column. Galvanized steel columns, approximately 5 cm (2 in.) in diameter and 15 cm (6 in.) long, that are threaded on both ends and for which endcaps can be purchased, are convenient for these experiments.

(a) Clean sand should be placed in the bottom endpiece of the column to facilitate collection of the effluent steam and recovered contaminants, and the column itself is then filled with approximately 600 g to 700 g (1.3 lb to 1.5 lb) of contaminated soil from the site. Soil from the most contaminated areas of the site should be used. The top

endpiece of the column is not packed with soil to help distribute steam evenly to the top of the soil.

(b) Thermocouples can be used at the effluent of the steam generator, at the top of the column, at the midpoint of the column, and in the effluent line. The column is wrapped with heater tape and then covered with insulation to ensure that the entire column remains at steam temperatures. Rubber-coated heater tape, 2.5 cm (1 in.) wide and 1.22 m (4 ft) long, has been used to wrap the column. The heater tape is plugged into a variable autotransformer to control the heat input to the column.

(2) Column effluent goes through a heat exchanger before being collected in a sample bottle immersed in an ice bath. For most cases, two to four pore volumes of steam are adequate to recover most of the contaminants.

(a) Effluent sample containers should be changed to approximately every half pore volume so that approximately how rapidly the contaminants are recovered as a function of the pore volumes of steam injected can be determined. However, when determining the sample size, the size needed for the chemical analysis to be performed should be considered. For some semi-volatile contaminants that are present in the initial soil at high concentrations, there may be the potential for them to condense and plug the effluent line.

(b) Care should be taken to monitor the sample collection and the pressure in the column to determine if this is happening. If volatile contaminants are being recovered, collection of the effluent vapors may be improved by using a solvent, such as dichloromethane or methanol, in the sample collection bottle to trap the vapors.

(3) During the steam injection, it is important to monitor the amount of steam injected versus the amount of effluent collected. As a steam front is established in the column, it displaces in front of it the liquids that were initially present in the soil pores. Thus, the mass of effluent collected is greater than the mass of water injected as steam owing to the significantly greater volume of steam versus that of water.

(a) If the soil was packed wet and the mass of effluent collected is not greater than the mass of water injected during the early stages of the steam injection, then a steam front has not been established in the column, and a hot water flood is taking place. Temperature in the column should also be monitored to indicate whether the experiment is a steam flood or a hot water flood. A temperature plateau at 100 °C (212 °F) indicates that evaporation is occurring in the column and thus a steam front is present and expanding.

(b) Once the water within the column has evaporated, the temperature may increase owing to heat input from the heater tape. In some cases, the temperature may be above 100 °C (212 °F), but pressure within the column can cause condensation of the steam and thus a hot water flood. For most types of contaminants, a steam flood is going to recover significantly more of the contaminants than a hot water flood. Thus, it

is important to ensure that a steam front is formed in the column to get a valid laboratory test of SEE technology.

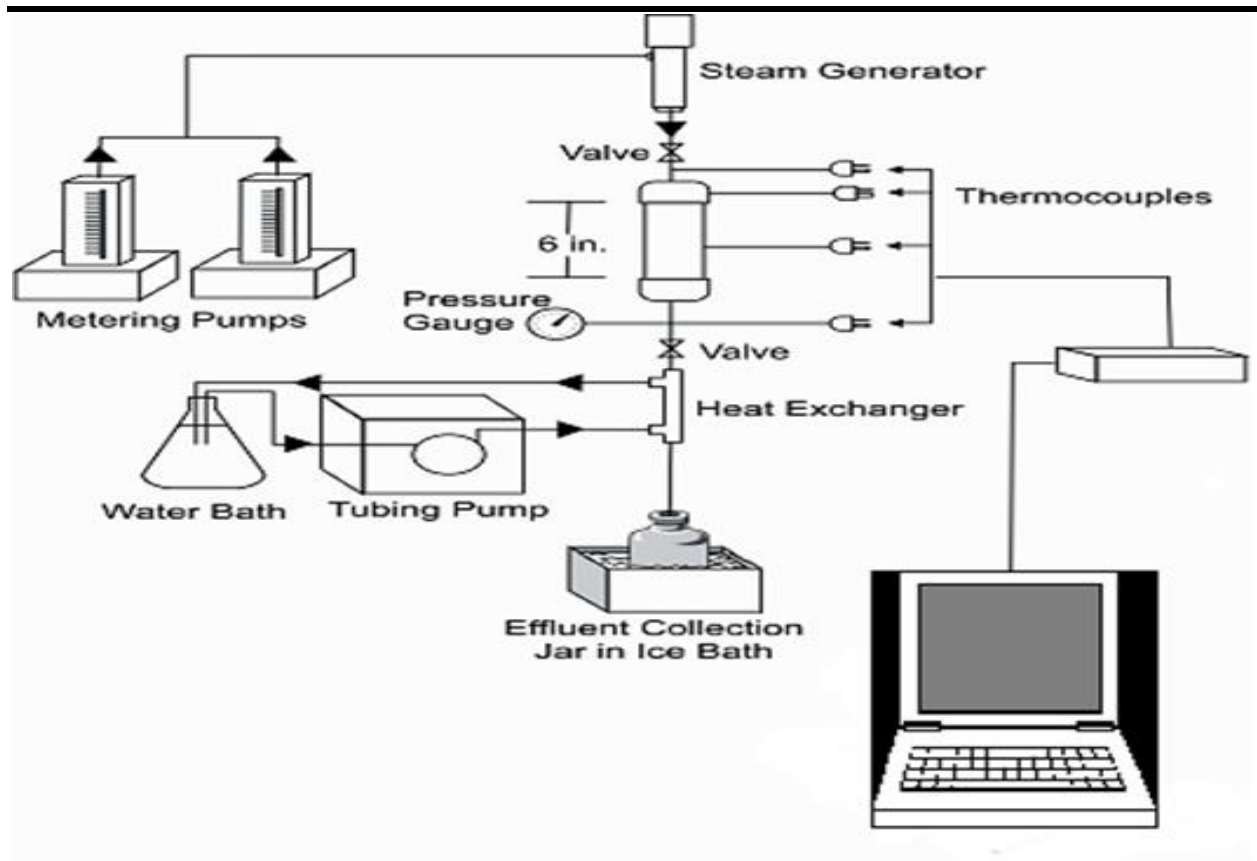


Figure 5-4. Laboratory setup for one-dimensional steam injection experiments

(4) After a steam front has been established throughout the column, pressure cycling can be used to increase contaminant recovery rates as a vapor. This is done by closing a valve on the effluent line of the column (while steam injection continues), allowing pressure to build up in the column. The pressure should be monitored by a pressure gauge in the effluent line above the valve. After about 70 to 100 kilopascals (10 to 15 pounds per square inch) of pressure has built up in the column, the valve is opened, and the pressure dissipates. This process mimics pressure cycling that can be done in the field during steam injection to increase the rate of volatile contaminant recovery.

(5) After completion of the steam injection, the column should be taken apart and the soil divided into two or three samples (for example, top, middle, and bottom of the column) for analysis. A sample of the initial soil should also be analyzed.

(6) It may be desirable to know the groundwater concentrations of contaminants in equilibrium with the residual contaminants adsorbed onto the soil after a steam injection. If so, water can be added to the column after the steam injection is complete and allowed to equilibrate with the steamed soil for a period. In the past, 24-hour

contact periods have been used; however, that time may not be adequate for full equilibrium between the adsorbed contaminants and the water. For comparison, an initial leachate sample should also be obtained before steam injection is started. After the equilibration period, the water is drained from the column and analyzed separately.

c. Pilot tests.

(1) For SEE, pilot tests may be carried out for these reasons.

(a) To confirm design parameters, like well spacing, injection pressures/rates, and pumping rates.

(b) To assess the feasibility of technology with respect to site conditions or contaminants, applications in bedrock where the technology is less proven determine feasibility with high boiling point compounds, soil stability, or stratification issues.

(c) Where there is uncertainty in the operation of the treatment equipment in dealing with the ranges of concentrations that may be encountered.

(2) Most of the considerations regarding the approach to pilot tests discussed are applicable to SEE.

Chapter 6 Design Considerations

6–1. Introduction and overall design strategy

a. Once the overall remediation strategy is defined (Chapter 4), the area to be treated is defined, and subsurface extent is established, the design process can begin. What must be kept in mind is that the application of these ISTR techniques is modular in nature.

(1) Thermal conduction is applied using a central vacuum well surrounded by heater wells, and the pattern is repeated to cover the area to be treated. The spacing is determined by the rate of heat input versus heat losses, the target temperature, the desired duration of treatment, and, to a lesser extent, by the thickness of soil to be treated.

(2) ERH, whether applied in six- or three-phase approaches, involves a regular pattern of electrodes, hexagonal arrangements for six-phase and triangular for three-phase. The spacing of the electrodes is dictated in large part by the effective diameter of the individual electrodes. The diameter of the electrode array for six-phase heating is typically 5.2 m to 12.2 m (17 ft to 40 ft), and the distance between electrodes is typically 2.6 m to 6.1 m (8.5 ft to 20 ft) for three-phase heating. Heat loss is an input parameter for determining treatment time but does not influence electrode spacing.

(3) Steam is applied in either a five-spot (four injection wells surrounding a central groundwater recovery well) or a seven-spot (six injection wells surrounding a central groundwater recovery well) pattern. The patterns are repeated, if necessary, to treat the area. The spacing of wells is determined by both vertical and horizontal hydraulic conductivity, time desired for heating, and depth and thickness of the zone to be treated. Heat loss is not typically factored into the design.

b. The following paragraphs discuss the factors to consider in designing remediation systems using individual technologies. Consider the requirements in ER 1110-1-8155, ER 1110-345-700, and ER 1180-1-9.

6–2. Thermal conductive heating

As with other thermal remediation technologies, the design of a thermal conduction remediation system, whether for an in situ application (such as ISTD) or an ex situ application (soil pile, in-pile thermal destruction), requires consideration of several site- and contaminant-specific factors. These include, but are not limited to, the target soil-treatment temperature and desired remediation time; heater and extraction-well components; energy and power delivery and distribution; vapor collection/conveyance system configuration; AQC system; and other regulatory requirements. These design considerations are discussed in the following paragraphs.

a. *Example calculation.* The energy balance for raising the subsurface temperature to the boiling point of water and boiling off all the pore water initially present (to thoroughly treat SVOCs) is found in Equation 6–1 (TerraTherm and Weston 1997).

$$\left[\rho_R C_R (1 - \phi) + \rho_w C_w \phi S_w \right] (T_b - T_i) + \rho_w h_w \phi S_w = \frac{\beta t_b}{A} \quad \text{Equation 6–1}$$

where (values to electrically heat a typical silica sandy soil):

$\rho_R = 2.650 \times 10^6 \text{ g}\cdot\text{m}^{-3}$ (density of quartz grains)

$C_R = 1.211 \times 10^{-5} \text{ W}\cdot\text{day}\cdot\text{g}^{-1}\cdot\text{°C}$ (heat capacity of silica)

$\phi = 0.35$ (typical porosity value for sandy soil)

$\rho_w = 1.00 \times 10^6 \text{ g}\cdot\text{m}^{-3}$ (density of water)

$C_w = 4.846 \times 10^{-5} \text{ W}\cdot\text{day}\cdot\text{g}^{-1}\cdot\text{°C}$ (heat capacity of water)

$S_w = 0.6$ (typical water saturation [fraction of the pore space occupied by liquid water] as estimated from descriptions of moisture content in soil boring logs, ranging from dry to moist above the water table)

$T_b = 100 \text{ °C}$ (boiling point of water at atmospheric pressure)

$T_i = 13 \text{ °C}$ (typical initial temperature value for near-surface soil)

$h_w = 0.0261 \text{ W}\cdot\text{day}\cdot\text{g}^{-1}$ (latent heat of vaporization of water at atmospheric pressure)

$\beta = 984.2 \text{ W}\cdot\text{m}^{-1}$ (average power input per unit length of thermal conduction well)

$t_b =$ time (days) required to heat and boil off all the initial water

$A = (2.13 \text{ m})(2.13 \text{ m})(\sin 60^\circ) = 3.942 \text{ square meters (m}^2\text{)}$ (area heated by each well set within an equilateral triangular pattern of wells spaced 2.13 m or 7 ft apart)

(1) The first term on the left is the energy required to heat the mineral grains, the middle term is the energy required to heat the water, and the third term is the energy required to vaporize the water. The right-hand side of the equation is the energy supplied by a heating well into the soil volume surrounding it. Note that ϕ , S_w , T_i , β , and A are typically user-specified input values, while the remaining terms are constant, except for t_b (to be solved for).

(a) This equation does not account for conductive heat losses to the adjacent formation and overlying surface or for convective heat losses through collected gas and water that originate from outside the treated volume.

(b) Rearranging Equation 6–1 to solve for t_b can be seen here in Equation 6–2.

$$t_b = \frac{A \left\{ \left[\rho_R C_R (1 - \phi) + \rho_w C_w \phi S_w \right] (T_b - T_i) + \rho_w h_w \phi S_w \right\}}{\beta} \quad \text{Equation 6–2}$$

(c) For the values given above, the time t_b required to heat the soil and boil off all the water initially present is approximately 33 days. From the result of Equation 6–2, it is seen that over the thermal treatment period, the amount of electrical power that each thermal well consumes is $t_b \beta = 780 \text{ kW/hr} \cdot \text{m}^{-1}$ ($238 \text{ kW/hr} \cdot \text{ft}^{-1}$) of heater length. Dividing by the treatment volume, $t_b \beta / A = \sim 200 \text{ kW/hr} \cdot \text{m}^{-3}$ treated, which at \$0.075 per kilowatt per hour is about \$11/cubic yard (yd^3) of electrical cost.

(2) The impact of water recharge is more complicated and requires numerical simulation to adequately address. There can still be water recharged above the water table during remediation from rain falling directly on the site or seeping in from the subsurface around the lateral boundaries, and to a lesser extent from capillary rise if the treatment zone is within the capillary fringe zone. Below the water table, sand or gravel layers that are laterally contiguous to the targeted interval, or utility trenches, especially, offer possible pathways for subsurface recharge. The capability of thermal conduction heaters to tolerate recharge of groundwater at a given site can be estimated by comparing the rate of energy injection per volume of treatment zone to the energy required to heat soil grains and water within that volume to the treatment temperature.

(3) As a first approximation, the flux of water Q_w in $\text{L} \cdot \text{day}^{-1}$ that can be heated and boiled off by a row of n thermal wells with submerged heaters b meters deep may be estimated in Equation 6–3 (preserving the units given above).

$$Q_w = \frac{(\beta b n)}{\left[\rho_w C_w (T_b - T_i) + \rho_w h_w \right] (1 \text{m}^3 / 1000)} \quad \text{Equation 6–3}$$

(4) Thus, continuing the example, a row of 10 thermal wells, the heaters that are initially submerged 4 m (13.1 ft) deep, has the capacity to heat and boil off approximately $1,300 \text{ L} \cdot \text{day}^{-1}$, or 0.24 gallons per minute (gpm). Equation 6–3 does not account for the potential of the generated steam to exert a pressure around each thermal well. This pressure diminishes or even opposes the pre-existing hydraulic

gradient, and that may therefore prevent the influx of outside water into the heated zone.

(5) Treatment of VOC-contaminated soil and waste located above the water table (in the vadose zone) by conductive heating may be considered a form of thermally enhanced SVE. As such, the requisite data needs are addressed in large part in other guidance. With the addition of in situ heating, however, permeability becomes much less of an issue than with SVE that is not thermally enhanced. Heating soil to raise the formation temperature a modest amount may substantially increase VOC removal rates, as a 10 °C (50 °F) temperature increase results in approximately a three- to four-fold increase in vapor pressure, resulting in greater VOC mass transfer to the vapor phase for removal by the SVE system. Heating of low-permeability or nearly saturated soil to the boiling point of water creates in situ steam generation, whereby VOCs can be effectively steam-stripped out of the soil.

(6) In the case of NAPLs forming azeotropes with water, steam distillation can be accomplished at a compound's eutectic point. For TCE in water, this eutectic point is 73.1 °C (163.58 °F) versus the boiling point of TCE at 87.1 °C (188.78 °F). Therefore, the water need not be entirely boiled off to accomplish effective treatment, in contrast to the treatment of SVOCs with higher boiling points. Although steam and organic vapors are readily captured and collected in moderate- to high-permeability soil, vapor extraction in low-permeability or heterogeneous (sandy till) soil is made possible through appropriate placement and spacing of extraction wells and use of surface barriers to prevent fugitive emissions. Even in clay soil that is massive in structure, in situ steam generation opens micro-fractures that enable steam and non-condensable, steam-stripped gases to find their way to nearby heater-vacuum wells.

(7) Soil with higher water content requires more energy to reach boiling than drier soil; therefore, knowledge of water content is needed to estimate the heating energy budget and project duration. Laboratory treatability studies showed that a soil sample heated to a temperature of ≥ 300 °C (≥ 572 °F) for three days was more effectively treated than a sample heated to ≥ 400 °C (≥ 752 °F) for one day, all other things being equal (see Figure 6–1). Thus, it is not necessary to achieve the boiling point of the COCs to achieve their full destruction and removal from the soil.

(8) Achieving a temperature at which the vapor pressure of the highest boiling COC is ≥ 10 mmHg does appear to be appropriate. Reaction kinetics also govern the effectiveness of TCH and vary as a function of temperature (Baker and Kuhlman 2002).

(a) The relationship between vapor pressure of the COCs and temperature (see Figure 2–3) determines whether the COC is amenable to TCH and provides an initial indication of the temperature to which the soil must be heated to afford volatilization of the COC. Figure 2–3 shows that the full range of organic contaminants can be treated by TCH, using thermal wells operating at typical temperatures of 700 °C to 800 °C (1,292 °F to 1,472 °F).

(b) Past research and TCH field experience with high-boiling compounds such as PCBs and PAHs suggest, for example, that higher removal rates for these COCs are achieved after the coolest portions of the soil have achieved the desired temperature (Uzgiris et al. 1995, Hansen et al. 1998).

(9) The presence of neat concentrations of highly halogenated organic liquids may require thermal wells and collection piping to be manufactured of exotic metals such as Hastelloy® (a group of corrosion-resistant alloys based on nickel). These types of NAPL, on heating, tend to hydrolyze or decompose to products such as HCl. Therefore, data regarding the nature and extent of such liquids are necessary to avoid adverse effects on materials and equipment.

b. Subsurface design. Underlying any thermal-conduction soil-remediation design are the contaminants to be remediated and the soil matrix in which they are contained. The site-specific nature of the contaminants, their concentrations, horizontal and vertical distribution, and the soil physical properties determine the design requirements for the other ancillary components, including component sizing, materials of construction, power distribution, and off-gas treatment unit processes. Careful evaluation of soil and contaminant properties is required to confirm that the design achieves the remedial goals in a safe, efficient, timely, and cost-effective manner.

(1) *Target treatment temperature.*

(a) Establishing target temperature. Target treatment temperature is established either through an examination of the contaminant's physical properties (melting point, boiling point, vapor pressure curves, etc.) or based on the outcome of bench or pilot testing. For compounds or classes of compounds that have previously been remediated using TCH, it may not be necessary to conduct site-specific bench or pilot testing, as the results and effectiveness of previous remediation projects may form the basis for selecting the desired target treatment temperature (Baker and Kuhlman 2002).

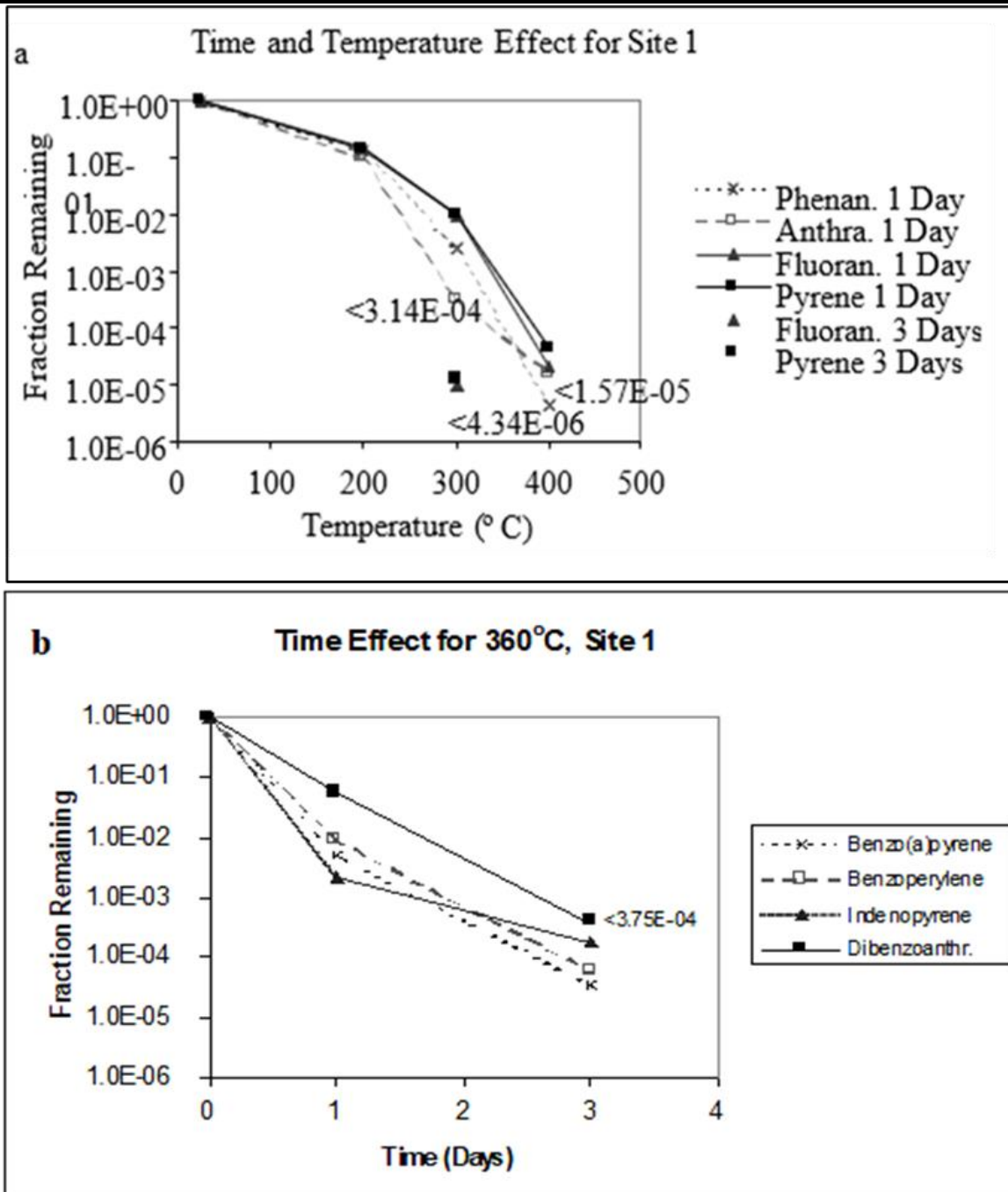


Figure 6-1. Fractions of initial concentrations remaining over time at 300 °C (572 °F) (Hansen et al. 1998). Diagram (a): Phenanthrene, anthracene, fluoranthene, and pyrene remaining as a function of temperature. Diagram (b): benzo(a)pyrene, benzo(g,h,i)perylene, indeno(1,2,3-cd)pyrene, and dibenzo(a,h)anthracene.

(b) Past research and field demonstrations. Stegemeier and Vinegar (2001), Uzgiris et al. (1995), and Hansen et al. (1998) have shown that contaminants can be effectively removed from soil at temperatures considerably below their boiling points.

1. Soil treatment should continue until the centroids of the triangles are formed by the well pattern (the coolest spots) to achieve and maintain the target temperature for a selected time. In practice, it is desirable to hold soils in centroid locations at or above the target treatment temperature for a minimum period of two to three days to verify complete and thorough remediation of the COCs. However, it should be noted that these soils closer to the operating thermal wells are much hotter, typically on the order of 500 °C to 550 °C (~930 °F to 1,020 °F).

2. As contaminants are desorbed from the soil, they travel toward the heater-vacuum wells through increasingly hotter soils over a period of hours or days. It is the extended residence time at these elevated temperatures that provides TCH with such high in situ destruction of contaminants.

(2) *Thermal well spacing and orientation.* Once the target treatment temperature has been selected, it then falls to the designer to determine the appropriate orientation and spacing of thermal wells to achieve the target temperature in an efficient and cost-effective manner. In most cases, a hexagonal heater pattern is used, with six heater wells installed around the perimeter of the hexagon and a single producer (heater-vacuum) well installed at the center of the pattern. Edge-centered heater patterns (heater wells located at the mid-point of the perimeter segments of the hexagon) typically provide better superposition and less heat loss than apex patterns (heater wells located at the points of the hexagon, Figure 6–2).

(a) This edge-centered hexagonal pattern results in a greater 3:1 heater to producer well ratio, as the heaters on the perimeter of the hexagons are each shared by two producers (refer to Figure 6–2 for an example of such a well pattern). Other patterns and ratios are possible and may be used by the designer to optimize the site design or to achieve a specific goal (such as early containment of contaminant vapors).

1. For a given heater power (expressed as $W \cdot m^{-1}$), smaller spacing between the thermal wells results in a shorter remediation period, as there is a higher energy density per unit volume of soil. Increasing the spacing between thermal wells reduces material requirements; however, it also extends the time required to achieve the target treatment temperature at the centroids and increases the amount of heat loss to areas above and below the target zone. Heating duration is proportional to the square of the distance between thermal wells.

2. As such, there is a tradeoff between the cost of capital equipment (well materials, electrical distribution equipment, fume manifold piping, etc.) and operating cost, which the designer should seek to optimize. Other site-specific factors may also enter the selection of appropriate well spacing, including minimizing disturbance to ongoing facility operations, property cleanup or transfer deadlines, or seasonal weather considerations.

(b) Another factor to consider in the layout of the well field may be termed “edge effects.” These “edge effects” include heat losses along the perimeter of the treatment zone or at the top and bottom of the treatment zone, where there is no superposition of

the heat fronts from adjacent wells. To counteract the “edge effects” around the perimeter of the TTZ, the thermal well field typically extends at least 1.5 m (5 ft) laterally beyond the limits of the delineated TTZ. To counteract the heat losses at the top and bottom surfaces of the TTZ, heater elements typically extend at least 0.6 m (2 ft) vertically beyond the limits of the delineated TTZ. In addition, at some sites, the top or bottom of the heater elements may be boosted to deliver more power to upper or lower zones.

(c) To minimize heat losses from the top of the treatment zone, thermal insulation may need to be added in the form of a surface cover (for example, constructed of mineral board insulation or lightweight concrete).

(d) In addition, vapors and air withdrawn from the producer wells for transmission to the off-gas treatment system carry away a portion of the heat energy delivered by the producer wells, reducing their thermal efficiency by approximately 30 percent. Thus, it may be desirable to alter the well pattern to minimize or eliminate producer wells along the well field perimeter. In other cases, where vapor containment along a perimeter is a primary and overriding concern (adjacent to residences), it may be necessary to sacrifice thermal efficiency and have an entire segment of the well field perimeter composed of producer wells. These perimeter heater-vacuum wells can be switched over to function as heater-only wells once vapor capture has been achieved at the edge of the contaminated zone.

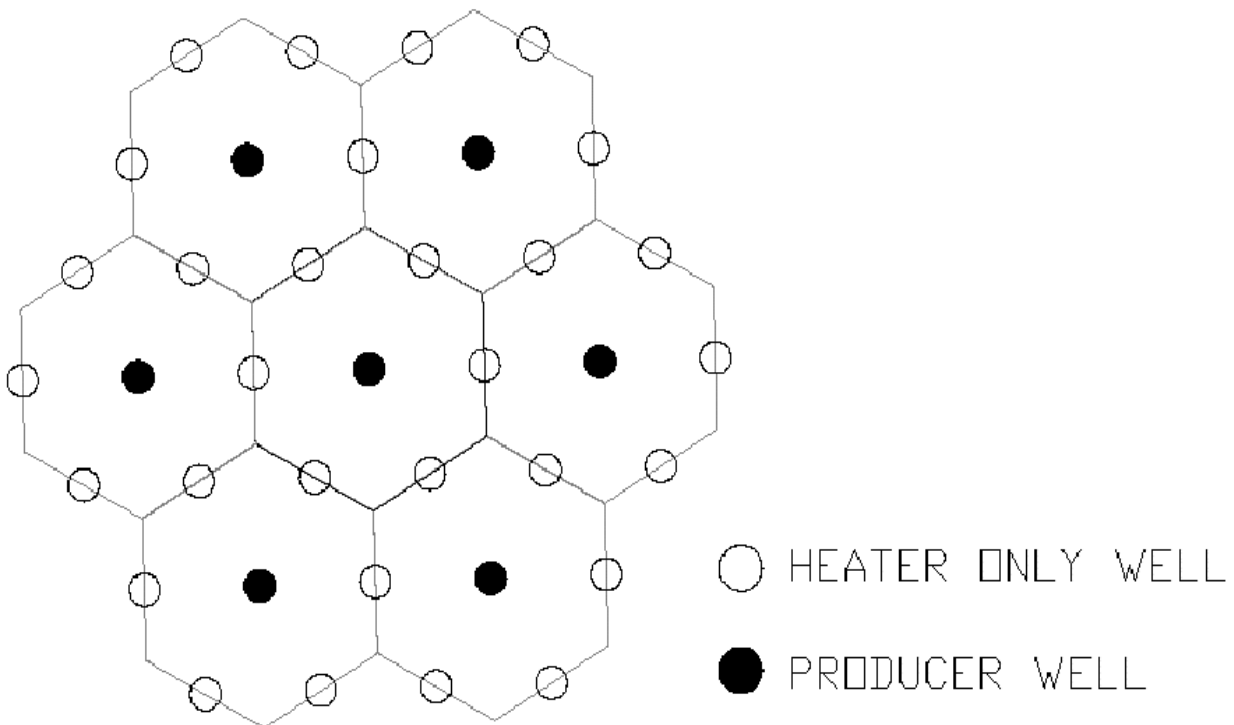


Figure 6–2. Edge-centered pattern 3:1 (producer well = heater-vacuum well)

c. *Thermal wells.* As stated previously, heater-only wells and heater-vacuum (producer) wells are two types of wells used for TCH projects. These are discussed in the following paragraphs.

(1) *Heater-only wells.* Heater-only wells consist simply of a heater element suspended in a protective can (Figure 6–3).

(a) The can, in most cases, is simply a segment or segments of pipe, sealed at the bottom. The heater element must be suspended in such a way that the heater element and heater can are electrically isolated from each other (when electrically powered heater elements are used). Typically, a drive point is affixed to the bottom of the can. Selection of heater-can diameter, schedule (wall thickness), and materials of construction depends on the well configuration, installation method, and depth, the COCs, and the expected operating temperature of the heater elements.

(b) Typically, heater cans are constructed of stainless steel owing to its significantly better corrosion resistance at elevated temperatures than carbon steel. For sites with particularly heavy corrosive contaminant loading, it may be necessary to upgrade to a better corrosion-resistant alloy; some examples include Hastelloy C-276, C-22, and Inconel 600. In most cases, heater cans used by TerraTherm, Inc. are 7.6 cm (3 in.) schedule 40 stainless steel, although various diameters, wall thicknesses, and materials have been used. In some cases, it is possible to install the heater elements directly into the soil without a can. However, this method makes servicing and replacement of the heater elements during operation difficult, making it more costly. Thus, it is typically avoided.

(2) *Heater-vacuum wells.* Heater-vacuum wells, or producers, consist of a flat-bottomed heater can as described in the previous section, suspended in a well screen (Figure 6–4). Screen placement, well-screen slot size, and sand pack selection may follow typical SVE-system design methods.

(a) Screened sections may be continuous over the entire heated interval or focused on specific segments of the heated sections where the greatest load of contaminant-laden vapors is expected to be produced. Selection of screen can diameter, schedule (wall thickness), and materials of construction depends on the factors described in the preceding paragraph. Typically, the well screen selected is at least one or two nominal pipe sizes up from the heater can and suspended within it.

(b) In most cases it is strongly recommended that a seal be installed in the annular space between the borehole wall and the casing of the heater-vacuum well to prevent leakage of vapors and steam upward through the borehole. Typically, a lean concrete or concrete grout seal is preferred over a hydrated bentonite seal, as it withstands the heat and will resist desiccation longer than bentonite alone.

(3) *Thermal well installation methods.* Thermal wells may be installed using conventional hollow-stem auger drilling equipment. However, because it is desirable to maintain close soil-to-well contact for efficient TCH whenever possible, it is also desirable to directly drive the heater-only wells into the soil, thereby locally increasing the density and effective thermal conductivity (there is more grain-to-grain contact) of the soils around the heater can. Given the relatively large diameter and closed bottom of the heater cans and the large number of thermal wells typically installed at a site, the rig selected for driving thermal well cans must have a sufficiently high hammer cycle rate and have sufficient downforce to drive the cans efficiently.

(a) Heater-vacuum wells are typically installed in augered holes, as driving screens can damage the screen and can lead to soil smearing and clogging of the slots. Solid stem augers may be used if soil conditions are such that the boreholes do not collapse when the auger is withdrawn to allow installation of the screen. This method offers the advantage of faster installation and minimizes drill cuttings; however, it is not possible at all sites. Otherwise, hollow stem augers are typically used.

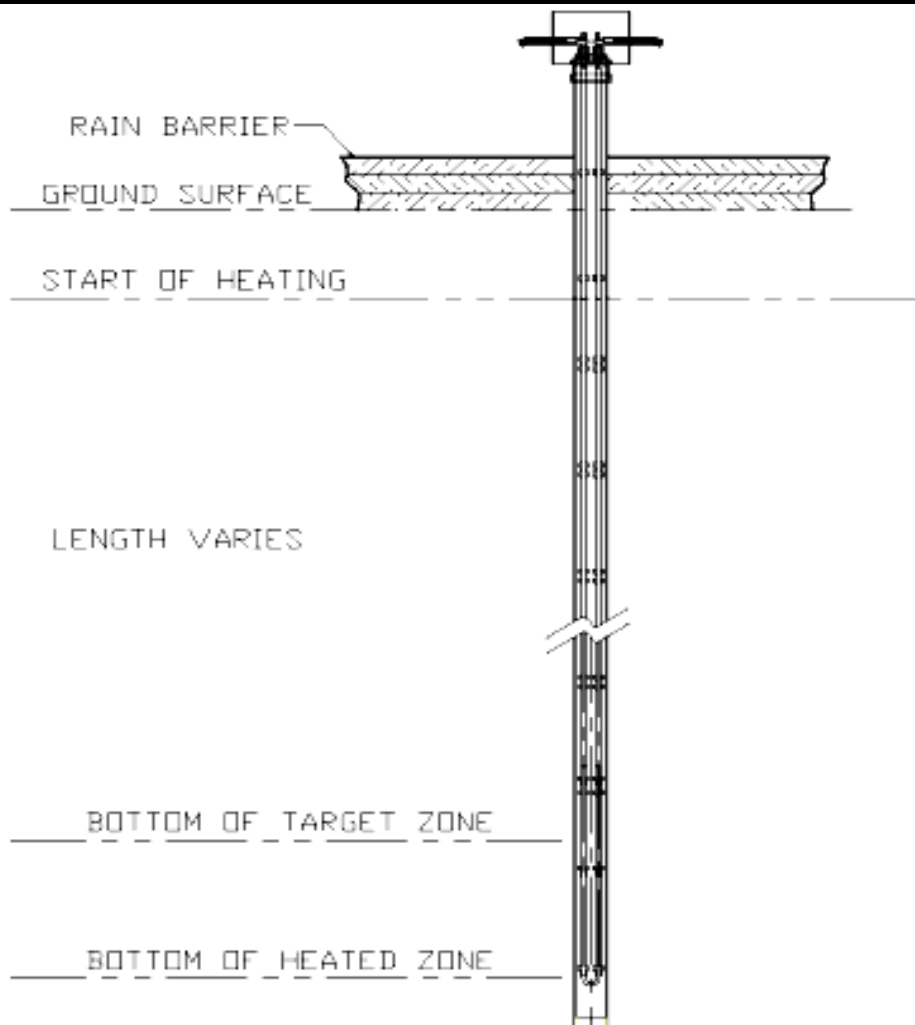


Figure 6-3. Heater-only well

(b) Rotary sonic installation methods also work well and achieve the goal of maintaining close contact between vibration-driven cans and the surrounding soil. Heater-vacuum well-screens installed by rotary sonic drilling are typically installed in a casing that is vibrated into the ground. The casing is then withdrawn as the sandpack is installed. Rotary sonic methods can achieve decent installation production rates (installed meters per day). This technique works well for sites that have significant amounts of debris; however, this method is substantially more expensive than hollow-stem auger installation methods.

(c) Heater-vacuum well screens and heater cans may also be installed using angled, horizontal, or directional drilling methods. In this case, minor modifications are necessary to ensure that heater elements and producer well cans are centralized. Material selection may also need to consider the bend radius of the proposed angled or directionally drilled borehole. Installation in trenches is an additional option.

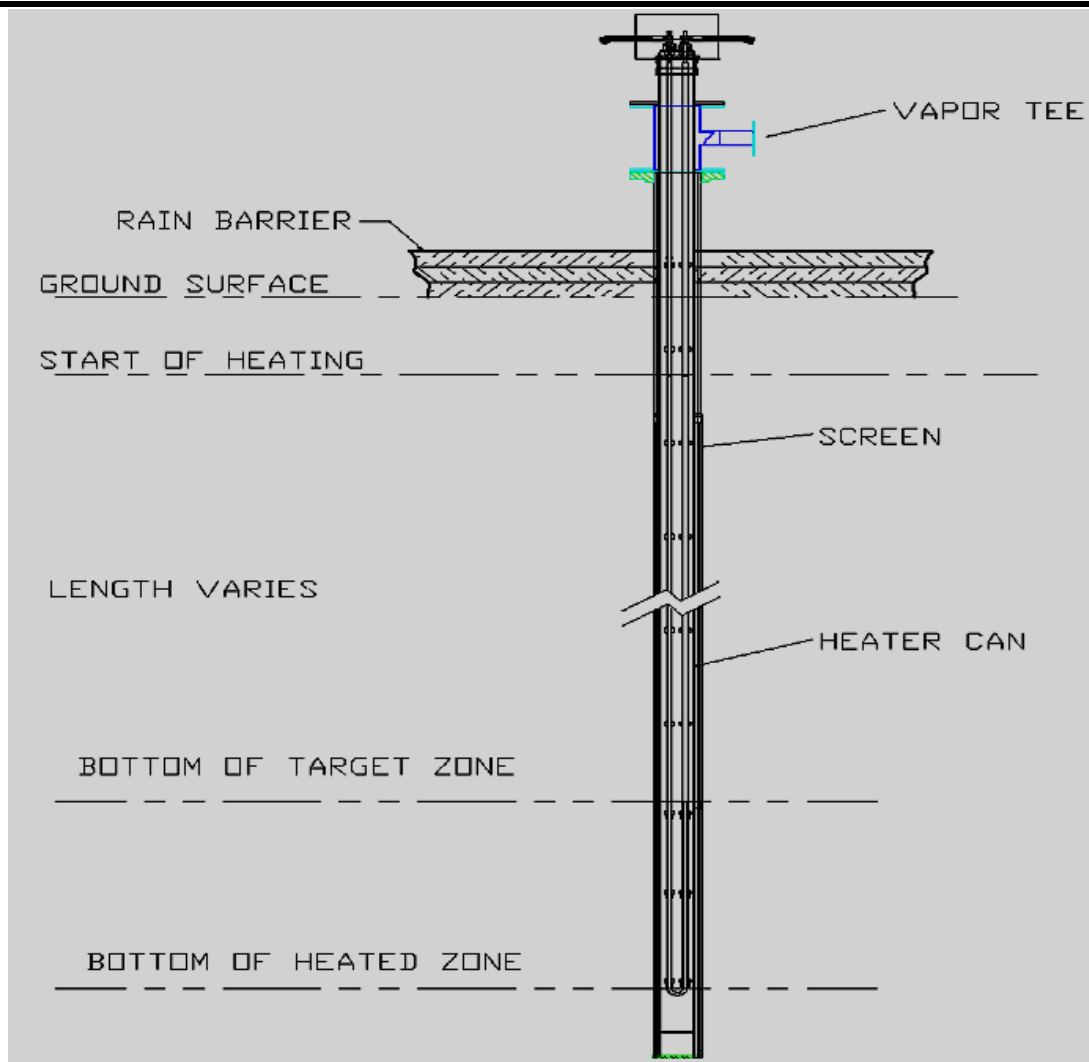


Figure 6-4. Producer well

(4) *Quality control requirements.* Inspections of wells and screen materials are needed to verify that the components are of the desired quality and material composition. In vertical applications, a maximum tolerance for deviation from verticality, particularly in long or deep wells, is necessary to ensure that the concentric components (heaters in cans and cans in heater-vacuum wells) can be installed after the wells are drilled or driven.

(5) *Groundwater control systems.* At sites where groundwater intersects the TTZ or where water-bearing stringers may transmit groundwater to the treatment zone, groundwater control may be required. It may not be possible for the thermal wells to deliver sufficient energy to boil off infiltrating groundwater (or surface water runoff, for that matter) and still raise the temperature of the target soils above the boiling point of water.

(a) Excessive or uncontrolled groundwater or surface water infiltration may limit the ability of ISTD to achieve the required target treatment temperature in some or all locations throughout the TTZ. Therefore, it is critically important to identify potential sources of groundwater or surface water infiltration and take appropriate measures to control them.

(b) In the case of groundwater, these control measures may include sheet pile or jet-grout barrier walls keyed into an aquitard layer, well-point dewatering systems, trenched or horizontally or directionally drilled dewatering wells, or freeze wall barriers. These actions may have significant cost impacts on the project. It may be cost-effective to remove any recoverable groundwater prior to the start of heating at those sites where groundwater can be readily contained and pumped out of the TTZ.

d. *Energy input and conveyance systems.*

(1) *Energy requirements.* Assuming negligible water infiltration or recharge into the TTZ and neglecting edge losses, a fixed amount of energy is required to raise the temperature of the soil to the boiling point of water, boil off a single pore volume of soil moisture, and then, for most TCH sites, raise the dried soil to the superheated target treatment temperature. For sites with relatively low boiling contaminants (PCE, TCE, benzene, styrene, etc.), it is not necessary to boil off the soil moisture, provided there is sufficient permeability in clayey soils to remove contaminants without drying the soil. At these sites it may be sufficient to simply approach the boiling point of water, 100 °C (212 °F), to achieve the desired degree of contaminant removal or destruction.

(a) Therefore, the energy required to raise the soil to the desired temperature can be estimated relatively easily using an analytical spreadsheet calculation. Numerical modeling may be used to provide a more accurate estimate of the energy requirements, allowing the benefits of superposition, convection, edge losses, heat loss through producer wells, infiltration, and other factors. Generally, most soils cannot accept more than approximately $985 \text{ W}\cdot\text{m}^{-1}$ ($300 \text{ W}\cdot\text{ft}^{-1}$) of heat input from a line source (such as a thermal well) (Stegemeier and Vinegar 2001).

(b) During the early stage of heating, when the soil is cool and moist, its thermal conductivity is high, and the soil is capable of absorbing high heat input from the heater with only a moderate increase in temperature. As the soil is heated and dried, the thermal conductivity decreases, thereby accelerating the natural temperature rise. Eventually, a stabilized heating rate is attained with relatively small increases in temperature at the well.

(2) *Heat delivery mechanisms.* Energy in the form of heat may be delivered to the soil using several methods, including electrical, gas combustion, or other methods. Electrically powered heater elements, proprietary stainless steel elements, and mineral-insulated cable elements have been used in all testing, demonstration, and full-scale projects to date. Gas-combustion soil heaters, claimed and protected by early ISTD patents, are currently under development for specific applications.

(3) *Heater elements (electrical).* Electrically powered heater elements may be operated with or without the use of controllers. In the first case, a power controller, typically a silicon-controlled rectifier, is used to modulate (automatically or manually) the power delivered to the heater elements based on the temperature input from one or more thermocouples on or in the immediate vicinity of the heater element.

(a) In the controllerless configuration, the resistive properties of the metal heater element (increasing resistance with temperature) may be used to construct essentially self-regulating heaters. In this configuration a constant voltage is applied to the heaters. As the heater element gets hotter, its resistance increases, and by Ohm's Law, the current decreases, resulting in a "self-regulating" watt output. The preferred approach is to use self-regulating heaters; however, for specific applications, controlled-output heaters may be desirable (for ramping up to temperature slowly or in instances where it is desirable to maintain the heaters or soil below a certain temperature).

(b) Careful consideration of the thermal expansion of the heater element, the heater can, and, for heater-vacuum wells, the well screen is required. Heater-only cans and heater-vacuum well screens are constrained at the bottom by the soil matrix and therefore tend to expand upward when heated. However, the heater elements suspended in the cans and heater cans suspended in heater-vacuum wells are free-hanging and tend to expand downward when they are heated.

(c) Adequate room for thermal expansion is required to prevent damage to the components. This is critically important on electrically powered systems, where contact between components during heating could potentially cause damage or, although unlikely, could cause the heater to ground out on the can.

(4) *Wellhead power and vapor connections.* Wellhead power connections are made in weatherproof electrical junction boxes that are attached to the heater cans with an electrical conduit compression fitting. Cold pin conductors welded to the free ends of the heater rods extend through an electrically insulated bulkhead or support plate at the top of each heater can and into the junction box. Mechanical lugs or other suitable terminations are used to attach the power cables to the heater rods.

(a) Heater-vacuum wells are typically completed with a flanged vapor tee, allowing for the insertion of the internal heater can. The lower flange of the vapor tee mates with the well screen riser, and the upper flange on the vapor tee mates with a plate flange welded on the internal heater can, thus sealing the well screen annulus.

(b) Vapors exit through the tee's branch to the piping manifold under vacuum. The tee's branch may also be fitted with an individual flow control valve, sample port, or pressure monitoring port where desired. The internal heater-can riser extends above the vapor tee, ensuring that the electrical connections for heater-vacuum wells are like those for heater-only wells.

(5) *Vapor conveyance piping systems.*

(a) Design of TCH vapor conveyance piping should follow existing USACE piping system design guidance. In selecting and specifying piping system components (including pipe, fittings, and valves), designers must consider the changing composition and state of the vapor stream (from relatively cool, moist steam to hot, dry air). Piping system materials of construction must be sufficient to withstand the nature of the contaminants, the potential acidity of the vapor stream, and the elevated temperatures to which they are exposed. Corrosion is often most troublesome in parts of the system where liquid can collect. The design of the system should protect against zones of liquid accumulation. Allowance must be made for thermal expansion as the piping system is heated to operating temperature.

(b) Typically, supplemental heat must be added to the piping system to prevent the extracted vapor stream from condensing in the conveyance piping. Supplemental heat may be added either through internal insertion heaters (installed in cans inside the manifold pipe spools) or through external heat tracing, as appropriate to the case. Insulation must be provided for personnel protection and to minimize heat losses. In some cases, it is desirable to allow vapors to condense in the pipe manifold and withdraw the condensed liquid for treatment separate from the air stream. In this condensing case, insulation needs only to provide protection for personnel exposures. Since the piping systems are typically installed outdoors, external jacketing must be weatherproof.

(c) Manifold piping spool pieces are typically prefabricated in standard lengths and fitted with flanged ends to allow a relatively rapid assembly of the manifold in the field. Since the TCH piping system is typically a temporary installation (on the order of months), the piping network is frequently supported on portable jack stands. However, in areas prone to seismic activity or where the piping system is in place for an extended period, more elaborate support and bracing may be required.

e. *Aboveground systems.*

(1) *Power distribution.* In electrically powered TCH systems, there can be a very significant power demand, depending on the volume of contaminant to be remediated. Once a preliminary estimate of the power requirement is available, designers should

consult with the on-site engineers, infrastructure managers, and local utility company representatives to determine whether there is sufficient power transmission and distribution capacity at the facility or off the local grid. Designers should weigh the cost and schedule impacts of running new power transmission lines from a nearby substation versus operating the TCH project in multiple smaller phases to reduce the overall demand load of a large project.

(a) Power is fed from high-voltage transmission lines to a transformer with a typical secondary voltage of 480 volts, alternating current. Power is fed from the transformer to a fused main disconnect switch or a main circuit breaker in an electrical switchboard. There may be one or more switchboards to distribute power to the well heaters, manifold pipe heaters, and vapor treatment equipment. Vapor treatment equipment may be operated from a packaged motor control center or fed separately through individual motor starters or variable frequency drives.

(b) Heaters for wells can be designed to operate at various voltages to balance circuits and obtain the desired power output; therefore, power distribution depends on the site configuration. Owing to the temporary nature of TCH installations and to speed field construction, portable power cables (also called mining cables) are typically used to feed power from the circuit breakers to the well field heaters.

(c) Where required by the National Electrical Code (NEC), National Fire Protection Association (NFPA) 70, and local codes, distribution gear must be provided with ground fault protection. Electrical distribution gear should be provided with appropriately sized overcurrent protection. Designers must remember to consider the length of heater power cable runs as well as the fact that the heaters operate continuously once energized and apply appropriate component size adjustments to comply with NEC requirements for continuous duty loads and minimizing voltage drops.

(d) Conductive components within a well field should be bonded and grounded. In addition, transformers, distribution panels, process equipment, trailers, and other conductive system components should be bonded and grounded in conformance with the NEC and any local requirements.

(2) *Vapor treatment systems.* Vapor treatment systems for field pilot tests were discussed in paragraph 5–2b, and a typical system is depicted schematically in Figure 5–4.

(a) Vapor treatment systems for full-scale systems are like pilot-scale systems, although typically larger to accept the larger flow rates in full-scale systems. Vapor treatment systems may be as simple as one or more carbon adsorbers or may require a more comprehensive vapor treatment system consisting of a thermal oxidizer, heat exchanger, acid gas scrubbers, silt knockouts, and one or more carbon adsorbers.

(b) Selection and sizing of vapor-treatment system components depends on the expected peak vapor-generation rate. This rate is typically estimated at 0.028 standard cubic meters per minute or 1 standard cubic foot per minute (scfm) of vapor per kilowatt

of heater power. The projected COC loading and the applicable air emission limits also determine the selection and size of vapor-treatment system components.

(3) *Emission monitoring.* Emission monitoring requirements vary depending on the site COCs and the applicable air emission standards. Emission monitoring can be as simple as daily screening of exhaust vapors with a flame ionization detector or photoionization detector or may entail the use of a continuous emission monitoring (CEM) system. Typically, the former is used with a simple carbon-only vapor treatment system, while the latter is usually required for vapor treatment systems that incorporate a thermal oxidizer. Typical CEM system monitoring parameters for ISTD applications include wet O₂, dry O₂, CO, CO₂, and THCs. Dust and opacity monitoring and chlorine/HCl monitoring may also be required. In some cases, stack testing using isokinetic sampling methods may be required to comply with emission standards.

(4) *Emergency power supply.* A standby power source, typically a diesel-powered emergency generator, is required to enable continuous operation of vapor collection and treatment equipment in the event of a temporary interruption in shore (grid) power, as the hot soil mass continues generating steam and vapors during a power interruption. The emergency power supply may also be used to feed power to the fume pipe manifold to ensure that the pipe heating system remains operational. An automatic transfer switch is the preferred method of starting the generator in the event of a power interruption, although for a continuously manned site, a manual transfer switch may be acceptable.

(5) *Design review checklist.* Appendix C provides a general guideline for information required to carry a design for an ISTD project from the conceptual level through completion.

6–3. Electrical resistivity heating

a. Subsurface design.

(1) The most cost-effective electrode spacing for an ERH system depends on a complex interaction among various factors. However, in most cases, an electrode spacing of between 2.6 m and 6.1 m (8.5 ft and 20 ft) is selected. Some of the factors that influence electrode spacing within this range include the following.

(a) Electrode borehole diameter affects spacing because larger electrode boreholes provide a greater surface area for electrical current flow into the soil and, thus, can be spaced further apart.

(b) ERH power density also affects spacing. High applied power requires either greater electrode surface area, larger electrodes, or more tightly spaced electrodes. Application of high power allows faster remediation.

(c) ERH energy (power × time) density affects spacing. High applied energy is needed for high boiling point compounds > 100 °C (> 212 °F) and < 150 °C (< 302 °F),

very high percentage reductions, or because high TOC requires a tighter electrode spacing to ensure that the energy is applied in the most uniform manner possible.

(d) Treatment of deep soils increase the drilling cost; therefore, greater electrode spacing is more cost-effective.

(e) The type of soil, the state of water saturation, and the electrical conductivity of the soil have almost no impact on the most cost-effective electrode spacing.

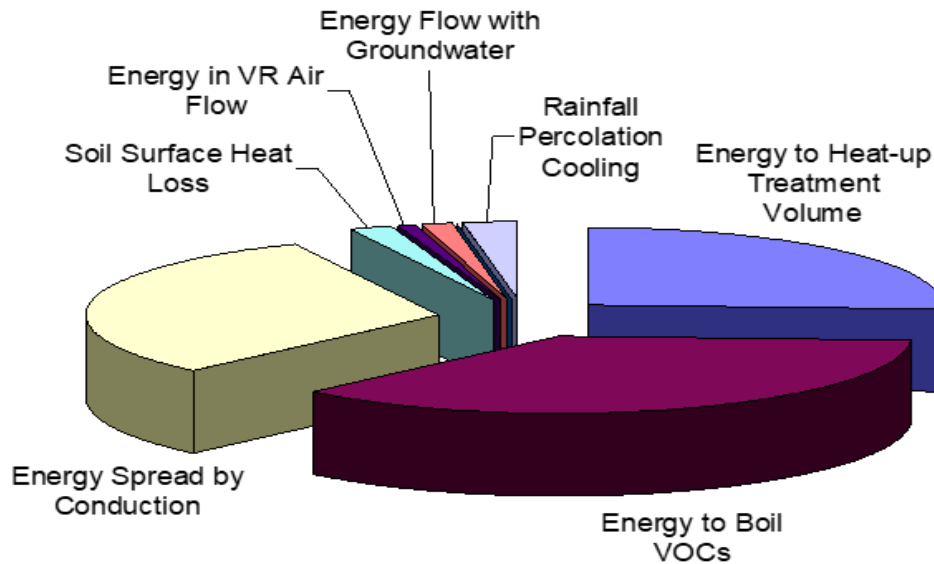


Figure 6-5. Electrical resistance heating energy distribution in the subsurface

(2) Electrodes are usually installed by hollow stem auger or some other conventional drilling technique and can be placed in angled boreholes. The current is carried down the borehole by either a steel pipe or a Teflon[®]-insulated electrical cable that is connected to a metal electrode element. The region surrounding the pipe or electrode element is backfilled with granular graphite or steel shot (or a combination thereof), enabling the conduction of electricity to the soil surrounding the borehole. Exercise caution to ensure that the steel shot does not displace bentonite seals during construction. These backfill materials have a particle size like coarse sand and can be used as well sand pack.

(3) To maintain soil moisture and electrical contact, a 0.6 m (0.25 in.) Teflon[®] tube is often inserted into the electrode backfill to provide a method to drip potable water. If the electrode is installed in geological material that readily allows water to flow through, a drip system is usually unnecessary. Electrodes can also have multiple completions. Up to six independent electrode elements have been installed in a single borehole to allow heating at six different depth zones.

(4) Electrodes can also be installed by driving a steel pipe into the ground. This method of electrode installation is usually reserved for treatment of soils that are shallow under saturated water conditions.

(5) Electrode boreholes often include one or more co-located VR wells. These VR wells may consist of steam vents that are located below the water table and operated at negative pressures for vapor capture. Within the vadose zone, there are trade-offs associated with co-locating a VR well within the electrically conductive zone of an electrode. The VR well tends to desiccate the soils immediately adjacent to the borehole, resulting in restricted electrical conduction.

(6) The purpose of the VR wells is to collect the produced vapor and prevent vapor migration. It is not necessary to try to drive airflow through the lithological unit (as in an SVE system), because it is the uniform in situ steam generation of ERH that produces the steam carrier gas for removal of VOCs from the soils as vapor. A surface seal is incorporated into the installation to maintain negative pressure to collect the vapors and to prevent steam breakthrough or exposure at the surface.

(7) If the depth to water is quite shallow, less than ~1.5 m (~5 ft) below grade, then horizontal VR wells or trenches may be preferred. Further, if there is the potential for a shallow water table to rise above the ground surface during the treatment process because of climatic conditions or generation of steam, controls may be necessary to prevent electrical hazards or exposure to hot liquids and vapors.

b. Energy input and conveyance systems. The VR piping is usually constructed of chlorinated polyvinyl chloride (CPVC), a high-temperature version of polyvinyl chloride. This piping has the advantage of relatively low cost and exceptional chemical and corrosion resistance. Its low heat conductivity keeps the outer surface sufficiently cool to avoid a burn hazard, and no insulation is required.

(1) CPVC expands significantly when heated. This expansion requires some care in piping design, as the VR piping expands by about 0.4 percent in length. The wells are especially rigid locations, and the use of piping offsets or expansion loops within the well field is often required. Below-grade piping installations often require expansion joints. CPVC piping loses strength and sags as temperatures rise. This must be considered in the design of piping supports.

(2) Although CPVC has been successfully used in thousands of VR wells and for miles of recovery piping at thermal remediation sites, it is not recommended for use in monitoring wells that are screened completely below the water table. The headspace of such a well does not have free exchange with the vadose zone. During steaming operations, steam and VOC vapors collect in the headspace of a submerged screen well. The top of the well is a condensation zone, and separate-phase VOCs are likely to condense there. The combination of high VOC exposure, high temperature, and slight pressure has caused submerged screen CPVC monitoring wells to fail and vent steam to the atmosphere.

(3) For this reason, stainless steel is recommended for submerged screen monitoring wells. In an ERH application, care must be taken to verify that the metal well does not transmit below-grade voltage to create a surface voltage hazard.

c. *Aboveground equipment.* The vapor recovered from the wells usually consists of about 75 percent steam, 25 percent air, and a small fraction of a percent of the target contaminant.

(1) The CPVC VR piping is connected to a steam condenser that includes a vapor-liquid separator. A silt knockout should also be considered in the design. The steam condenser cools the air and VOC vapors to near ambient temperatures for conventional vapor treatment. The target VOCs do not condense in the condenser; in fact, a condenser is an ideal application of Henry's Law, and over 99 percent of common VOCs remain in the vapor state as they pass through the condenser. After cooling by the condenser, conventional vacuum blowers and vapor treatment methods can be used. The vapor treatment process is like SVE systems, except that the typical flow rates are lower (because about 75 percent of the flow has been condensed and removed) and the vapor concentrations are much higher. These effects reduce the overall vapor treatment costs considerably in comparison to conventional SVE systems.

(2) Two types of steam condensers are common: air-cooled and water-cooled.

(a) Air-cooled condensers are simpler and less expensive. However, they can only cool the extracted vapor to a temperature of about 20 °F above ambient. This leaves about twice as much absolute humidity in the air as a water-cooled condenser and, thus, reduces GAC loading efficiency.

(b) A water-cooled condenser uses a recirculated water stream, and heat is rejected to the atmosphere via a cooling tower that evaporates a portion of the recirculated water. A water-cooled condenser can cool the extracted vapor to ambient temperatures; in low-humidity environments, the vapor is cooled a few degrees below ambient temperatures. A water-cooled condenser requires a source of makeup water to replace the water that is evaporated in the cooling tower.

(c) Typically, the condensed steam is recycled for use as this make-up water. This results in the emission to the atmosphere of a fraction of 1 percent of the extracted VOCs (as described above); however, recycling of the steam condensate eliminates the need for an independent condensate water treatment system and may eliminate the need for water discharge.

(3) An ERH PCU adjusts the utility voltage to the proper level to deliver to the electrodes. The electrode voltage inversely varies with soil electrical conductivity. Soil electrical conductivity usually parallels groundwater total dissolved solids concentrations. The PCU also has safety interlocks to shut down the ERH system in the event of an unsafe condition and includes a temperature monitoring system. The PCU should include a modem connection to allow remote monitoring and control of all aspects of the heating process. The VR process can also be automated and remotely monitored; however, this is generally not cost-effective for simple vapor treatment systems such as GAC.

(4) Where required by NEC, NFPA 70, and local codes, distribution gear must be provided with ground fault protection. Electrical distribution gear should be provided with appropriately sized overcurrent protection. Designers must remember to consider the length of heater power cable runs as well as the fact that the heaters operate continuously once energized and apply appropriate component size adjustments to comply with NEC requirements for continuous duty loads and minimizing voltage drops.

(5) Conductive components within a well field should be bonded and grounded. In addition, transformers, distribution panels, process equipment, trailers, and other conductive system components should be bonded and grounded in conformance with the NEC and any local requirements.

d. Design review checklist. The following ERH design issues should be reviewed.

(1) Has the designer of the ERH system taken measures to protect workers and the public from the hazardous voltage that is applied in the subsurface? Appropriate measures include the following.

(a) Physical separation (usually at least 6 m (20 ft) from electrically conductive components for worker safety and at least 9 m (30 ft) for public safety).

(b) Electrical insulators (such as plastic, rubber, or rounded pea gravel to cover large areas).

(c) Electrically conducting material to create an equipotential surface (for example, a metal grid over the site to damp surface voltage to a low value). Monitoring wells should be locked shut such that a “danger tag-out” is required to open them.

(2) Has the ERH system designer taken measures to protect workers from steam and high temperatures?

(a) Monitoring wells pose the greatest risk; if the top of the well screen is below the water table, the well pressurizes during ERH operation.

(b) Opening a pressurized well can cause a geyser effect.

(3) Has the ERH system designer considered the effects of elevated subsurface temperatures on underground utilities?

(a) If the top of the heated interval is 1.5 m (5 ft) or more below grade, utilities at common burial depths are generally not a concern.

(b) If utilities are within the heated volume, plastic piping and electrical power conductors are most vulnerable (due to internal ohmic heating).

(c) Metal utilities, fiber optics, and concrete or clay sewer lines are generally less temperature sensitive.

(d) Utility trenches may carry vapors and steam away from the treatment area, leading to loss of control and potential off-site health/safety risks.

(4) Has the designer considered the potential for migration of vapors into basements?

(5) Has the designer considered a rising shallow water table (due to climatic events or steam generation) and the potential for electrical hazards or exposure to hot liquids and vapors?

(6) Are the soils expansive clays, and do soil desiccation and shrinkage near the water table pose a concern for foundations and utilities? How are vapor and steam to be captured?

(a) In the vadose zone, vacuum influence captures steam and vapor.

(b) In the saturated zone, low-permeability lenses can pool or divert rising steam and VOC vapors.

6-4. Steam enhanced extraction

a. *Subsurface design.* The design of a full-scale steam injection system should maximize the removal of contaminants from the subsurface in an efficient manner. To achieve this objective, the design should incorporate thermal modeling, analysis of site hydrogeological and contaminant distribution data, and analysis of mass movements both above and below the source zone.

(1) To control the migration of the contaminants, steam should be injected outside, below, and above the source zone (assuming a single array of steam injection wells surrounds a vapor and groundwater recovery well). Recovery occurs in the middle of each array for applications having a multiple array of wells.

(a) The injected steam creates a thermodynamic driving force, moving the contaminants toward the center of the target volume, where liquids and vapors are extracted. The success of this strategy depends on the careful delineation of NAPL in the source zone. The vertical and horizontal extent of the NAPL should be well defined, as discussed in Chapter 3.

(b) In this way, steam always sweeps from the outside in, carrying NAPL with it and thus preventing NAPL from spreading to the surrounding area. Downward NAPL migration can be prevented by sweeping steam below the source zone first (Heron et al. 1998b, Gerdes et al. 1998). This creates a steam blanket below the NAPL. Droplets sinking into this zone are vaporized and carried with the steam to the extraction well. Research conducted in Germany has also shown a benefit in the co-injection of air with the steam in preventing downward migration of NAPL (Betz et al. 1998, Schmidt et al. 1998). The co-injection of air should be examined through additional design modeling work to determine its feasibility at the site.

(2) As steam is injected into the subsurface, it propagates outward and upward from the injection well screen in a shape determined by the horizontal and vertical permeabilities of the soil and by the steam injection rate. The lateral radius of the steam zone surrounding each well depends on the soil characteristics (the greater horizontal-to-vertical permeability typical of sedimentary deposits helps to spread steam laterally around the well). For steam injected into the vadose zone, good horizontal sweep is expected, as the steam flow is only mildly affected by gravity forces. Enough steam injectors should be used to ensure that a very uniform steam zone develops below the NAPL zone.

(3) If multilevel wells are used, steam is typically injected into the NAPL zone only after the upper and lower zones reach steam temperature. Cyclic steam injection may start when the entire zone reaches steam temperature, either by varying pressure in each well or by varying the wells where steam is injected. At the same time, the vapor extraction system should be operated continuously. This creates large pressure changes in the target volume through time that have been shown to enhance the removal of contaminants from low permeability zones (Itamura and Udell 1995). The cycling is expected to cause the following conditions.

(a) Create a condition where the pressure in the soil pores is less than atmospheric, resulting in “flashing” of residual NAPL.

(b) Expand the treated soil layers to include low-permeability regions.

(c) Reduce aqueous-phase concentrations and assist in desorption of contaminants from soil particle surfaces.

(4) Liquid should be extracted from the central well clusters. These include deep and shallow groundwater/vapor extraction wells. The extraction rate must be equal to or greater than the rate that groundwater is replaced by the expanding steam zone. This rate is typically between 100 percent and 300 percent of the equivalent steam injection rate (expressed as $\text{kg}\cdot\text{s}^{-1}$ or $\text{lb}\cdot\text{hr}^{-1}$ of water). During steam zone expansion, extraction should be aggressive to create a driving force toward the central extraction well clusters. During steam cycling operations, the extraction rates may be varied to optimize the steam flow, to prevent stagnant zones, and to achieve uniform heating of the entire source zone. Typically, vacuum pressure is set at 50.7 kilopascals (0.5 atmospheres) but should be less than the minimum predicted vacuum during the shut-in portion of pressure cycles.

(5) Vapor should be extracted through the whole period of operation using a wellhead vacuum. The actual vacuum depends on the steam injection rate, the observed groundwater level in the central groundwater extraction well, and the operation of the effluent treatment system. The applied vacuum assists in directing vapors toward the center wells and, thus, controls the heated zone.

(6) During the entire operation period, sub-atmospheric pressure should be maintained in the shallow vadose zone, minimizing the risk of upward migration of

contaminants to the soil surface. Vadose-zone air pressure should be monitored, if feasible, based on the operational conditions.

(7) The number and location of extraction and injection wells required is highly site-specific and depends on many factors, such as the extent and depth of the contamination, physical and chemical properties of the contaminants, soil characteristics, and most importantly, soil permeability. Steam zone development can be estimated by several mathematical methods.

(8) Typical temperature monitoring detail is presented in Figure 6–6, while a simplified process and instrumentation diagram for a steam injection system is presented in Figure 6–7.

b. Energy input and conveyance systems. A typical steam injection system consists of steam injection wells, groundwater/vapor extraction wells, conveyance piping, a NAPL/water separator, a transfer pump, controls, and gas/water treatment equipment. Figure 6–7 shows an example of a process flow diagram (PFD) of a typical steam injection system. The steam injection system usually uses steam generated by a mobile industrial steam boiler. Regulated steam is supplied from the boiler to the main treatment area, where steam pressure and flow rate are controlled at the wellhead.

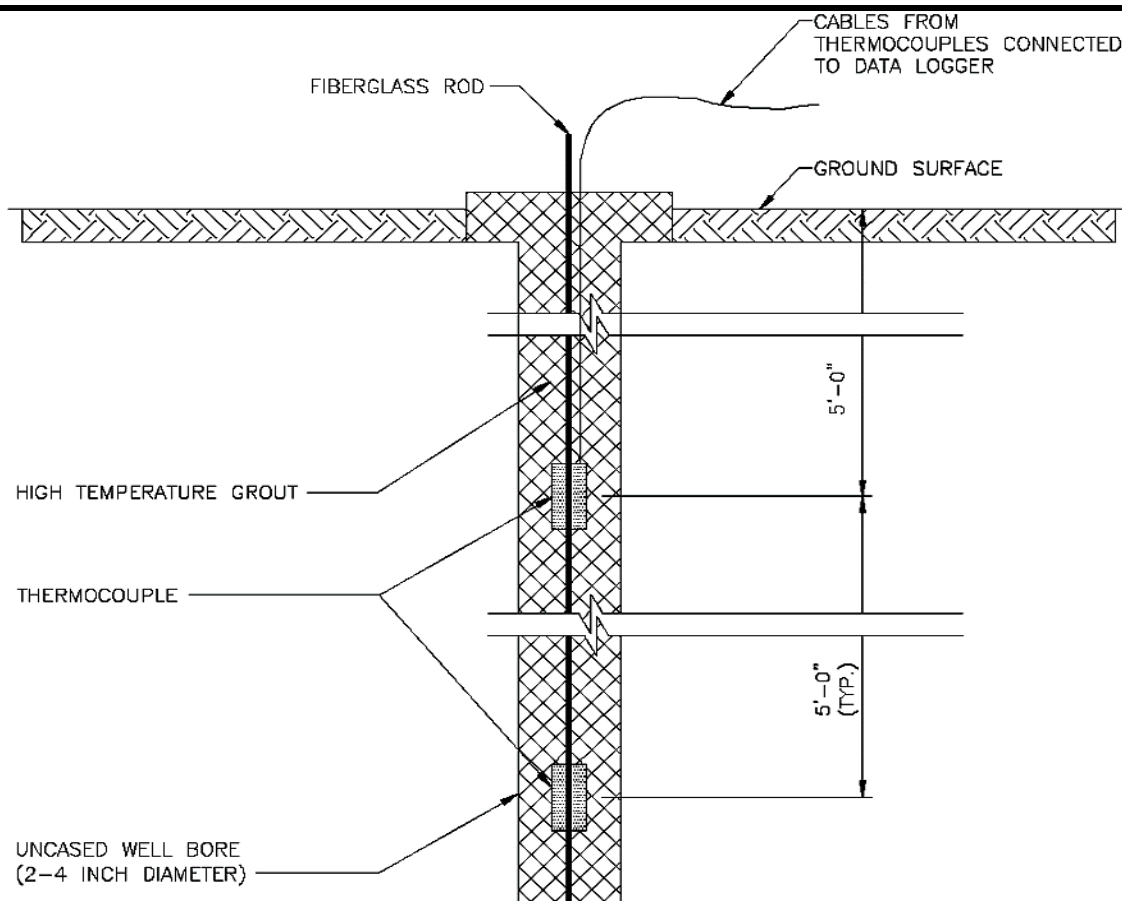


Figure 6–6. Temperature monitoring detail

(5) Requirements for system enclosure and foundations for system components, including storage tanks and treatment equipment.

(6) An operation, maintenance, and monitoring plan.

6-5. Waste stream treatment options

This section provides a summary of treatment options applicable to ISTR technologies. Figure 6-8 provides a simplified PFD for a treatment system used in ISTR applications to help the reader visualize the processes involved. Table 6-1 and Table 6-2 summarize applications and limitations of each technology described within this section for liquid and vapor treatment, respectively. A detailed discussion of waste-stream treatment design is not included but may be found in other USACE documents (see Appendix A).

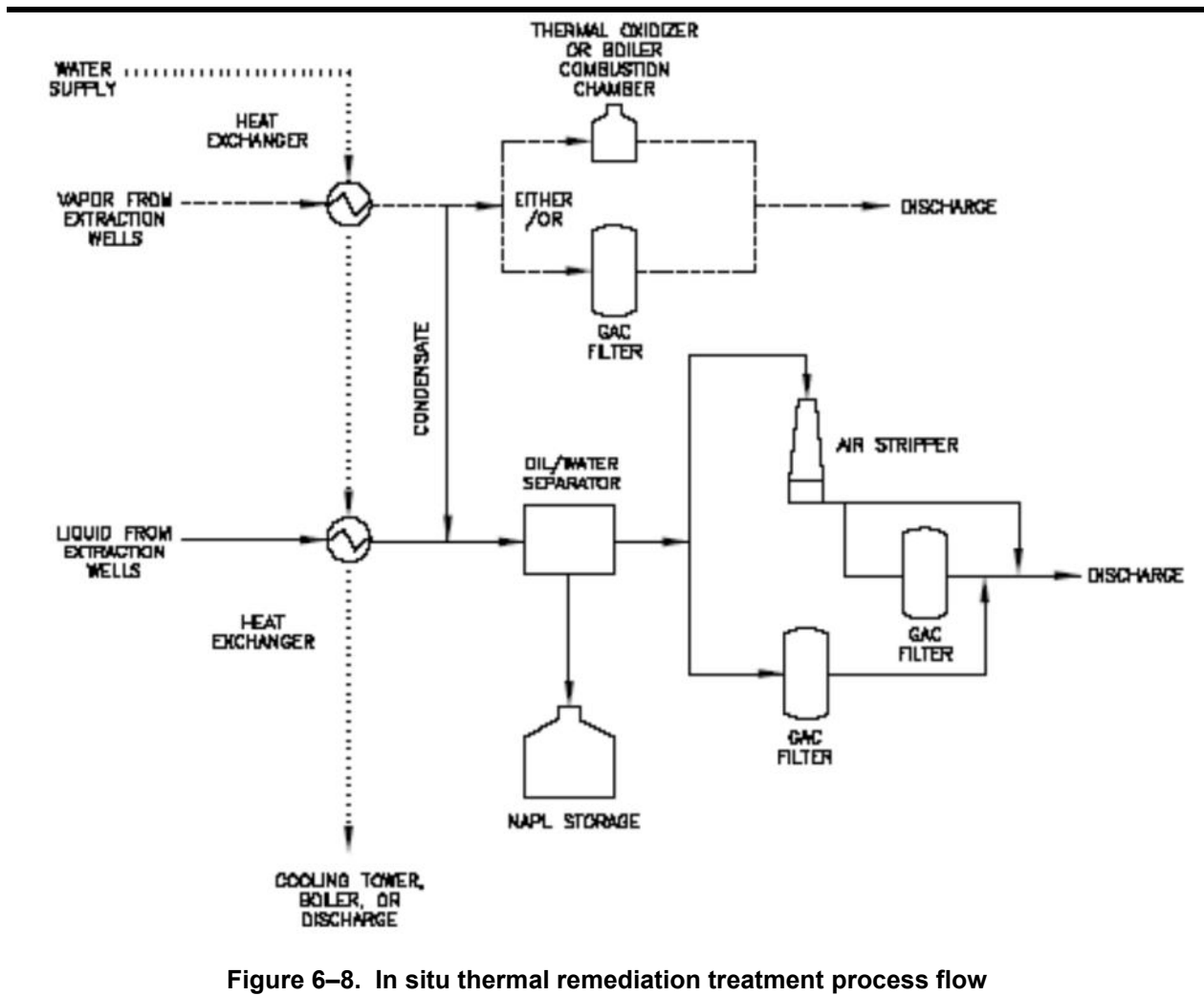


Figure 6-8. In situ thermal remediation treatment process flow

a. Liquid treatment.

(1) *Pretreatment via heat exchange.* The temperature of the extracted liquid may affect materials of construction.

(a) For example, plastic piping may be chemically resistant, but high temperatures may cause the piping to expand and become thermally stressed. Therefore, temperature effects on the materials of construction should be considered to determine and design the most appropriate treatment method. Extracted liquid from ISTR operations must be cooled before it can be treated effectively by other methods. This is typically done by passing the liquid through a heat exchanger; thus, the hot extracted liquid is cooled by air or water.

(b) Air cooling transfers heat directly to the atmosphere and generally requires a large flow of air. Water for water-cooling may come from a supply source such as a well and may either be discharged or used as boiler-feed water for steam generation. Closed systems are used, where cooling water is recirculated through a cooling tower.

(2) *Pretreatment via oil/water separators.* Oil/water separators are used to remove NAPL from the groundwater stream prior to physical, chemical, or biological treatment of dissolved constituents. Gravity separation is typically used, where separation is achieved by the difference in liquid densities.

(3) *Pretreatment via carbon adsorption.* Carbon adsorption is widely used and is applicable to a broad range of soluble organic compounds. Dissolved organic compounds adsorb onto the carbon particles. Typically, configurations are of the fixed-bed type, where units are operated in parallel or series. Operation in series typically uses a secondary unit that acts as a backup when the primary unit is out of service. Once carbon adsorption capacity is reached, carbon is either regenerated or properly disposed of. Carbon adsorption units can be used as a polishing step for other treatment methods before discharge. Other media (like sorptive clays) may be used.

(4) *Pretreatment via air stripping.* Air stripping is the mass transfer of volatile contaminants from water to air. This process is usually conducted in a packed tower. The typical packed tower air stripper includes a spray nozzle at the top of the tower to spread contaminated liquid over the packing in the column, a fan to force air countercurrent to the water flow, and a sump at the bottom of the tower to collect treated liquid. Vapors produced from an air stripper may require treatment before discharge.

(5) *Posttreatment.* Primary treatment methods may not always be able to achieve applicable emissions standards owing to inherent inefficiencies or because of changed influent characteristics. In these situations, additional treatment methods may be used as a polishing step. For example, carbon adsorption is often used as a polishing or backup method for an air stripper. Sand filters may be used to remove suspended solids in the groundwater stream. Solids build up, and the unit is typically backwashed. Frequency of backwash depends on the solids concentration of the stream entering the filter.

**Table 6–1
Groundwater treatment technologies**

Technology	Application	Limitations
Carbon Adsorption	<ul style="list-style-type: none"> - Target compounds include hydrocarbons, semi-volatile organics, and explosives, halogenated VOCs. - Effective as a polishing step to other treatment technologies. - High contaminant removal efficiencies. - Effective for removing contaminants of low concentrations from a wide range of flow rates. - Effective for removing contaminants of high concentrations from low flows (depends on size of vessel). 	<ul style="list-style-type: none"> - Multiple contaminants may impact performance. - High-suspended solids or oil/grease may cause fouling, requiring frequent treatment. - Spent carbon must be regenerated (on- or off-site) or disposed of properly. - Can be costly for highly mobile compounds (low K_{oc}). - Biological growth in carbon or high particulate loadings can reduce flow through the bed. - Elevated liquid stream temperatures may increase vessel corrosion. - Water should be cooled prior to treatment.
Air Stripping	<ul style="list-style-type: none"> - Primarily used to treat VOCs. - May be applicable to certain halogenated SVOCs. 	<ul style="list-style-type: none"> - Contaminants are not destroyed but physically separated from the liquid stream to air. The effluent air stream is subject to regulatory standards and may need further treatment. - May not always be fully effective, and additional groundwater treatment may be necessary. - Large surges in influent concentrations can reduce removal efficiency. - Cold weather can reduce efficiency. - Air stripping is not as effective for compounds with low Henry's Law constants or high solubilities. - The presence of solids in the liquid stream can foul packed towers, requiring more frequent cleaning. Packing material may be chemically incompatible. - High concentrations of chlorinated compounds can turn packing material brittle, resulting in annual material replacement. - Biofouling and mineral deposition are expected. - An increase in temperature may contribute to packing and tower/tray material corrosion.

b. Vapor treatment.

(1) *Pretreatment via heat exchange.* Extracted vapor from ISTR operations must be cooled before it can be treated effectively by other methods. Cooling is typically done using air or water as the coolant through a heat exchanger/condenser. Air-cooling transfers the heat directly to the atmosphere and generally requires a large flow of air. Water for water-cooling may come from a supply source such as a well and can either be discharged or used as boiler-feed water for steam generation. Closed systems are also used where cooling water is recirculated through a cooling tower. Condensed vapor is then conveyed to the liquid treatment system. If very high levels of contaminants are present in the condensate, a pretreatment step may be required before the condensate can be introduced into the liquid treatment system.

Table 6–2
Vapor treatment technologies

Technology	Application	Limitations
Carbon Adsorption	Target compounds include hydrocarbons, semi-volatile organics, explosives, and halogenated VOCs. However, removal of high contaminant concentrations using vapor-phase carbon may not be economically favorable. Pretreatment of the VOC stream, followed by using a vapor-phase GAC system as a polishing step, is more cost-effective.	<ul style="list-style-type: none"> - Spent carbon transport may require hazardous waste handling. - Spent carbon and the adsorbed contaminants must be disposed of or regenerated (off or on site). - Relative humidity greater than 50% can reduce carbon capacity. - Elevated temperatures from ISTR operations (greater than 38 °C or 100 °F) inhibit adsorption capacity. - Biological growth in carbon or high particulate loadings can reduce flow through the bed.
Thermal/Catalytic Oxidation	The target contaminant groups for oxidation include non-halogenated VOCs, SVOCs, and fuel hydrocarbons.	<ul style="list-style-type: none"> - If sulfur, halogenated compounds, or high particulate loadings are in the emissions stream, the catalyst can be poisoned/deactivated, requiring replacement. - Destruction of halogenated compounds requires special materials, construction, or special catalysts (if using a catalytic oxidizer). - Influent gas concentrations must be < 25% of the lower explosive limit for catalytic and thermal oxidation. - The presence of chlorinated hydrocarbons and some heavy metals (lead) may poison a certain catalyst.
Energy Recovery	Primarily applicable for fuel hydrocarbons and some SVOCs.	<ul style="list-style-type: none"> - Some contaminants can damage combustion chambers or burners. - Some combustion chamber configurations cannot achieve emissions standards for certain contaminants. - System fine tuning may be required to meet emissions standards.

(2) *Pretreatment via drying/dehumidification.* Primary vapor treatment methods may require the vapor stream to have a low relative humidity for optimal operation. A knockout tank or a mechanical dryer may be used to lower the relative humidity of the vapor prior to primary treatment.

(3) *Treatment via carbon adsorption.* Vapor phase carbon adsorption is like the liquid treatment application, where compounds adsorb from the vapor stream onto the carbon particles. Operational configuration may be either in parallel or in series. Carbon can be regenerated or disposed of off-site. High relative humidity or temperature in the vapor stream decreases the efficiency of the treatment.

(4) *Treatment via thermal/catalytic oxidation.* Oxidation units are used to destroy contaminants in the vapor stream.

(a) Thermal oxidation units are typically single-chamber and refractory-lined, equipped with a propane or natural gas-fired burner and a stack. Burner capacities in the combustion chamber range from 527,000 to 2,100,000 kJ•hr⁻¹ (0.5 to 2 million British Thermal Units [BTUs]) per hour. Operating temperatures range from 760 °C to 927 °C (1,400 °F to 1,700 °F), and gas residence times are typically one second or less.

(b) Catalytic oxidation units use a catalyst to accelerate the rate of oxidation, which enables the unit to destroy contaminants at a lower temperature than conventional thermal oxidation units. VOCs are thermally destroyed at temperatures typically ranging from 320 °C to 540 °C (600 °F to 1,000 °F). Thermal oxidizers can often be converted to catalytic units after initially high influent contaminant concentrations decrease to less than between 1,000 and 5,000 ppm by volume. This method may not be appropriate for the treatment of halogenated compounds, owing to the formation of HCl, which could foul the catalyst.

(5) *Treatment via energy recovery.* Energy recovery (using the extracted vapor as a fuel) is a vapor treatment alternative to common technologies. Energy recovery is used for in situ thermal techniques involving steam injections where the extracted vapor can be introduced to the fuel stream for a gas- or oil-fired boiler. Using extracted contaminant vapors as an energy source for the boiler likely requires additional monitoring of the stack gases to assure compliance with the air discharge permit or other requirements.

c. *Process residuals and off-site waste management.* Process residuals generated from the treatment process need to be managed. Process residuals include spent carbon, filter material, and sludges. Such residuals should be characterized for proper disposal. Disposal options depend on cost. The spent granulated carbon may be taken off-site for disposal (landfill or incineration) or regeneration. Depending on the amount of carbon usage, regeneration on-site may be more cost-effective. NAPL separated in the dissolved air flotation or other oil-water separator must be stored for proper disposal.

6–6. Other system considerations

a. Enclosures/buildings. ISTR methods may be housed inside buildings or exposed to the elements. Systems inside buildings should have adequate ventilation to prevent buildup of vapor. Mechanical and electrical components placed outside should be rated as weatherproof.

b. Surface covers. To control vapor migration, a surface cover or impermeable cap should be constructed at the site. Soil pore spaces can be filled by water infiltrated from the surface, reducing the airflow. If horizontal extraction wells are installed, infiltration water can fill the trenches. Installation of a surface cover helps minimize infiltration of water. In addition, the radius of influence of the VR wells may be increased by using an impermeable cap at the surface. Short-circuiting of the surface air is prevented if a good surface seal is achieved and forces air to be drawn from a greater distance.

(1) Concrete or asphalt is the most common surface cover. If the site has pre-existing pavement, it may act as the surface cover. The pavement should be sealed so that it is water-resistant and relatively impervious to airflow.

(2) A temperature- and contaminant-tolerant geomembrane may be used for the ISTR surface cover if no pavement exists at the site. The area should be graded and smoothed to eliminate ponding of rainwater. Follow the installation procedure of the geomembrane provided by the manufacturers.

(3) To minimize damage to the geomembrane by personnel, equipment, or the natural elements, an appropriate 15 cm to 30 cm (5.9 in. to 11.8 in.) thickness of fill (pulverized soil, sand, or pea gravel) may be placed over it. It is not recommended to leave the geomembrane exposed. However, if exposure is not avoidable, its perimeter should be keyed into a trench and backfilled to prevent short-circuiting of air. In addition, runoff water should be directed to ditches that divert the water away from the treatment area.

c. Noise control. Sound levels are measured in decibels using a logarithmic scale. The standard measure for environmental sound levels is the A-weighted decibel (dBA) sound pressure level. The dBA scale was developed to simulate the frequency response of the human ear to sounds at typical environmental levels.

(1) The EPA has identified yearly day-night average sound levels (Ldn) sufficient to protect public health and welfare from the effects of environmental noise. The EPA emphasizes that since the protective sound levels were derived without concern for technical or economic feasibility and contain a margin of safety to enhance protective values, they must not be viewed as standards, criteria, regulations, or goals. The EPA has no authority to regulate ambient noise levels. Ldn should be viewed as the level below, at which there is no reason to suspect that the general population is at risk from noise-related effects. According to the EPA, levels are sufficient to protect public health

and welfare if they do not exceed a yearly average Ldn of 55 dBA outdoors and 45 dBA indoors in sensitive areas such as residences, schools, and hospitals (USEPA 1977).

(2) The Occupational Safety and Health Administration (OSHA) has established maximum permissible worker noise exposure levels to protect against hearing damage. The level is based on a worker's noise exposure over a specific time.

(a) For example, as stipulated in Title 29 of the Code of Federal Regulations, Part 1910, a worker cannot be exposed to an average sound level beyond 90 dBA for over an 8-hour period. When noise exposure exceeds the permissible level, noise must be reduced through feasible engineering or administrative controls. When such controls fail to reduce noise exposure to a permissible level, personal protective equipment must be provided and used to reduce noise exposure. In addition, when worker noise exposure exceeds 85 dBA over an 8-hour period, the employer must provide hearing protection and establish an annual audiometric testing program to track potential hearing loss.

(b) Therefore, OSHA requirements allow areas within facilities to exceed 85 dBA, provided that feasible noise control has been implemented. These areas are to be designated as high-noise areas that require hearing protection at all times. Compliance with the OSHA noise exposure limits is achieved by providing noise mitigation equipment and by identifying the high-noise areas with warning signs that prescribe hearing protection.

(3) The construction phases of the ISTR system consist of site preparation, injection/extraction/heater well or electrode drilling, equipment erection, and startup. Noise emissions vary with each phase of construction, depending on the activity and the associated equipment. Construction activities should be scheduled during daytime periods (0700 hours to 2000 hours) to the extent possible. Some activities may require extended hours of operation because of scheduling constraints. Nighttime construction should be limited to low noise-producing activities to the extent possible.

(4) The primary noise sources anticipated from the treatment site are the steam generator, the air compressor, the heat exchanger, blowers for VR and air strippers, and the thermal oxidizer exhaust stack. Noise reduction design features should be included where feasible (stack silencer for the thermal oxidizer stack, low-noise fans on the heat exchanger, enclosure of the air compressor, blowers, etc.).

d. Subsurface barriers. NAPL migration may be contained, and groundwater recharge may be controlled with the use of subsurface barriers. The type of barrier wall should be selected based on the specific installation configuration, required installation depth, contaminant type, and installation cost. Typical subsurface barriers are, but are not limited to, soil-bentonite slurry, (steel or plastic) sheet piles, pressure-injected grout curtains, or a synthetic material (high-density polyurethane).

(1) Slurry wall barriers are constructed by excavating a relatively narrow vertical trench, typically 0.6 m to 1.5 m (2 ft to 5 ft) wide, through a previous soil stratum to an

underlying impervious layer. The trench is filled with bentonite-water slurry during excavation to stabilize the trench walls, allowing excavation to continue through the slurry to the desired depth. Once the desired depth has been reached, the slurry trench is backfilled with a soil bentonite water mixture designed to provide a low-permeability barrier wall (10^{-7} to 10^{-8} cm•s⁻¹).

(2) Designers should consult Unified Facilities Guide Specifications 31 56 13.13 for Hazardous, Toxic, and Radioactive Waste projects and other USACE reference documents if considering use of a soil-bentonite cut-off wall.

6–7. Modeling

a. General. Mathematical models have proven to be useful for simulating and predicting physical and chemical processes during thermal treatment. Modeling efforts may utilize varied mathematical tools, ranging from simple engineering calculations to sophisticated numerical modeling codes. The level of detail required for thermal modeling depends on several factors, including site conditions, cleanup objectives, and budgetary constraints. Always remember that the utility of modeling results depends on the quality of the input data. In general, appropriately selected and properly implemented modeling procedures should result in construction and operations cost savings that are much greater than the cost of the modeling. Previous guidance on modeling for SVE systems (USEPA 1995) is also applicable to ISTR projects.

(1) Note that ISTR simulations can yield misleading results unless they are very carefully performed. Input parameters such as the anisotropy ratio (horizontal to vertical permeability) and low-permeability lenses can totally control the heating pattern and should be captured in the models. Models that are intended for uses other than preliminary design analyses should incorporate the following features.

(a) Geological layering and heterogeneity.

(b) Intrinsic permeability (affects injection rates and radius of influence).

(c) Anisotropy ratio of major layers (influences the degree of vertical steam rise and the ability to heat the base of thick aquifers).

(d) Heterogeneity and discontinuities in low-permeability layers (affects upward steam migration through aquitards).

(2) Ideally, predictive modeling should be done using a model that has been calibrated or verified by comparison to actual field steam or heat flow (Ochs et al. 2003).

b. Applicability and objectives.

(1) Modeling is primarily applicable to feasibility studies and design analyses of thermal remediation projects; however, models may also be used during operations and long-term monitoring. The objectives of modeling should be carefully weighed before

selecting the modeling strategy. Minimum objectives for modeling include estimation of the following parameters.

(a) *Injection and recharge rates for wells.* These data are necessary for designing fluid conveyance and treatment systems.

(b) *Well or electrode spacing and design.* Trials with different well spacings, depths, and screen lengths can help optimize design for energy or steam distribution and contaminant recovery.

(c) *Heating duration.* Simulations can predict the length of time required to achieve treatment temperature throughout the TTZ for a given well spacing and energy input.

(d) *Energy requirements.* Electrical power or steam injection requirements must be predicted to estimate plant capacities, total energy costs, and project duration.

(2) Additional objectives could include evaluations of the following.

(a) *Contaminant removal.* Models can be used to evaluate the effectiveness of the removal of dissolved, sorbed, or NAPL contaminants and to predict the removal rate, including the effects of chemical reactions such as hydrolysis, oxidation, and pyrolysis.

(b) *Site hydraulic control.* To prevent the spreading of contaminants, it may be necessary to control groundwater flows during treatment.

(c) *Aquitard heating.* Predictions of time and energy required to heat low-permeability materials may be useful for system design or selection of the treatment strategy.

(d) *Heat losses.* Evaluations of the extent of heat losses to surrounding zones and to the atmosphere and the need for surface insulation; identification of zones where contaminants may be deposited due to condensation; assessments of the effects of heating on sensitive utility lines and structures; and the need for protective measures such as insulation jacketing.

(e) *Environmental impacts.* Thermal effects on biota surrounding the treatment area or on the ground surface above the treatment zones may be of concern.

(f) *Emissions.* Vapor discharges and concentrations at the ground surface may be estimated.

(g) *Operations scenarios.* Scenarios include shutdown of power for sampling events.

(h) *Procedures.* Procedures like pressure cycling or variations of energy input, pumping, or vacuum extraction rates may be evaluated before implementing in the field.

c. *Model solutions and codes.* Models may be divided into two broad categories: analytical solutions or numerical modeling codes. Available solutions and codes are listed in Table 6–3 and Table 6–4, along with the processes that can be modeled.

(1) *Analytical solutions.* Analytical solutions are relatively easy and inexpensive to use; however, the results are subject to uncertainties caused by their inherent assumptions (homogeneous and isotropic media, domains of infinite horizontal extent, and steady-state conditions). The following analytical solutions are applicable to thermal remediation projects.

(2) *Energy budget calculations.* Simple thermodynamic calculations can be made of the total energy or heat input requirement to raise a given volume of soil and groundwater to a required temperature (see paragraph 6–2a for a calculation example).

(3) *Heat flow.* Numerous heat-transfer equations are available for estimating the migration of heat through materials by both conduction and convection (Carslaw and Jaeger 1959, Incropera and DeWitt 1996).

(4) *Liquid flow.* Well-hydraulics equations are applicable to all in situ thermal technologies that employ liquid extraction wells. Radial flow solutions such as the Thiem (1906), Theis (1935), or Jacob (1940) equations may be used to estimate groundwater pumping rates. If single-phase conditions can be assumed, and if adjustments are made for liquid density and viscosity, the same equations can also be used to estimate NAPL removal rates for known NAPL thicknesses.

(5) *Vapor flow.* Well-hydraulics equations that have been adapted for gas flow are applicable to all in situ thermal technologies that employ gas extraction wells and may be used to estimate gas extraction rates. The same equations may also be used to estimate steam or air injection rates. Steady-state solutions are applicable to gas extraction and injection because underground vapor flow tends to stabilize rapidly. If pressure differentials greater than 0.2 atmosphere exist within the treatment zone, however, the equations must also be adapted for compressible fluid flow (Massman 1995). Additional gas-flow equations for planar sinks may be used to estimate non-condensable gas leakage through barrier walls, from the ground surface, or through low-permeability caps.

d. *Numerical modeling codes.* Numerical models tend to be more costly and labor-intensive than analytical solutions, but they can simulate site geometry and stratigraphy, heterogeneous and anisotropic media, multiple processes, interactions between multiple flow and energy sources, and time-variable conditions or treatment operations. A distinct advantage of numerical models is the ability to predict the three-dimensional shape and migration pattern of steam zones and NAPL-condensation zones; this capability has proven useful for well design and selecting well/electrode spacing. In general, numerical simulations are appropriate for projects with relatively complex site conditions or stringent cleanup objectives. Three broad classes of modeling codes are listed below, in order of increasing data requirements.

(1) *Groundwater models (single-phase, isothermal)*. If control of contaminant migration is necessary, conventional groundwater models may be used to simulate groundwater flow patterns during thermal treatment. This is particularly convenient for projects where a site groundwater model has already been developed.

(2) *Combined heat, groundwater, and gas flow with phase changes (two-phase, thermal)*. This is the most useful model for simulations of steam and heat migration. Most of the required fluid property data are already contained in the computer code, and typical design issues involving wells, soil caps, subsurface barriers, and operations scenarios can be addressed.

Table 6-3
Applicability of models to individual technologies

Analytical Solution or Numerical Modeling Code	Technology			Reference
	Thermal Conduction	Electrical Resistance Heating	Steam Injection	
ANALYTICAL SOLUTIONS				
Fluid Flow				
- Radial flow of liquid to a well.	X	X	X	Jacob (1940), Theis (1935), Thiem (1906)
- Radial flow of gas to/from a well.	X	X	X	USEPA (1999c)
- Linear flow of gas to a plane sink.	X	X	X	-
Heat Flow				
- Heat balance.	X	X	X	-
- Radial flow from a line source.	X	-	-	Carslaw and Jaeger (1959)
- Linear flow from a plane source.	X	-	-	Carslaw and Jaeger (1959), Incropera and DeWitt (1996)
Combined Heat/Fluid Flow				
- Marx-Langenheim equation.	-	-	X	Marx and Langenheim (1959)
- Marx-Langenheim with radial gas flow.	-	-	X	USEPA (1999e)
Van Lookeren solution.			X	Van Lookeren (1983)
NUMERICAL MODELING CODES¹				
HYDROTHERM	X	2	X	U.S. Geological Survey Hydrologic Analysis Software Support Program 437 National Center

Analytical Solution or Numerical Modeling Code	Technology			Reference
	Thermal Conduction	Electrical Resistance Heating	Steam Injection	
				Reston, VA 20192
Multiphase Multicomponent Non-Isothermal Organics Transport Simulator or M ² NOTS	X	²	X	University of California 6147 Etcheverry Hall Berkeley, CA 94720-1740
Non-isothermal Unsaturated Flow and Transport or NUFT	X	X	X	LLNL 7000 East Ave. Livermore, CA 94550-9234
PORFLOW [®]	X	²	X	Analytical and Computational Research, Inc. 1931 Stradella Road Bel Air, CA 90077
STAR	X	²	X	Science Applications International Corporation 10260 Campus Point Drive San Diego, CA 92121
STARSTM	X	X	X	Computer Modeling Group Paragon Center One 450 Gears Road, Suite 860 Houston, TX 77067
Subsurface Transport Over Multiple Phases or STOMP	X	X	X	Pacific Northwest National Laboratory 3200 Q Avenue Richland, WA 99352
TETRAD Geothermal Simulator	X	X	X	ADA International Consulting 705 Hawkwood Blvd. NW Calgary, Alberta T3G 2V7 Canada
Transport of Unsaturated Groundwater and Heat or TOUGH2 (Version 2)	X	²	X	Lawrence Berkeley National Laboratory 1 Cyclotron Road, 90-1116 Berkeley, CA 94720

Notes:

¹ All codes run on computers and can simulate phase changes and flow of heat and liquid water/vapor.

² These numerical models do not include code modeling electrical heating but can simulate the process using simplifying assumptions discussed in paragraph 6–7i.

Table 6–4
Features of numerical modeling codes⁴

Code	Features									
	NAPL Flow	Interphase Partitioning	Solute Transport	Vapor Transport	Emulsions	Chemical Reactions	Electrical Fields	Graphical User Interface	Pre-processor	Post-processor
HYDROTHERM	-	-	-	-	-	-	-	-	-	X
M ² NOTS	X	X	X	X	-	-	-	-	-	-
NUFT	X	X	X	X	-	1	X	2	2	2
PORFLOW [®]	X	-	X	-	-	X	-	X	X	X
STAR	-	X	X	X	-	1	-	3	3	3
STARS [™]	X	X	X	X	X	X	X	X	X	X
STOMP	X	X	X	X	-	1	X	-	-	-
TETRAD	X	X	X	X	-	X	X	3	3	3
TOUGH2 (version 2)	X	X	X	X	-	1	-	3	3	3

Notes:

¹ Decay only.

² Groundwater modeling system Non-isothermal Unsaturated-saturated Flow and Transport model only.

³ Commercially available.

⁴ Minimum capabilities include simulation of liquid water, water vapor, and heat flow with water phase changes. Codes with pre-processors and post-processors are generally easier to use.

(3) *Combined heat, groundwater, gas, and non-aqueous phase liquid flow with phase changes (three-phase, thermal).* Many multiphase-thermal modeling codes can simulate NAPL flow as well as mass transfer between NAPL, aqueous and gas phase. Some of the codes can simulate separate contaminant compounds in the NAPL, or “pseudocomponents” with averaged properties for combined groups of contaminants. The effectiveness of the thermal treatment can be evaluated, and design parameters such as NAPL recovery rates, contaminant concentrations in recovered fluids, and cleanup times can be estimated. A few numerical codes can also simulate chemical reactions involving contaminant constituents.

e. *Input data.* Media or formation data required for modeling include soil physical properties (density, porosity), thermal properties (heat capacity and conductivity), and hydraulic properties (permeability, pressure-saturation permeability characteristics).

(1) Groundwater and steam properties, such as density, viscosity, and thermal characteristics, are temperature-dependent; this information may be obtained from steam tables and is generally computed automatically by the numerical modeling codes. If groundwater and soil contamination are simulated, chemical transport properties for

each component are required (solid-liquid and liquid-vapor partitioning coefficients, enthalpy, and degradation constants).

(2) NAPL flow simulations require additional NAPL properties, including density, viscosity, and pressure-saturation permeability characteristics. Since NAPL physical and chemical properties are temperature-dependent, care needs to be taken to utilize appropriate data for the required temperature ranges.

f. Implementation of model results. Models may be used at various stages of project development. A model may be useful in the feasibility stage to evaluate potential energy costs or environmental effects for one or several technologies. Models are particularly important during the design stage, when plant and well-field parameters must be developed.

(1) The trade-off relationship between cost, performance, and project duration can also be evaluated by modeling. Sensitivity studies, based on known uncertainties in site soil and fluid properties, can be used to develop safety factors for equipment design. Models providing useful information for planning treatment cycles, treatment zone size, monitoring programs, or project duration may also simulate operation strategies.

(2) Models that are updated and calibrated during testing and operations may be used to evaluate operational problems and to provide refined designs based on initial or pilot test results. Predictions of cooling rates, contaminant degradation rates, and required duration for long-term monitoring can be made through the continued use of a project model after completion of active thermal treatment.

g. Applicable modeling codes. Refer to Table 6–3 for references and availability regarding modeling codes versus specific technologies. The applicability of various solutions or modeling codes to specific technologies is discussed further in the remaining paragraphs.

h. Modeling aspects for thermal conductive heating.

(1) *Analytical solutions.*

(a) *Energy budget.* The energy input requirement for a known treatment volume can be calculated (example shown in paragraph 6–2), based on the required treatment temperature, thermal capacities of the soil and groundwater, and the latent heat required to convert the groundwater to steam, as necessary. Additional allowances may be needed for heat that is lost to the atmosphere or surrounding soil.

(b) *Heat conduction equations.* Heat flow from heater blankets and heater wells can be simulated with transient solutions for linear heat conduction from a plane source and radial conduction from a line source, respectively. A summary of analytical equations used to describe phenomena in thermal conduction processes is available (Stegemeier and Vinegar 2001).

(c) *Superposition.* Temperatures within an area being treated with multiple heating wells and blankets can be calculated by superimposing planar and line sources (summing the predicted temperature change at a given point attributable to each source to predict the total temperature change at the point due to all sources).

(d) *Gas flow equations.* As discussed, compressible fluid flow equations may be used to estimate gas extraction rates for contaminant recovery.

(2) *Numerical modeling codes.* All numerical modeling codes listed in Table 6–3 and Table 6–4 may be used for simulating conduction heat sources. The sources may be implemented as boundary conditions, for example, the upper model boundary for a heater blanket or a column of cells for a heater well. Some of the codes have well options that include energy input only with no fluid. Sources may be given a specified temperature or a specified thermal energy input rate.

i. Modeling aspects for electrical resistivity heating.

(1) *Analytical solutions.* The energy budget calculation is also applicable to ERH; however, the total energy requirement must be converted to electrical energy units (such as joules or BTU converted to kilowatt-hours). Typically, the spacing between electrodes is established by the ratio of the diameter of the electrode array to the diameter of the electrode. The electrode's diameter is equal to the diameter of the pipe used to make it, plus the graphite and steel shot. Spacing is modified through engineering judgment or established "rules of thumb" derived from previous experience, instead of relying on analytical solutions.

(2) *Numerical modeling codes.* All the numerical codes listed in Table 6–3 and Table 6–4 may be used for simulating ERH sources by using the simplifying assumption that the input electrical energy is applied uniformly within a finite soil volume surrounding or between electrodes. Some of the computer codes can also simulate the electrical field as well as soil heating based on electrical currents and soil resistance. An essential feature in electrical heating codes is the ability to vary soil resistance with temperature and fluid saturation; this capability is particularly important near electrodes, where the flow of electrical current can be impeded by dry soil conditions.

j. Steam injection modeling aspects.

(1) *Analytical solutions.*

(a) *Radial gas flow.* As discussed, steady-state radial compressible-fluid flow equations may be used to estimate both steam injection and gas extraction rates.

(b) *Steam zone radius.* The Marx-Langenheim equation (Marx and Langenheim 1959) is widely used for calculating the growth of a cylindrical steam zone around a single steam injection well for an assumed injection rate and steam temperature. The optimum well spacing can be selected as the predicted steam zone radius at a desired steam breakthrough time (time for steam to reach the extraction wells), typically in the range of two to three weeks. Users of the Marx-Langenheim equation need to consider

the potential for underestimation of the steam radius when the actual steam volume is non-cylindrical, owing to the effects of steam override and adjacent injection wells.

(c) *Coupled gas flow and steam-radius calculations.* A steady-state gas flow equation may be combined with the Marx-Langenheim equation to simulate a variable steam injection rate with time, as the steam radius increases. The calculation is implemented in a spreadsheet, over a series of time steps (Lawrence Livermore National Laboratory 1994).

(2) *Numerical modeling codes.* All numerical modeling codes listed in Table 6–3 and Table 6–4 are capable of simulating steam injection remediation. Most of the codes have well options that include productivity coefficients, well-efficiency corrections, and pressure control versus flow control. An important feature provided by some of the modeling codes is the ability to simulate a multiphase well (pressure-controlled vapor extraction and flow-controlled liquid extraction from the same well).

(a) It should be noted that steam simulations can yield misleading results unless they are very carefully done. Input parameters such as the anisotropy ratio (horizontal to vertical permeability) and low-permeability lenses can totally control the heating pattern and should be captured in the models. Models that are intended for use other than preliminary design analyses should incorporate the following features.

1. Geologic layering and heterogeneity.
2. Intrinsic permeability (affects injection rates and radius of influence).
3. Anisotropy ratio of major layers (influences the degree of vertical steam rise and the ability to heat the base of thick aquifers).
4. Heterogeneity and discontinuities in low-permeability layers (affect upward steam migration through aquitards).

(b) Ideally, a predictive model that has been calibrated or verified by comparison to actual field steam flow should be used (Ochs et al. 2003).

k. *Checklist for review of models for in situ thermal remediation.* A checklist for reviewing models for ISTR is in Appendix C of this document. This list is focused on issues specific to thermal and multiphase modeling. General guidelines for the use of groundwater models are also applicable (Anderson and Woessner 1992).

Chapter 7

Cost and Performance Results

7–1. Introduction

Pilot studies and full-scale deployments are increasing our understanding of the underlying scientific principles and the practical field engineering aspects of ISTR technologies.

a. This chapter provides an overview of case study information. Appendix B provides the case study information that includes the types of sites and site conditions (stratigraphy, permeability, vadose/saturated conditions, depth, etc.) where the technologies are being employed. Appendix B also provides not only cleanup goals but also the performance of the technologies used to meet those goals, along with cost information and trends where available.

b. Sites identified and described in this chapter and the appendix are intended to illustrate the types and range of deployments rather than give a comprehensive inventory of all applications. EPA maintains an online database of in situ thermal technology deployments. Projects are organized by technology. The database is at <http://www.cluin.org/thermal>.

c. On completion of the ISTR project, a cost and performance remedial action report should be completed. Final costs are included and shown to the third level of the Hazardous, Toxic, and Radioactive Waste remedial action work-breakdown structure.

7-2. General observations

While the experience base is growing, there is not an extensive database of projects, thus limiting general insights. It is worthwhile noting that in virtually all applications of ISTR documented herein, much more contamination was recovered than was originally thought to be present.

a. At the Visalia wood treater, an SEE project recovered over 1×10^6 pounds of contamination where a pump-and-treat system had been operating for over 20 years, recovering as little as 10 pounds/week.

(1) Based on groundwater concentration data for the SEE application in Skokie, IL, the site was initially estimated to have in the order of 1,000 kg (2,200 lbs) of TCE and 1,1,1-TCA, based on groundwater concentration data. At the completion of the project, an estimated 29 metric tons of solvent had been removed or degraded through biodegradation or hydrolysis using both SEE and ERH.

(2) At the most recent application of SEE at a fractured rock site, a pilot-scale demonstration project at Edwards AFB recovered 910 kg to 1,360 kg (2,000 lbs to 3,000 lbs) of solvents in an area thought to have on the order of 45 kg (100 lbs) of contamination. Thus, as has been noted elsewhere, in anticipation of significant recoveries, it is important that contaminant recovery systems be adequately sized.

b. Full-scale deployments have occurred in various settings. Many of these applications involve successful subsurface heating and contaminant recovery, despite the presence of underground appurtenances such as sewer lines, phone lines, and optic fiber lines. While engineering adjustments must be made for these features, they are not an insurmountable challenge. TCH applications have been set up in proximity to residences. As discussed more fully in the ERH section, ERH has been implemented in active commercial settings and within and beneath an operating manufacturing plant.

c. Standards of practice are beginning to emerge about appropriate materials for various contaminant/concentration scenarios. Materials of construction are an important consideration, particularly where corrosive waste is involved. ERH applications have experienced failures of CPVC piping in monitoring wells. ISTD TCH has experienced severe corrosion of piping while treating highly concentrated pesticide wastes. Similarly, it has become common practice for vendors to identify, locate, and shut in wells whose materials or methods of construction are not compatible with the expected temperature regimes. It is also common practice to identify, locate, and cut off horizontal conduits that could serve as a lateral preferential pathway for migration of contaminants or steam.

d. ISTR unit costs are subject to economies of scale and other factors. Subject to adjustments for factors such as contaminant volatility, treatment requirements, etc., as discussed below, unit costs (such as \$/cubic meters [m^3] or \$/yd³) decrease significantly as quantities to be treated increase. Pilot-scale studies may appear to be disproportionately expensive, as many of the mobilization/demobilization and personnel costs are independent of project size. It is also the case that, from a total cost standpoint, "ideal" applications are those involving smaller volumes of media, with large quantities of waste.

e. Unit costs for treatment also depend on the depth of the application, the need to treat various waste streams generated during ISTR, the treatment time and temperatures required for adequate removal to achieve goals, the availability of fuel or power, the risk allocation between client and vendor, the level of required monitoring, and the need for engineering controls of groundwater flow and utility protection.

(1) As the volume of vapor or liquid streams requiring treatment increases, treatment costs may significantly increase, depending on the type of treatment. Sites where vapors may be directly discharged to the atmosphere (rarely the case for ISTR sites) or where condensate or extracted water is not generated in significant quantities have lower unit costs for ISTR. This is better than those sites where elaborate treatment systems for vapors and liquids must be constructed for the project.

(2) Since operating costs, including labor and power or fuel, are related to operating time, the longer heating is required to achieve the objective, the more expensive the job. In locations where contaminants cannot be readily eliminated through thermal treatment or where cleanup standards are particularly strict, expenses may be significantly greater compared to sites with contaminants that are easier to remove and less demanding remediation objectives.

f. Other factors may have a significant impact on some sites. If fuel or power is not readily available at the site, such as at the Wyckoff Superfund site, the costs for providing the energy source may significantly increase costs for the project.

(1) The more risk the vendor is allocated by contract mechanism at a site, generally the higher the bid cost, though there may be benefits to a risk-averse client for such arrangements. Costs increase somewhat as the amount of required monitoring increases, both for process control (such as stack sampling) and environmental purposes (such as assessment of contaminant migration toward nearby water bodies or structures). Lastly, the project costs are at times influenced by the need to overcome issues such as protection of utilities, prevention of thermal impacts to water bodies, and the need for groundwater control through measures such as sheet piling or pumping.

(2) In all, the costs for ISTR applications range widely, and the estimated cost for a given application must consider the project-specific conditions and goals.

g. ISTR technologies have achieved a range of cleanup goals, ranging from very stringent residential and MCL-type standards to state and site-specific industrial/non-residential standards. In a fair number of cases, the cleanup levels achieved significantly exceeded the required performance. In at least one case, the Charleston Navy Yard, where ERH was implemented as an interim remedial measure, significant quantities of contamination were recovered, but the specific percentage reduction goals were not achieved.

h. There is considerable interest in combining ISTR as an aggressive source removal/reduction technology with other more cost-effective polishing approaches to achieve ultimate remediation objectives at the lowest total cost.

7-3. Technology-specific applications

a. Thermal conductive heating.

(1) *Waste types.* Many of the initial deployments of thermal conduction addressed PCBs in soil. Conductive heating has been selected to address contamination from manufactured gas plant coal tars, pesticide residues (hexachloropentadiene), chlorinated solvents, and wood-treatment creosote. It is not necessary to operate conductive heating at maximum temperatures. Thus, the technology is potentially suitable for the full spectrum of VOC and SVOC contaminants as well as the non-volatile contaminants for which it was originally designed. Other soil contaminants, including metals such as mercury and arsenic, have not been tested at present but are theoretically volatile enough to be remediated by TCH.

(2) *Site conditions/characteristics affecting performance and cost.*

(a) Conductive heating in more permeable soils below the water table often requires control of water infiltration across the site. At the Entergy/Lake Charles manufactured gas plant site, conductive heating was selected to address coal tar and PCB contamination; however, difficulties in dewatering resulted in terminating treatment.

(b) At the Rocky Mountain Arsenal facility near Denver, Colorado, implementation of ISTD was discontinued following severe corrosion of pipes and equipment. As heat was applied to the hexachloropentadiene pit, extremely low pH waste streams were generated, quickly damaging the vendor's equipment. This problem was not revealed by the lab-scale treatability studies that preceded the deployment. The application was stopped after it was determined that it was not cost-effective to retrofit the entire treatment system with the necessary Hastelloy to withstand the corrosive conditions.

(3) *Cleanup goals.* Table 7–1 compares the initial maximum concentrations and the final cleanup concentrations for sites where ISTD has been applied. The PCB projects reduced contamination below 0.033 mg/kg.

Table 7–1
Summary of completed in situ thermal desorption and thermal conductive heating projects

Site	Contaminant	Initial Maximum Concentration (mg/kg)	Final Concentration (mg/kg)	Duration	Cost
South Glen Falls, NY	PCB 1248/1254	5,000	< 0.8	Not Available	Not Available
Cape Girardeau, MO	PCB 1260	20,000	< 0.033	March 1987 to June 1997	\$2M
Vallejo, CA	PCB 1254/1260	2,200	< 0.033	September 1997 to December 1997	\$912K
Portland, IN	PCE	3,500	< 0.5	July 1997 to December 1997	Not Available
	TCE	79	< 0.02		
Saipan, Northern Mariana Islands	PCB 1254	10,000	< 1	1 year	\$5.34M
Eugene, OR	Benzene Gasoline/Diesel	3.3 3,500/9,300 (+LNAPL)	< 0.044 250,000 lbs LNAPL removed	June 1997 to September 1998	\$3M
Ferndale, CA	PCB 1254	800	< 0.17	September 1998 to April 1999	\$456K

(4) *Cost.* Turnkey costs for remediation of 8,400 m³ (11,000 yd³) of material at a solvent site in Ohio, being cleaned up under the Ohio Voluntary Cleanup Program, were reported as \$1.3 million, yielding a unit cost of \$154/m³. The project included a performance guarantee. These numbers are within the range of general costs provided by the vendor. Higher (by two times or more) unit costs for treatment of recalcitrant compounds such as PCBs have been reported due to the higher temperatures and longer treatment times required.

b. Electrical resistivity heating.

(1) *Waste types.* ERH has been used most widely to address VOCs (such as TCE, PCE, and methylene chloride). As presented in Appendix B, it has also been used to address a diesel range organic waste at a facility in Atlanta, GA. Contaminants are generally recovered as vapor, but at least one application (Waukegan, IL) appeared to have experienced a significant amount of in situ destruction.

(2) *Site characteristics/conditions affecting performance and cost.* ERH is particularly suitable for lower permeability zones. It has been used in fine-grained lacustrine sand at Skokie, IL, and glacial clay tills in Waukegan, Lisle, and Elk Grove Village, IL. ERH has been used to recover contaminants from sand, silt, clay, and gravel strata, and various combinations thereof.

(a) In Paducah, KY, ERH has been used as deep as 30 m (100 ft). In at least one application, Fort Wainwright, AK, ERH has been used for the primary purpose of creating conditions favorable to in situ biodegradation.

(b) An important feature of ERH is that the technology can be installed and operated entirely below grade, if necessary. The first example of such an application was for a confidential client at a dry cleaner in western Washington state. An ERH system was installed beneath the building and adjacent roadways and parking lots so as not to interfere with vehicle or pedestrian traffic. A subsequent deployment in Portland, OR, involved subgrade installation of piping and wellheads for a portion of the contamination that extended beneath an adjacent roadway. A full-scale ERH application was completed at Air Force Plant #4 in Texas. The system was installed in a building where active F-16 jet fighter aircraft manufacturing activities were underway.

(3) *Cleanup goals.* ERH is reported to have achieved MCLs for a dry cleaner site in western Washington state.

(a) At the Skokie, IL, ERH project, initial cleanup goals were established as site-specific Illinois Tier III (industrial) criteria. ERH performance was sufficiently promising that heating was continued after achievement of the Tier III standards to ensure that, after treatment was discontinued, the expected subsequent intrinsic biodegradation did not result in the production of vinyl chloride beyond the Tier III criteria. When the project was terminated, 4 of the 13 monitoring wells established for post-treatment monitoring achieved the more stringent Tier I, Illinois Class II groundwater standards.

(b) Subsequent monitoring indicated a continuing downward trend in contaminant concentrations, such that, 18 months after completion of ERH treatment, 11 out of 13 wells had achieved the Class II groundwater standards (Smith et al. 2000). At that time, the Illinois EPA approved discontinuing monitoring and removal of the monitoring wells so that the property could be redeveloped.

(4) *Cost.* Table 7–2 provides vendor-supplied information indicating the range of costs for various contaminants and quantities.

**Table 7-2
Summary of selected electrical resistance heating projects**

Site	Contaminants	Quantity m ³ (yd ³)	Cost
Skokie, IL	TCE, TCA	27,000 (35,000)	\$32 ¹
Portland, OR	TCE	16,400 (21,500)	\$42
Waukegan, IL	Methylene Chloride	12,000 (16,000)	\$61
Chicago, IL	PCE	9,000 (12,000)	\$80
Fort Lewis, WA	TCE, Hydrocarbon	61,000 (80,000)	>\$200 including water treatment

Note:

¹ Off-gas treatment not required. Vendor estimated an additional \$9/yd³ if it had been required.

c. Steam enhanced extraction.

(1) *Waste types.* Steam injections have been used to recover many compounds.

(a) Examples of these compounds include wood-treatment wastes (creosote, PCP) found in Visalia, CA. Chlorinated solvents (TCE and PCE) were recovered in Alameda, CA; Skokie, IL; Northlake, IL; and the Young-Rainey Science, Technology, and Research Center in Largo, FL. Jet fuel was found in Lemoore, CA; mineral spirits in Northlake, IL; and gasoline-range petroleum hydrocarbons at the LLNL Gas Pad.

(b) At the Yorktown Naval Facility, steam within horizontal stainless steel wells are being used to reduce the viscosity of Navy Special Fuel Oil to facilitate recovery in a system of trenches. Further work is under way to use steam to recover diluent from Unocal's Guadalupe field in California. SEE has been selected for use at the Port of Ridgefield wood treater, and a pilot study was conducted at the Wyckoff National Priorities List wood-treater site on Bainbridge Island, WA.

(2) *Site attributes/conditions affecting cost and performance.* As previously noted, steam injections are most appropriately applied for conditions with adequate permeability to transmit the steam. Low permeability zones may be amenable to steam injection remediation through conductive heat transfer if they are of limited thickness and steam can be delivered above and below the low permeability zones. At the Visalia site, significant contamination was recovered from a 9 m (29.52 ft) thick aquitard at a depth of 30 m (98.4 ft) by installing injection wells through the aquitard and injecting steam from below the confining layer.

(a) Previously, steam injections were used in different hydrogeological settings. It is generally not necessary to dewater the site prior to steam injection. At the Visalia, Skokie, and Northlake sites, most of the contamination addressed was in the saturated zone. Groundwater flow/recharge rate at the Visalia site was on the order of 0.3 m/day

to 0.9 m/day (1 ft/day to 3 ft/day), while at the Skokie and Northlake sites there was minimal natural movement.

(b) For porous media sites, stratigraphy along with the thickness of individual layers is important for the steam injection approach. For sites with multiple aquifer zones separated by aquitards, multiple injection and extraction intervals may be necessary (Livermore Gas Pad, Savannah River Site, SC; Visalia Pole Yard, CA). Sites with a low anisotropy ratio (ratio of horizontal to vertical permeability), such as Alameda Point, CA (consisting of fill material and bay muds), and the Guadalupe Sand Dunes (consisting of wind-deposited sands), must be carefully designed to prevent excessive steam override. This approach can involve multiple injection intervals; shallow vapor extraction systems to capture steam; quenching designs to inject cold water where steam is undesired; and potentially using air injection to block steam migration into certain areas.

(c) SEE has been used on a site as large as 12,100 m² or 3 acres (Skokie and Northlake, IL). It has been used as deep as 41 m (135 ft) at Visalia and as shallow as 3 m (10 ft) at Alameda, where heating occurred beneath a concrete pad in front of a former hangar.

(d) At several sites, SEE was selected owing to the availability of previously existing on-site steam generation capacity.

(e) SEE has been deployed at fractured bedrock sites at Edwards AFB and former Loring AFB under the auspices of EPA's Superfund Innovative Technology Evaluation program. These rock sites were treated to 18 m and 27 m (60 ft and 90 ft), respectively. Two additional pilot-scale demonstrations were conducted in 2003 and 2004.

(f) Case study summaries for these projects are provided in Appendix B.

(3) *Cleanup goals.* Provided below is a listing of the cleanup goals that have been put in place for varying SEE applications.

(a) Demonstrate that heating can be achieved and that mass removal can be accelerated compared to previously deployed methods (Savannah River Site, Edwards AFB Site 61, Loring Quarry, Beale AFB).

(b) Achieve predetermined numeric standards for soil and groundwater concentrations (Alameda Point, Young-Rainey Science, Technology, and Research Center).

(c) Remove mobile NAPL and restore groundwater quality at compliance points (Visalia Pole Yard, Wyckoff-Eagle Harbor, Port of Ridgefield).

(d) Eliminate source zone input of COCs to down-gradient dissolved plume (Alameda Point).

(e) Meet Model Toxics Control Act standards for soils or MCL for groundwater (Wyckoff-Eagle Harbor).

(f) Implement the best available steam technology, operate it until diminishing returns are achieved, and follow up by sampling and negotiations with regulators for site closure with or without alternative contaminant levels.

(4) *Cost information.* At the Visalia Pole Yard National Priorities List site, Southern California Edison (SCE) spent roughly \$21.5 million to remediate the 8,100 m² (2-acre) parcel. Information on the cost per pound or gallon of contaminant is also available. SCE had been conducting pump-and-treat operations at the facility since 1976, recovering approximately 4.5 kg (10 lbs) per week at a cost of \$1 million per year. Cost per pound for pump-and-treat was on the order of \$4,400/kg (\$2,000/lb). In approximately 3 years of steam heating, SCE recovered or destroyed more than 590,000 kg (1.3 million lbs) of creosote and PCP waste. The cost for SEE was less than \$44/kg (\$20/lb) and less than \$130/m³. Unit costs at other sites varied from \$20/m³ for a full-scale operation to more than \$500/m³ for a pilot project. Refer to Table B-22 and Table B-23 for additional information on costs for SEE.

Chapter 8

Performance Monitoring and Operations and Maintenance

8-1. Subsurface monitoring for in situ thermal remediation technologies

Subsurface monitoring during ISTR operations is essential for regulating energy input into the treatment zone. It helps measure success in terms of subsurface heating and removal of contaminants. In general, instrument data are reduced and interpreted daily during active thermal treatment to facilitate timely changes in operational strategy. The frequency of evaluations of other information, such as analytical chemistry data, may be dictated by budgets and laboratory turnaround time. Monitoring costs represent a large portion of the ISTR budget; therefore, it is necessary to develop detailed data quality objectives prior to specifying a monitoring program. Although manually read gauges and meters are often used on ISTR projects, thought should be given to the use of electronic transducers, electrical resistance tomography (ERT), and data logging equipment, which may reduce labor costs and provide efficient data management.

a. General.

(1) Monitoring data can either be obtained from instruments installed on or in wells or from instruments that are buried at locations of interest. Wellhead instrumentation devices can be read manually or electronically, while electronic transducers are used for buried instrumentation. Buried instruments generally consist of instrument strings (assemblies of vertically spaced temperature and pressure transducers) installed in a backfilled or grouted borehole. Instruments that are installed by direct burial should be resistant to both high temperatures and aggressive fluids that are present in the subsurface.

(2) Table 8–1 of suggested monitoring requirements for ISTR projects is included at the end of this chapter. The table is intended to provide information for planning ISTR projects; actual monitoring likely varies with site-specific objectives and conditions. In addition, monitoring practices may be varied through different project phases (startup, initial heating, treatment including pressure cycling, post-treatment extraction, and monitoring), or as the project team gains new insights from the data.

b. Fluid pressure.

(1) Pressure data has several uses for ISTR.

(a) Feedback on subsurface pressure conditions may help to prevent blowouts, leakage, or fugitive emissions.

(b) Pressure data from enough measurement points allows interpretation of subsurface flow patterns.

(c) Monitoring gas pressures may help to evaluate whether volatilized contaminants are being captured.

(d) Pressure data may help to evaluate the duration and effectiveness of pressure cycles.

(2) The gas pressure at each steam injection or groundwater extraction well may be measured by a pressure gauge or transducer on the wellhead or associated piping.

(a) If a surface-vapor collector layer is used, gauges or transducers may be installed on the collector pipe risers. One or more additional pressure transducers can be installed in the filter pack adjacent to well screens, allowing direct measurement of pressures in the formation without well losses. Gas pressures away from extraction or injection wells can be measured by installing PMPs. PMPs may be pressure transducers at the bottom of buried temperature instrument strings, or they may be small-diameter stainless steel well fitted with either pressure transducers or magnehelic pressure gauges.

(b) PMPs are installed at differing depths and intervals of interest. Capture of volatilized contaminants is indicated by negative pressures (vacuum) at PMPs installed at treatment zone boundaries. If steam is not present in the subsurface, hydraulic head can be measured with a water-level probe in an open well; otherwise, the hydraulic head or fluid level can be estimated from pressure readings.

(3) Gas-flow measurements should be taken at every extraction and injection well. It is also more common to monitor the combined flow rate to track total contaminant removal. Conventional gas-flow measurement, based on the pressure differentials across orifice plates or venturis, can be cost-prohibitive if done at every well. A less expensive alternative is to use a calibrated flow-control valve on each well, with connectors to allow periodic measurements of the pressure differential with a calibrated

portable gauge. The mass flow rate can then be calculated using an estimated specific gravity for the injected steam or extracted steam-air mixture.

c. Fluid flow. Fluid flows are monitored during conductive heating and ERH operations to track removal rates and balance the well field vapor-extraction system. During the process of steam injection, measurements of fluid injection and extraction rates are essential for management of energy flow in the treatment area, to estimate contaminant removal rates from each treatment array, and to maintain overall hydraulic control on the project site. Liquid extraction rates are easily measured using conventional flow meters or by stroke counters if piston pumps are used. As flow meters do not differentiate between groundwater and NAPL, it may be necessary to estimate the NAPL flow rate at each extraction well as a percentage of the total extraction rate. This may be done by observations in a sight glass or periodic collection of liquid samples from the wellhead.

d. Temperature.

(1) *General.* Temperature is the most critical parameter to be monitored on an ISTR project, requiring the best resolution. Temperature data have these uses.

(a) Evaluation of heat migration and distribution, to include effectiveness of energy delivery to the subsurface.

(b) Identification of zones where heating has achieved target temperatures or where thermal destruction is occurring.

(c) Determination of the presence of groundwater (groundwater is present at locations where the temperature is below the boiling point).

(d) Estimation of steam pressures and evaluation of steam flow patterns (when the temperature is above the boiling point, saturated-steam pressure can be calculated directly from the temperature).

(e) Comparison of observed data with predictions from design calculations or modeling.

(2) *Temperature monitoring.* Monitoring temperature at multiple depths and locations is recommended. Temperature measurements should be recorded at least once daily; the rate of temperature change on ISTR projects is typically appropriate for twice-daily readings. Temperature measuring point (TMP) sensors are typically thermocouples installed in vertical strings set in the filter packs of injection or extraction wells and at one or more locations in backfilled boreholes between each well. A typical vertical spacing for temperature sensors is 1 m to 2 m (3.2 ft to 6.5 ft). In general, there are three types of TMP locations.

(a) *Thermal sources.* TMPs located in or near electrodes, thermal wells, or steam injection wells show the maximum temperatures being achieved at the site. For conductive heating projects, these temperatures indicate the level of thermal destruction of contaminants.

(b) *Between thermal sources.* TMPs located between electrodes, thermal wells, or steam injection wells can help determine when target temperatures have been achieved within the treatment zone and if energy is penetrating adequately to areas away from electrodes and wells. TMPs are usually set at the centroid between electrodes, heater wells, or steam injection wells, as this is the location that is slowest to heat.

(c) *Margins of treatment zone.* TMPs at the edges of the treatment zone indicate achievement of target temperatures to the full extent of the material to be treated and can provide protection for sensitive areas beyond the treatment zone.

(3) *Thermocouples.* Thermocouples are the most common temperature-measuring device. The temperature readings are obtained electronically and are based on the voltage difference across a bimetallic sensor element.

(a) Many different types of thermocouples are available for different uses. Types E and K thermocouples, with stainless steel sheaths and Teflon insulation, are the best suited for high temperatures and potentially corrosive groundwater and NAPL. Consideration must be given to the expected temperatures and the heat tolerance of the cable insulation. Use of some thermocouples at electrodes during ERH or very near heater wells at TCH sites may not be appropriate.

(b) Thermocouples can be read by an automatic data logger or manually by connecting a meter to the thermocouple leads. Where large numbers of thermocouples are installed, thermocouple extension wire is often run to an indicator board located at the edge of the exclusion zone, allowing operational staff to scan through and record the entire set of temperature readings quickly at designated intervals. In ISTD remediation, subsurface temperatures and pressures typically change at a rate that is appropriate for periodic (twice daily) manual measurement; extension wires generally run to a single location outside the treatment zone for more efficient data retrieval.

(4) *Fiber optic distributed temperature sensors.* Distributed temperature sensor (DTS) systems measure temperature by means of laser signals transmitted along an optical fiber. The optical fiber is created by placing double loops of thin (0.635 cm or 0.25 in.) tubing in wells and backfilled borings and pumping the tubing full of an optical fluid. A single, continuous fiber can cover a large area with many wells and instrument borings using vertical loops in each well or instrument string. DTS systems can provide vertically continuous temperature data but are typically designed to record temperatures at 1 m (3.2 ft) vertical intervals. Since the electronic controller is the most expensive item in the system, DTS is most economical for larger sites.

(5) *Electrical resistance tomography*. ERT is a geophysical technique whereby electrical energy is passed through the region of interest by multiple paths, allowing the creation of a high-resolution two- or three-dimensional image of subsurface resistivity.

(a) The multiple transmission paths are the result of progressive activation of vertically spaced electrodes that are installed in boreholes surrounding the region of interest. Surface electrodes may also be used along with the buried electrodes. Relatively few boreholes are required to provide good ERT coverage, and few if any electrodes are required within the treatment area itself.

(b) Interpretation of ERT imagery is not straightforward, however, because resistivity is affected by several factors, including soil and fluid temperature, soil mineralogy, fluid saturation and chemistry, salinity, and the presence of NAPL or gas. A baseline ERT image must be generated before the start of the thermal treatment, and subsurface fluid and energy flow are evaluated from images of resistivity. Some of the ambiguity of ERT interpretations can be reduced by the concurrent use of directly measured temperature data from thermocouples or DTS.

e. *Chemistry*. Chemical testing of extracted fluids provides data for estimating mass-removal rates, contaminant destruction rates, and the proportion of contaminants recovered in each operational phase. The analytical data can also be used to evaluate the overall effectiveness and potential duration of the treatment.

(1) *Liquid*. Liquids may be sampled directly from monitoring points, or extraction wells, via sampling taps on each wellhead. Many useful parameters, such as pH, conductivity/total dissolved solids, dissolved O₂, CO₂, and turbidity, can be measured daily with portable instruments and field kits.

(a) The frequency of sampling for site COCs, such as PAHs, PCPs, and VOCs, depends on treatment progress and laboratory turnaround; typical sampling intervals vary from 72 hours to 2 weeks. Sampling should follow standard operating procedures for handling hot liquids, including using proper personal protective equipment (full-face shield over safety glasses, chemical-protective and insulating gloves, waterproof suits, or rain gear). Ideally, low-flow purging and sampling procedures should be followed. Groundwater being pumped from the well should run through a cooling coil in an ice bath before reaching the pump, flow-through cell, or sampling point. Immediately capping the jars and immersing them in ice should prevent the loss of volatile components.

(b) A submerged screen monitoring well also poses a significant risk to samplers. If the well is opened while the subsurface is hot, this provides the conditions analogous to a natural geyser, and steam may flash, blowing hot water out of the well. Submerged screen wells must not be opened when the subsurface is hot. Figure 8–1 depicts a modified monitoring well that allows safe and accurate sampling of groundwater, provided that the depth to water is less than 7.62 m (25 ft) using a peristaltic pump. The Teflon sample line is connected to a stainless steel cooling coil that is immersed in ice water. The cooling coil is connected to a peristaltic pump for sampling. This cools the

groundwater to about 4 °C (39 °F) before it reaches the sample container. Such a sample technique protects the worker from hot or pressurized liquids. The cooling technique prevents loss of VOCs and allows accurate measurements.

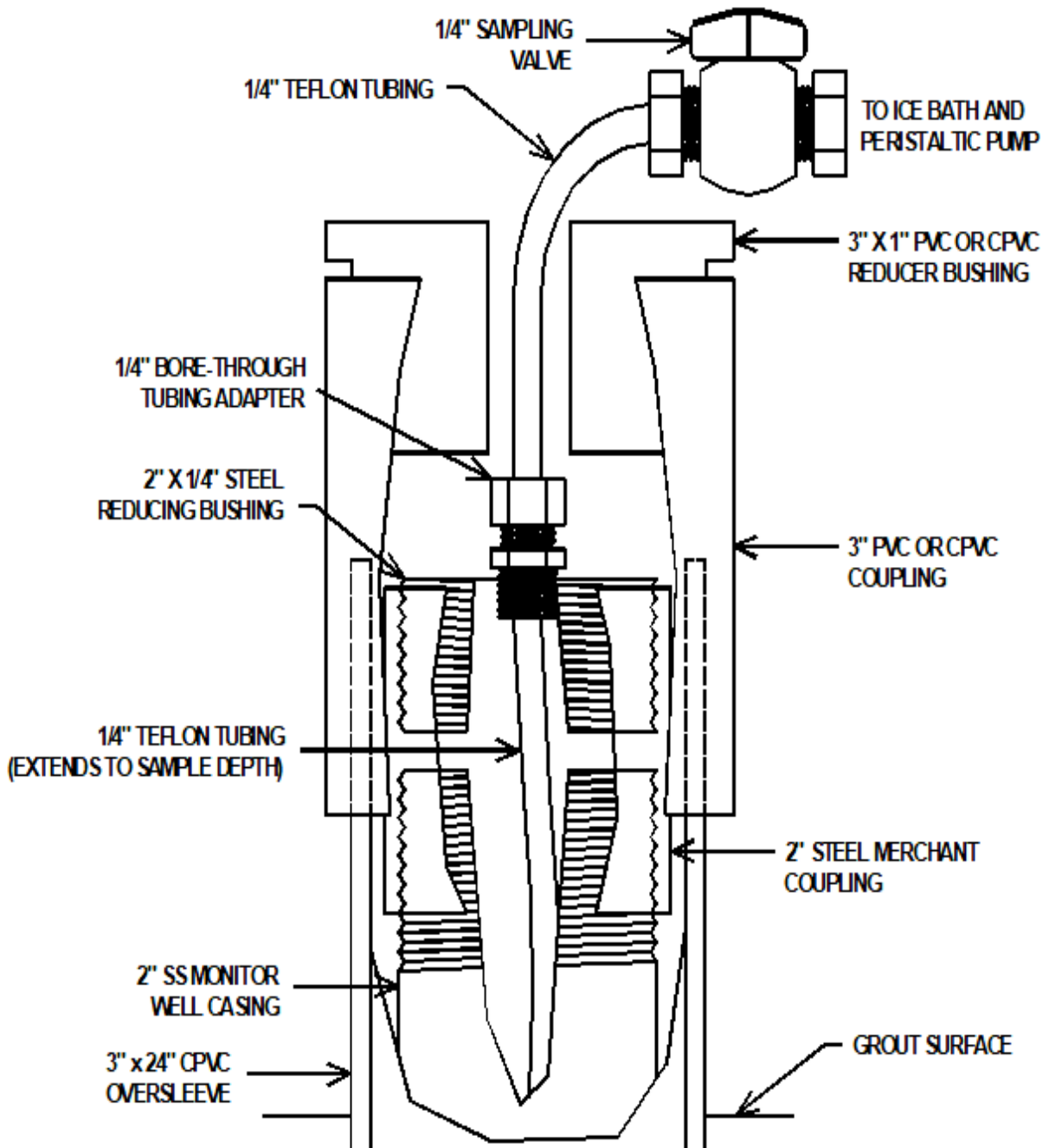


Figure 8-1. Modified monitoring well

(2) *Vapor*. Vapor samples are typically obtained from extraction wellheads with vacuum canisters or Tedlar® bags. Since a portion of the hot vapor sample condenses

when it cools, it is necessary to know the contaminant concentrations in both phases of the cooled sample to determine the original concentrations in the hot extracted vapor. As an alternative to vapor sampling, vapor concentrations can be estimated from liquid concentrations by assuming equilibrium partitioning at the original temperature of the extracted fluids. When interpreting vapor concentration data for steam injection and ERH projects, it is key to remember that steam and volatilized contaminants tend to condense in and around unheated extraction wells (see paragraph 2–1). Due to this, vapor concentrations derived from vapor or liquid sampling may misjudge the true mass of contaminants transported to extraction wells in the vapor phase.

(3) *Electronic sensors.* Electronic sensors may be placed in well discharge lines to provide continuous readings of chemical parameters, including TOC, pH, conductivity, and dissolved oxygen. Continuous TOC data are especially useful for tracking contaminant removal trends throughout each operational phase. Electronic instrumentation for chemical parameters may be too expensive to be installed at each extraction well and may be installed in the main influent lines upstream of the treatment plant. Electronic sensors require periodic calibration and maintenance, and TOC sensors need to be periodically verified with laboratory testing.

f. *Saturation.* At sites that must undergo dewatering prior to application of conductive heating (sites where the soil must be superheated to enable treatment of high-boiling SVOCs), monitoring of saturation during dewatering can aid in minimizing the volume of water that must be boiled off during heating. For example, heating may best be initiated when, following drainage, saturation values have diminished and approached asymptotic levels. Saturation levels can be monitored non-destructively by various methods, including the use of a neutron moisture meter lowered into an access tube and time-domain reflectometry waveguides pushed into the soil. These methods penetrate deeply into the formation, while less costly methods tend to be biased by density or moisture artifacts immediately adjacent to the access tube or probe.

8–2. Operations and maintenance for in situ thermal remediation technologies

This section discusses O&M considerations for TCH, ERH, and SEE heating technologies. Appendix D provides an example Table of Contents for O&M manuals for ISTR projects. This example Table of Contents could be used by people preparing a project-specific O&M manual or could be used as a checklist by persons doing a quality review of an O&M manual prepared by others. Part 3 of Unified Facilities Guide Specifications 02 53 16.16 also includes guidance on O&M.

a. Thermal conductive heating.

(1) O&M of TCH systems is multifaceted and varies from project to project. Most projects have relatively short operational periods, with heating ranging from one to three months. General categories of O&M activities include the items listed here.

(a) Pre-commissioning and start-up.

(b) Normal day-to-day operations.

(c) Normal maintenance.

(d) Data collection and management/record keeping, ensuring compliance with health and safety requirements, emission limits, and equipment operational ranges.

(e) Response to identified problems requiring troubleshooting and contingencies.

(f) Emergency or end-of-heating shutdown.

(2) O&M of subsurface equipment (thermal wells) is mostly straightforward and involves daily monitoring of amperage being delivered to heater circuits, monitoring of subsurface temperatures and pressures, and occasional repair/replacement of faulty components, if necessary.

(a) Other SVE guidance describes the adjustment and balancing of vacuums and flows among heater-vacuum wells and manifolds. However, in the case of thermal conduction systems, it is common to apply only ~50 cm (~20 in.) of water vacuum at the wellhead; that is usually sufficient to enable capture of vapors at the treatment borders.

(b) Toward the end of the heating process, it may be desirable to temporarily convert scattered heater-vacuum wells into passive air injection wells and thereby introduce air into zones that may otherwise be anoxic. Another optional late-term adjustment is to slightly unbalance the flows at individual wellheads to vary the position of subsurface airflow stagnation zones.

(3) O&M of aboveground equipment (collection piping and process components) may, depending on the nature of the project, range from simple to complex. Relatively simple systems are those involving components typical of SVE off-gas treatment equipment, such as a GAC canister or blower and discharge stacks. These systems often enable passive (primarily unmanned) O&M.

(4) More complex systems include those addressing harder-to-treat contaminants, such as chlorinated SVOCs (including PCBs), pesticides, and dioxins.

(a) Such systems may include the use of insertion heaters within insulated piping manifolds, a cyclone separator, a thermal oxidizer, a heat exchanger, a condensate trap, an acid-gas scrubber, GAC vessels, blowers, and a discharge stack. Depending on emission limits and other requirements, such systems may include a computer programmable logic controller; flow, temperature, and pressure measuring instrumentation; a CEM system; several rounds of source testing; and may, depending on site requirements, need to be manned around the clock.

(b) Typically, with complex systems, a minimum of two operators should always be available for safety reasons. Occasionally, collection and treatment of liquid condensate at various points within the piping system is also required and may be integrated into the ISTD off-gas collection and treatment equipment. Ancillary equipment may include fuel (propane) storage tanks for the oxidizer. It is beyond the scope of this document to discuss all the various O&M and monitoring activities that such systems can entail.

(5) Electrical distribution equipment for TCH systems typically includes transformers, distribution panels, and circuit breakers. A backup generator and automatic or manual transfer switch are often provided to power the off-gas treatment equipment (although not the thermal wells) in the event of a power outage. Ancillary equipment includes fuel (diesel) storage tanks for the generator. The O&M requirements of the electrical distribution equipment tend to be minimal.

b. Electrical resistivity heating. During a typical VOC remediation, about 20 percent of the operating time is spent in heating the site to steady temperatures near 100 °C (212 °F). In the vadose zone, temperatures are somewhat less than 100 °C (212 °F). The action of the VR system pulls air through the site and retards temperatures through evaporative cooling. In the saturated zone, temperatures increase more due to hydrostatic pressure and boiling points increasing with depth. Note that the rate of heating varies by vendor. During heat-up, the ERH energy that exceeds the heat-loss rate results in an increase in subsurface temperatures.

(1) ERH power is not reduced when steady-state temperatures are reached. The ERH energy beyond the heat loss rate directly results in the evaporation of soil moisture and target contaminants.

(2) The most energy- and time-efficient remediation results from the application of the greatest practical ERH power. The ERH power can be limited by several factors.

(a) The ERH electrodes have a practical power limit that usually is in the range of 0.25 to 1 kilowatt per square foot (ft²) of electrode borehole surface area. Electrode designs with low electrical resistance generally allow higher power application rates. Attempts to exceed the electrode limit can dry out (vadose zone) the soil adjacent to the electrode or create a steam blanket (saturated zone). This can reduce the soil's electrical conductivity, resulting in uneven heating.

(b) For planning, assume that the PCU is operated 80 percent of the time and is run at 80 percent of its full capacity. This limits the average ERH power input rate to about 65 percent of the PCU capacity.

(c) The vapor treatment capacity may limit the VOC evaporation rate, especially if an oxidation technology is used. However, varying ERH power can control the VOC evaporation rate. Within the saturated zone, a reduction of ERH power is reflected in a reduction of vapor treatment system loading in a few minutes. Within the vadose zone, the coupling is not as strong because the VR airflow through the soil cools them while maintaining a near-constant evaporation rate. Within the vadose zone, ERH power and VR flow rates are adjusted to reduce treatment system loading.

(3) If the vapor treatment system fails completely, the ERH system is shut down and the subsurface enters a quiescent state. Steam and VOC vapors begin to diffuse outward from the heated zone, condensing as they encounter the surrounding cooler soils. The rate of outward steam and heat spread is quite slow, usually much less than a foot per day. When VR is restored, air is pulled through the expanded warm region and, through evaporation, cools the newly warmed soils while returning the moisture and VOCs to the treatment region. If temperature monitoring indicates areas are not reaching the target temperatures, modifications to the power distribution or the installation of additional electrodes in the cooler areas may be necessary and should be undertaken by the operator.

(a) Various maintenance activities for ERH include those routine activities required for the PCU, blowers, and treatment system. The system for adding moisture at the electrodes gets regular maintenance. Personnel also check the electrical connections for corrosion and inspect the piping systems for potential failure.

(b) The consistent production of fine materials from the vapor extraction system may be a sign that in situ moisture content is low and that significant mobilization and removal of fine materials from the vadose zone may be occurring. This has happened at least at one ERH site.

c. *Steam enhanced extraction.*

(1) This section presents an overview of a general O&M strategy for steam injection, including operational guidelines, monitoring parameters, and system modification considerations. The typical fieldwork and O&M procedures include the following.

(a) Collection of background data (water levels, contaminant concentrations, temperature, and other parameters expected to be affected).

(b) Maintenance and analysis of the water softening and steam generation system (including monitoring of incoming water quality, water softening efficiency, steam production rate, pressure, and temperature).

(c) Maintenance of the vacuum extraction system.

(d) Maintenance of the vapor treatment system (including the condenser).

(e) Liquid treatment system (cooling, gravity separation, water treatment efficacy, discharge concentrations).

(f) Subsurface monitoring and wellhead measurements as described above.

(g) Maintenance of the hydraulic control system (including verification of capture or containment).

(h) Computation of mass balance (injected steam, water, and air, extracted water and vapor).

(i) Computation of energy balance (injected as steam, extracted as steam, and heated fluids, heat losses, and calculated average temperatures of treatment zone).

(2) Information on subsurface conditions should be updated prior to the implementation of steam injection. This information provides a baseline against steam injection impact and can be compared and evaluated. An efficient way to verify that the necessary baseline data are collected is to produce a checklist of parameters to be measured, including measurement locations and methodology. An estimate of the total mass of contaminants and distribution among all phases and subsurface treatment zones is critical for measuring the effectiveness of the steam injection project.

(3) The major components of a steam injection system consist of a steam generation and distribution unit, injection/extraction wells, process controls, and an effluent treatment unit. Thermal modeling is usually used to determine steam injection parameters. The goal is to optimize the injection rate and pressure so that maximum heating efficiency, maximum volume of heated area, and optimized steam front shape can be achieved. The variables that can be modified to optimize the remediation system include steam pressure, steam flow rate, and locations of injection and extraction wells. As physical parameters of the steam are interdependent, setting injection rate, pressure, and steam quality should be enough for the system operation.

(4) Prior to the start-up of the entire ISTR system, equipment and piping should be inspected and tested. A pre-commissioning/shakedown checklist should be developed and followed. The site health and safety officer should also verify all safety devices are operable and that site personnel have all the necessary training and the appropriate personal protective equipment available.

(5) During operation, particular attention should be paid to the vapor and liquid recovery systems due to unanticipated consequences of contaminant removal, including unwanted condensation or crystallization of contaminants or inorganic materials. Such occurrences have caused problems at SEE sites. Piping should be regularly inspected for potential failures or clogging.

**Table 8-1
In situ thermal remediation monitoring summary**

Monitoring Activity, Characteristic	Data Use	Monitoring Location	Analyte, Parameter	Monitoring Type, Method	Measurement Equipment, Sensitivity	Typical Monitoring Frequency
Media: <u>Vapor - Air</u> Technology: <u>All</u> Monitoring Objective: <u>Performance</u>						
- Contaminant Mass Removal.	- Determine points of diminishing returns for system shutdown. - Treatment operations decisions.	- Vapor treatment influent header.	- Contaminant VOCs (possibly SVOCs).	- Grab sample. - Laboratory. - Field Gas Analyzer.	- Varies (depending on site conditions and contaminants).	- Varies (can be hourly with automated Field Gas Analyzer, daily, or longer if samples manually).
- Vacuum Extraction Monitoring.	- Verify vapor control.	- Vapor monitoring points.	- Vacuum.	- Gauge or transducer reading.	- Varies, +/- 5% (reading should be >20% and <80% full scale).	- Daily.
Monitoring Objective: <u>Performance/Compliance</u>						
- Treatment System Air Emission.	- Verify compliance with permit(s). - Make operational decisions.	- Discharge stack.	- Contaminant VOCs and any byproducts of treatment as required by permit.	- Grab sample.	- Laboratory analysis or Field Gas Analyzer, site specific requirements.	- As required by permit, more frequent at startup. - Daily to weekly during operations.
Monitoring Objective: <u>Compliance</u>						
- Surface Emissions.	- Regulatory compliance.	- Perimeter monitoring.	- Contaminant VOCs.	- Grab sample. - Time average sample.	- Laboratory analysis or Field Gas Analyzer, site specific requirements.	- Varies.
Media: <u>Vapor - Steam</u> Technology: <u>SEE</u> Monitoring Objective: <u>Performance</u>						
- Boiler Steam Production.	- Document quantity of steam injected.	- Steam injection header pipe.	- Flow rate. - Temperature. - Pressure.	- Gauge/meter.	- Resolution 0.05 kg/second (range varies).	- Near continuous.
- Steam Pressure and Flow Rates.	- Evaluate injection well performance.	- Injection well heads.	- Flow rate. - Temperature. - Pressure.	- Gauge/meter. - Gauge or thermocouple. - Gauge.	- Resolution 0.05 kg/second (range varies). - +/-2 °C 0 °C to 150 °C (Type K thermocouples). - Varies.	- Weekly.
Media: <u>Water - Condensate</u> Technology: <u>All</u> Monitoring Objective: <u>Performance</u>						

Monitoring Activity, Characteristic	Data Use	Monitoring Location	Analyte, Parameter	Monitoring Type, Method	Measurement Equipment, Sensitivity	Typical Monitoring Frequency
- Contaminant Mass Removal.	- Determine points of diminishing returns for system shutdown. - Treatment operations decisions.	- Condenser liquid effluent piping.	- Contaminant concentrations. - Flow rate. - Temperature	- Grab samples. - Meter with totalizer. - Gauge.	- Laboratory analysis of Field Auto Sampler and Analyzer, site specific requirements. - +/- 2% (range varies). - +/- 2 °C. - 0 °C to 150 °C.	- Weekly to monthly.

Media: Water - Groundwater

Technology: All

Monitoring Objective: Performance

- Groundwater Extraction or Migration Monitoring.	- Verify groundwater contaminant migration control.	- Monitoring wells and points.	- Piezometric levels.	- Water level indicator transducer.	- +/- 0.3 cm. - Stainless steel or titanium construction (range varies).	- Weekly to monthly.
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Media: Water - Groundwater

Technology: All (if goal is groundwater remediation)

Monitoring Objective: Performance

- Natural Attenuation Parameters.	- Evaluate degree of natural attenuation.	- Monitoring wells.	- Dissolved O ₂ , ORP. - NO ₃ . - Ferrous Iron. - SO ₄ and Chlorides (for sites with chlorinated organics). - Alkalinity	- Direct reading field instrument. - EPA 353.2. - Field Kit (Hach). - EPA 300. - EPA 310.1.	- +/- 0.5 ppm, 10% variability. - Report limit: 0.1 ppm. 0.1 ppm. 1 ppm (SO ₄). 0.05 ppm (chloride). 1 ppm.	- Monthly.
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Media: Water - Groundwater

Technology: SEE; ERH and TCH (if groundwater extraction included)

Monitoring Objective: Performance

- Groundwater chemistry.	- Operational decisions for water treatment plant.	- Liquid influent header, extraction wells if necessary.	- TOC. - Cations (Ca, Mg, K, Na, Mn).	- Field Analyzer or EPA 415.1. - EPA 6010B.	- 1 ppm. - Ca: 0.25 ppm. - Mg: 0.15 ppm. - K: 10 ppm. - Na: 2.5 ppm. - Mn: 0.1 ppm.	- Monthly.
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Media: Water - Extracted Groundwater

Technology: SEE; ERH and TCH (if groundwater extraction included)

Monitoring Objective: Performance

- Contaminant Mass Removal.	- Determine points of diminishing	- Liquid influent header,	- Contaminant concentrations.	- Grab sample.	- Laboratory Analysis or Field Auto Sampler and Analyzer,	- Site specific (may be hourly with Field Analyzer or Auto
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Monitoring Activity, Characteristic	Data Use	Monitoring Location	Analyte, Parameter	Monitoring Type, Method	Measurement Equipment, Sensitivity	Typical Monitoring Frequency
	returns for shutdown. - Treatment operations decisions.	extraction wells.	- Flow rate. - Temperature.	- Meter. - Gauge or thermocouple.	site specific requirements. - +/- 2% (range varies). - +/- 2 °C - 0 °C to 150 °C	Sampler, daily, or longer if sampled manually.

Media: Water System Effluent

Technology: All

Monitoring Objective: Performance/Compliance

- Contaminant Concentrations.	- Verify compliance with discharge permit(s). - Make operational decisions.	- Discharge point or injection header.	- Contaminant concentrations. - Other permit-required parameters (temperature, biochemical or chemical oxygen demand, pH, total dissolved solids.	- Grab sample or time average composite.	- Contaminant and parameter dependent.	- As required by permit. - Daily to weekly.
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Media: NAPL

Technology: SEE; ERH and TCH (if LNAPL is extracted or if vapor-phase NAPL is condensed)

Monitoring Objective: Performance

- Contaminant Mass Removal.	- Determine points of diminishing returns for shutdown. - Treatment operation decisions.	- NAPL storage tank. - Monitoring wells.	- Flow rate. - Tank levels. - NAPL thickness.	- Meter. - Sensor or sight glass. - Field interface probe.	- Construction varies depending on flow and contaminant.	- Daily.
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Monitoring Objective: Compliance

- Waste Disposal Characterization.	- Determine proper disposal of NAPL.	- NAPL storage tank.	- NAPL storage tank.	- Grab sample.	- Requirements vary.	- Varies.
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Media: Soil

Technology: All

Monitoring Objective: Performance

- Treatment area status.	- Verify adequate heating to achieve remedial goals.	- In situ temperature monitoring points.	- Temperature.	- Thermocouples. - Fiber optic (DTS).	- +/- 2 °C (Thermocouples, Type K). - Range 0 °C to 150 °C (higher for TCH, 0 °C to 400 °C).	- Daily during heat up. - Longer intervals once target temperatures reached.
- Contaminant removal.	- Determine progress toward soil remediation goals.	- Treatment area. - Emblematic selected sites.	- COCs.	- Grab soil samples. - Laser-induced fluorescence sensor.	- Varies.	- Site specific. - Based on required heating time and observed

Monitoring Activity, Characteristic	Data Use	Monitoring Location	Analyte, Parameter	Monitoring Type, Method	Measurement Equipment, Sensitivity	Typical Monitoring Frequency
				- Others.		mass recovery rates.

Media: Utilities

Technology: All

Monitoring Objective: Performance

- Total electrical use.	- Verify energy use for payment. - Operational decisions.	- Main electrical drop.	- Kilowatts.	- Meter.	- Varies.	- Daily
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Media: Utilities

Technology: ERH, TCH

Monitoring Objective: Performance

- Electrical input.	- Operational decisions.	- Electrodes.	- Current draw.	- Meter.	- Varies.	- Daily.
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Media: Utilities

Technology: SEE

Monitoring Objective: Performance

- Water consumption.	- Operational decisions.	- Makeup water supply header.	- Total quantity provided.	- Meter.	- +/- 5%.	- Daily.
- Fuel consumption.	- Operational decisions.	- Fuel supply to boiler.	- Total quantity. - Fuel flow rate.	- Meter with totalizer.	- Varies.	- Daily.

Media: Utilities (Other)

Technology: All

Monitoring Objective: Compliance

- Noise monitoring.	- Verify that noise levels are not objectionable.	- Site perimeter. - Adjacent community.	- Noise (decibels).	- Type I sound level meter.	- +/- 1 dBA - 30 dBA to 100 dBA.	- As needed at start of operations.
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Media: Utilities (Other)

Technology: ERH

Monitoring Objective: Compliance

- Surface voltage.	- Safety. - Verify no stray voltages.	- Various locations in and near treatment area (especially exposed metal).	- Voltage.	- Meter.	- Various ranges from 0V to 20V up to 0V to 200V.	- At start-up and after changes in the active electrode array.
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Media: Spent Carbon

Technology: All (if carbon is used in vapor or liquid treatment)

Monitoring Objective: Compliance

- Waste disposal characterization.	- Determine proper	- Carbon vessels.	- Contaminant concentrations.	- Grab sample.	- Varies.	- As needed for disposal.
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Monitoring Activity, Characteristic	Data Use	Monitoring Location	Analyte, Parameter	Monitoring Type, Method	Measurement Equipment, Sensitivity	Typical Monitoring Frequency
	disposal of NAPL.		- Other parameters as required by disposal facility.			

Media: Spent Filters

Technology: All (if carbon is used in vapor or liquid treatment)

Monitoring Objective: Compliance

- Waste disposal characterization.	- Determine proper disposal of NAPL.	- Storage drums.	- Contaminant concentrations. - Other parameters as required by disposal facility.	- Extraction from filter.	- Varies.	- As needed for disposal.
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Chapter 9 System Shutdown and Confirmation of Cleanup

9–1. Introduction

Robust remediation systems like ISTR are expensive to operate for extended periods. Therefore, to provide efficient remediation operations, it is important to monitor and understand the data that is gathered in the context of achieving the remediation goals. Decisions about the continued operation and eventual shutdown of an ISTR system typically hinge on whether the system has reached a point of diminishing returns with respect to the anticipated performance.

a. While performing ISTR, the project manager or engineer is typically monitoring several parameters. Examples include subsurface temperature (distribution and trends), concentrations of organic compounds in the recovered vapor, vapor flow rates, groundwater flow rates, condensate recovery, steam injection rates, electricity (or fuel) consumption, groundwater concentrations, and, potentially, periodic soil sampling results. These parameters are used to monitor the system operations, track treatment progress, and determine when the system should be shut down.

b. Operation of an ISTR system should cease when remediation objectives, as specified for the treatment area, have been met. As described in paragraph 4–2, remediation objectives for ISTR can be based on numerical targets (soil cleanup levels) or other measurable endpoints or narrative goals established prior to treatment (mass removal percentage). This paragraph discusses various strategies and protocols used by industry, many of which have been accepted by regulators, to confirm and document cleanup using ISTR. Multiple indicators of ISTR performance (lines of evidence) are used to determine when to terminate the thermal treatment phase and transition to a more passive polishing stage or to site closeout.

9–2. Shutdown strategy

Before starting an ISTR system, it is important to not only establish technology-specific objectives for the response action (numerical cleanup levels or narrative goals), but also to have in hand an overall adaptive site strategy for the site that guides the project manager or engineer through subsequent phases of the remediation, including transition and termination.

a. According to ITRC guidance on adaptive site management strategies at complex contaminated sites (ITRC 2017), the steps in the development of an adaptive site strategy entail the following.

(1) Refine the CSM based on new information, including data collected during construction of the ISTR system.

(2) Set and verify the appropriateness and attainability of the cleanup objectives.

(3) Develop a set of performance metrics, interim goals, decision criteria, and endpoints. These are used to assess how the response progresses. They also help identify transition points to subsequent technologies after thermal treatment. Finally, they demonstrate when the objective has been reached or if an unacceptable condition/deviation occurs.

(4) Establish a contingency plan that is implemented if data indicate an interim goal or cleanup objective is unable to be met.

b. With a clear understanding of the expected performance and endpoints established, decisions about shutdown can be made. It can be difficult, however, to predict the performance of ISTR systems and come up with reproducible endpoints and shutdown criteria because there are limited performance data from full-scale ISTR deployments. Therefore, expert field judgment must be relied on to determine when to shut a system down, and a certain amount of flexibility must be incorporated into the exit strategy.

c. Shutdown of an ISTR system requires ongoing assimilation of data from different sources. These sources include subsurface temperature profiles and contaminant removal or destruction rates. This information helps decide if the remediation objectives have been met. When an assessment of these lines of evidence tells the project manager or engineer that performance objectives are not being met, efforts to optimize or enhance the ISTR system in some way should be made. If the assessment indicates that the system is not likely to succeed within the constraints of the existing design, then it may be necessary to implement a contingency plan.

d. Routine system-monitoring data are collected and used by operators to assess system performance and make operational adjustments during operation. Details on monitoring for ISTR were discussed in paragraph 8–1. System monitoring data, when viewed collectively, are used to evaluate and optimize system performance, as well as

make critical judgments as to the effectiveness of treatment and help determine if continued operation is warranted.

9–3. Shutdown criteria

a. General considerations for shutdown criteria. Shutdown criteria are measurable, technology-specific parameters used by the project manager or engineer to gauge whether the current remedial phase is complete and the system is ready to be shut down or transitioned to the next phase. Shutdown criteria for ISTR methods are typically based on numerical targets or endpoints against which process monitoring data are compared. Establishing shutdown criteria, like RAOs, requires an understanding of the potential performance capabilities of the selected ISTR technology and the expected or theoretical behavior, as well as the remediation goals. But it also must consider the practical limitations of verifying the performance of ISTR in the field. System performance and efficiency may focus on optimizing mass removal from the subsurface, yet remediation goals are typically (soil or groundwater) concentration-based.

(1) It is difficult to directly monitor subsurface conditions and the real-time effects of thermal treatment on the source zone. Piping, cables, and wiring for monitoring systems make access to interior treatment areas difficult. Further, drilling into and handling hot soils and groundwater present health and safety concerns. If shutdown criteria are unreasonable or impossible to quantify using readily available instruments, then the decision to cease operation of the system is typically made based on temperature data and trends in mass removal. In certain instances, shutdown decisions may be made based on non-technical criteria, such as operating costs or remedial timeframes that may appear as arbitrary endpoints.

(2) Shutdown criteria are inherently process or technology specific, unlike RAOs. RAOs are broader and tend to focus on reducing source area volumes (mass) or contaminant mass flux to groundwater to attain a certain level of risk reduction or protectiveness. Shutdown criteria should be based on parameters that are easy and inexpensive to measure, most of which are already collected as part of the system's process monitoring program (temperature profiles, vapor concentration). Direct measures of contaminant mass remaining in the subsurface, based on soil samples, typically have not been used as shutdown criteria. This is because of the difficulty in sampling hot media and the need to make quick, cost-effective decisions regarding the continued operation of a remedial system. The next section discusses some of the parameters that can be considered for use as shutdown criteria for ISTR projects.

b. Mass removal. A goal of source zone remediation may be to reduce the mass of NAPL in the subsurface. By charting the amount of NAPL recovered from the subsurface over time, the technology's performance can be assessed and used as a basis for system shutdown. The mass of NAPL brought to the surface by the extraction system can be estimated by measuring the concentrations of contaminants in the extracted fluids (liquids and vapors) before these streams enter aboveground treatment units. NAPL content and the concentrations of site contaminants in extracted water and

vapor are typically measured as part of the process monitoring scheme and can be used as shutdown criteria, forming two or three lines of evidence.

(1) There are two ways mass removal information can be utilized as a shutdown criterion: mass removal percentage and mass removal rate. Of the two ways, determining the percentage of mass removed is the more difficult and uncertain calculation to make. This is because of the difficulties inherent in quantifying or measuring contaminant mass either before or after treatment.

(2) If a fairly accurate estimate of the mass is available before the start of ISTR, then it may be useful to track the cumulative mass recovered in the extracted fluids and shut down the system after a certain percentage of the mass believed to be present initially is recovered. The level of confidence of initial estimates of NAPL mass is often low and based on inaccuracies inherent with sampling. Some initial estimate is often made to determine how much mass might be removed for permitting purposes. It also helps estimate loads on surface treatment systems. There have been cases where greater than 200 percent of the mass originally present in the treatment area was removed. This does not reflect well on the accuracy of the pretreatment characterization. It also questions the use of mass removal percentage as a criterion for shutdown.

(3) A better strategy is to operate the ISTR system until the rate of mass removal, based on observations of vapor or aqueous-phase concentrations in the extracted fluids, reaches a point of diminishing returns or until no NAPL product is recovered.

(a) Like SVE systems, vapor concentrations often approach an asymptote at some level where increases in the rate of energy input (in the form of heat for ISTR) fail to result in a higher mass removal rate. Asymptotic conditions alone may not be reason to shut down an ISTR system, particularly if there is still significant mass being removed from the ground.

(b) A criterion suggested for SVE system shutdown is “specific energy consumption,” defined as the amount of energy needed to remove 1 kg (2.2 lbs) of chlorinated hydrocarbons from the unsaturated subsoil using SVE. However, in taking this approach, a well-designed and constructed VR system is required that one is confident is being effective. To evaluate that treatment is complete, the rate of removal should be the result of limited VR rather than the result of leaks diluting the concentrations.

c. *Temperature distribution.* A measure of performance often used as the initial basis for shutdown of ISTR systems is temperature distribution and duration.

(1) Temperature monitoring is integral to any ISTR project, providing a measure of heat distribution and a way to evaluate the effectiveness of energy delivery to the treatment zone (methods of temperature monitoring are discussed in paragraph 8–1c). Temperature distribution is typically used as a shutdown criterion in conjunction with other lines of evidence, such as concentrations of VOCs in the VR system. If the

desired temperature is attained throughout the treatment area, and concentrations in the VR system are declining or trending toward an asymptote, then the system is at or near the end of its useful period of operation.

(2) Depending on the ISTR technology and the contaminants to be treated, a target temperature and residence time required to mobilize or destroy the contaminants have been established during the design. Attaining and maintaining this temperature throughout the treatment zone for a specified period is likely to be a performance objective for the ISTR system and a decision criteria operation.

d. Groundwater concentration. Restoring groundwater quality in the vicinity of a NAPL source area being treated by ISTR is one of the most stated remediation objectives. This is because of the presence of residual NAPL in the saturated zone and the slow release and dissolution of these contaminants from the NAPL phase into the groundwater phase.

(1) During ISTR treatment, it is common for concentrations in groundwater to increase as a response to heating. This is attributable to the temperature-sensitive nature of aqueous solubility and to disturbance of the subsurface during treatment. The concentrations in groundwater increase until the boiling point of the mixture of VOCs in groundwater is achieved, and then concentrations in groundwater decline.

(2) It is also important to monitor groundwater quality outside the source area during ISTR to ensure that containment is achieved. It is not recommended that groundwater chemistry data alone be used to determine when to shut down an ISTR system.

e. Plume load. Another indicator of performance based on measurements of groundwater quality is to track decreases in plume load, or the mass release rate at steady state from the NAPL source to the groundwater plume. Plume load is the “rate at which solute mass in the groundwater plume crosses a spatial plane oriented at a right angle to the direction of groundwater flow” (USEPA 2003).

(1) Using plume load as a criterion, shutdown of the ISTR system is considered when the mass release rate from the source to the groundwater falls below the natural assimilative capacity of the aquifer. This obviously requires an understanding of the natural assimilative capacity of the aquifer (see paragraph 4–2). Perhaps the simplest and most direct way of calculating plume load entails capturing the entire plume using one or more extraction wells pumping at a continuous rate and collecting steady-state concentration data.

(2) Based on the measured flow rate and concentration data, plume load can be calculated. This could be a cost-effective approach to system shutdown, especially for ISTR systems that completely control the plume using hydraulic containment. Another way to measure plume load is to collect groundwater data from numerous, closely spaced sampling points along a transect of wells that are oriented perpendicular to the groundwater flow direction, using direct-push multi-level sampling tools. The plume

load is then calculated by multiplying the estimated groundwater flow velocity by the average groundwater contaminant concentration. This method requires relatively more sampling costs but allows more rapid decision-making and analysis.

f. Emerging methods to track remediation progress.

(1) Isotopic techniques provide a possible method to track the progress of ISTR remediation and may be factored into decision-making to shut down the systems. Stable isotopes of carbon and chlorine have been used to track the progress of an ISTR groundwater remediation site in the greater Chicago area (Sturchio et al. 2000).

(a) Researchers there determined that isotopes of ^{13}C and ^{37}Cl in groundwater contaminated with chlorinated compounds show increases in both ^{13}C and ^{37}Cl when the chlorinated compounds were being biodegraded. Where volatilization of chlorinated compounds from groundwater systems was occurring, the groundwater was enriched in ^{37}Cl , but ^{13}C concentrations decreased. Heat-enhanced dissolution into groundwater was reflected in a reduction of both ^{13}C and ^{37}Cl . This relationship is presented in Figure 9–1. Plotting concentrations of delta (δ) ^{13}C and $\delta^{37}\text{Cl}$ over time provides insight into the fate of the compounds, and hence the active fate mechanism. Isotopic data is expressed in conventional δ notation, where $\delta = [(R_{\text{sample}}/R_{\text{reference}}) - 1] \times 1,000$. $R = ^{13}\text{C}/^{12}\text{C}$ or $^{37}\text{Cl}/^{35}\text{Cl}$, and δ values are reported in units of parts per thousand.

(b) For instance, Figure 9–2 presents data from well F3 from the site over various sampling events. The single data point located on the left portion of the graph is a reference standard for the site from a sample of DNAPL in water recovered earlier in the ISTR remediation process. Samples from January 1998 and April 1998 showed a trend toward this reference standard, and this was interpreted as heat-enhanced dissolution into groundwater, consistent with the pattern depicted in Figure 9–1 (Sturchio et al. 2000).

(c) From April 1998 to December 1998, the trend was relatively flat, such that there may have been a combination of biodegradation and volatilization. The data trend from December 1998 to January 1999 indicated that volatilization was occurring. Treatment was discontinued after January 1999, for this well had achieved the cleanup criteria.

(d) Figure 9–3, regarding well Ca6 from the same Chicago area site, is particularly interesting, for there was concern that DNAPL had continued to persist at this location during treatment. There was concern that the presence of DNAPL was toxic to microorganisms and biodegradation might contribute to concentration reductions. However, the isotopic data from this well show a consistent trend, indicating that biodegradation is the predominant fate mechanism, and the well later achieved the cleanup criteria after termination of active thermal treatment.

(2) The utility of this technique is that it provides a greater understanding of the mechanisms in the subsurface. This improved understanding leads to better analysis of groundwater monitoring data. As a result, informed decisions on remedial progress and when systems may be shut down can be made. These isotopic data assisted the

project manager in making decisions as to whether portions of the treatment system could be shut down, what areas required additional treatment, and what areas were being treated according to plan.

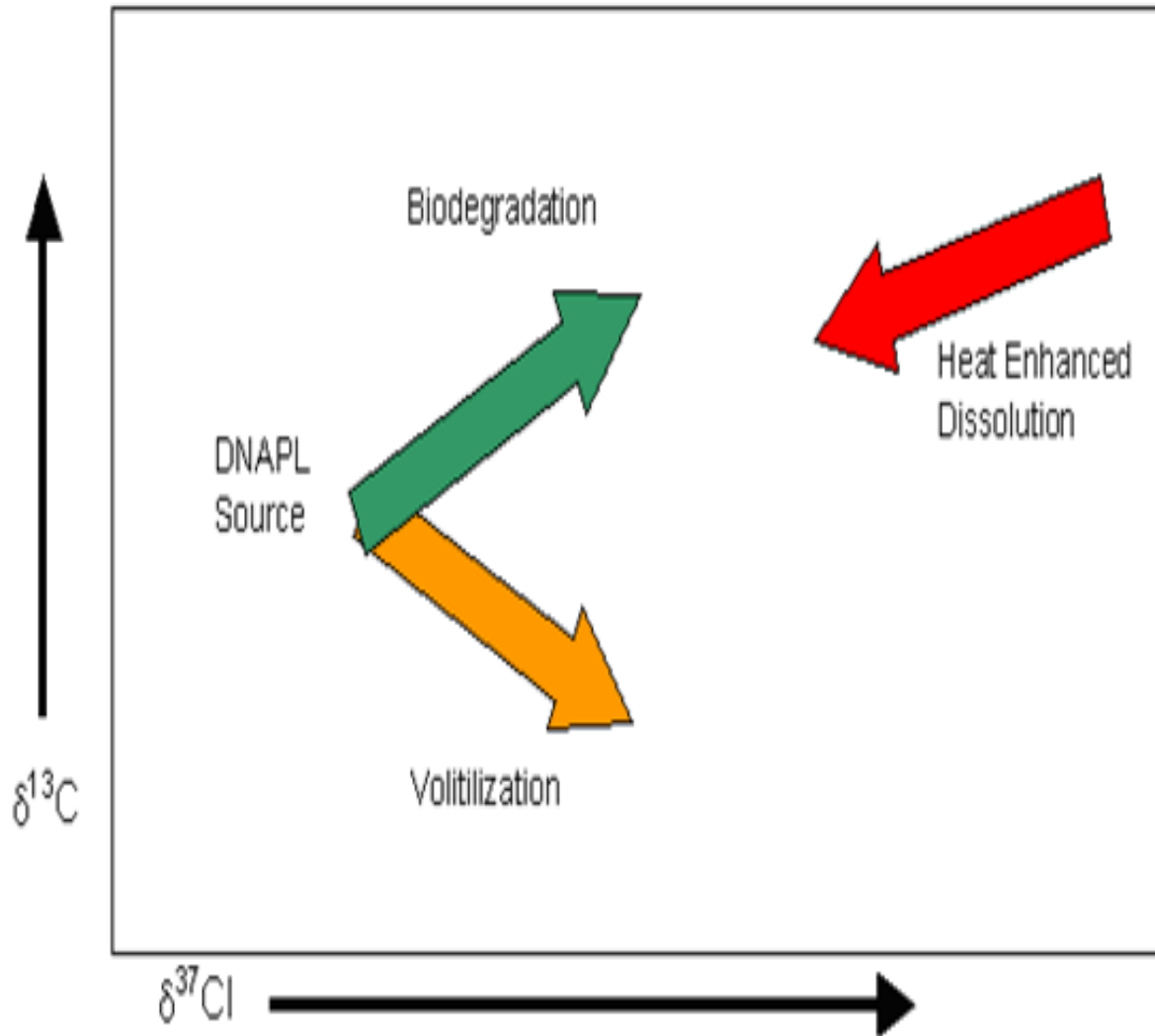


Figure 9-1. Changes in isotopic composition of groundwater contaminated with chlorinated organic compounds under three scenarios

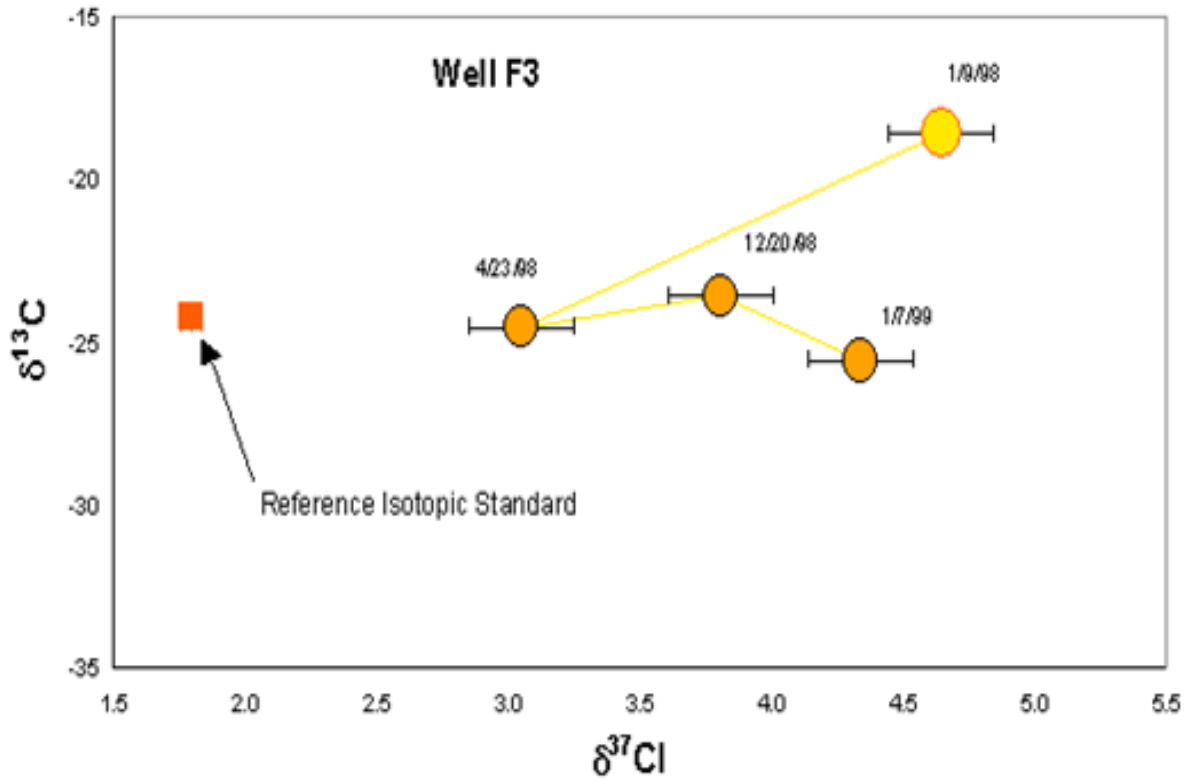


Figure 9-2. Changes in groundwater isotopic constituents during thermal treatment for well F3

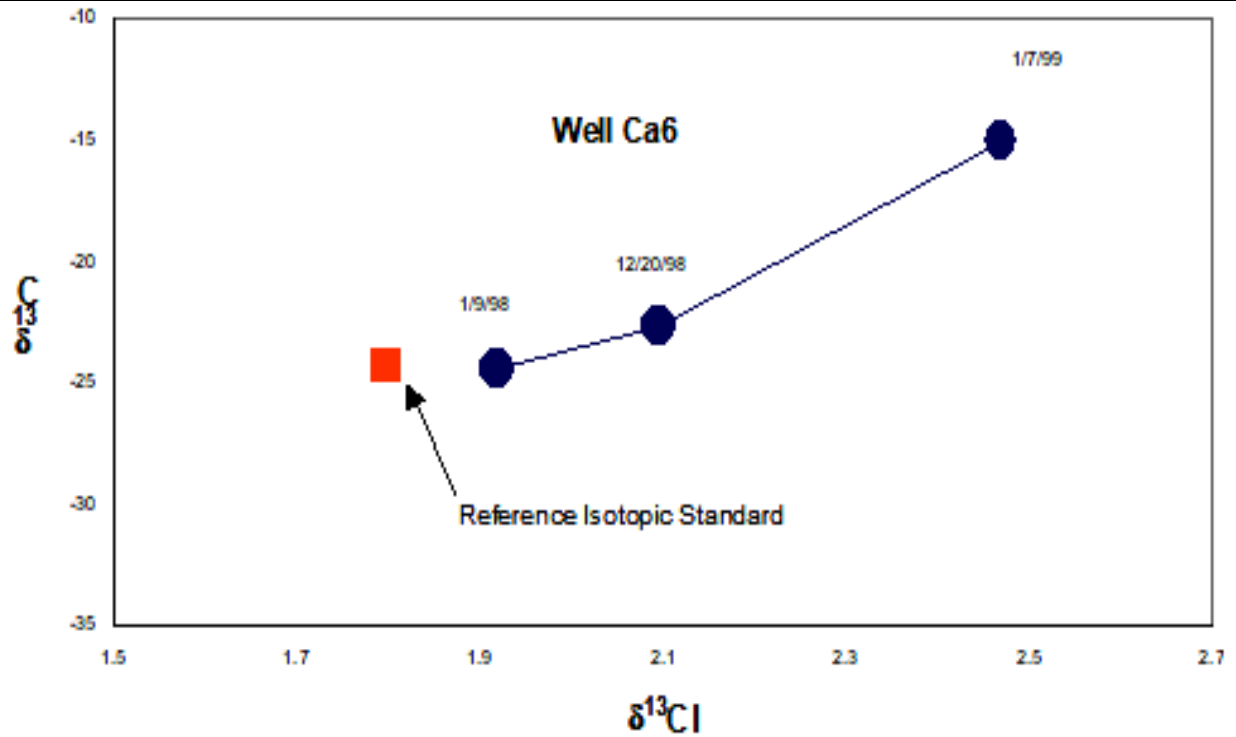


Figure 9-3. Changes in isotopic constituents in groundwater during thermal treatment for well Ca6

9–4. Confirmation of cleanup

Once shutdown criteria have been reached and a decision to turn off the system has been made, based on multiple lines of evidence, it is important to compare the results to remediation objectives and confirm that the cleanup requirements have been met. This usually entails collection and analysis of environmental media within the treatment area and a statistical evaluation of the resulting chemical concentration data.

a. Sampling strategy. Before collecting samples of soil or groundwater, it is important to devise a plan for generating and analyzing the confirmatory data, the goal being to verify that cleanup has taken place. The Sampling and Analysis Plan should present details of the post-treatment sampling. In general, the confirmatory sampling program should be more exhaustive, both spatially and analytically, than that used during routine monitoring.

(1) The confirmatory sampling plan should be designed and implemented in conformance with statistically derived protocols and procedures, considering the estimated variability of concentrations and the desired level of confidence. Biased sampling may be appropriate in areas that were furthest from the heat sources or in areas that did not fully reach target temperatures or reached target temperatures for the least amount of time. This is particularly applicable in cases where the remedial objectives required achieving a baseline contaminant concentration or NAPL content throughout the treatment volume. Rigorous adherence to quality assurance/quality control procedures is also critical at this stage.

(2) The sample collection approach specified in the plan also depends on the media-specific remediation objectives. If the RAO wants to meet numeric cleanup criteria for soil, then a soil sampling program must be designed and implemented to demonstrate cleanup. If the RAO was to reduce the plume load, then measurements of groundwater concentrations at points along a transect or some other method of measuring mass release rate must be incorporated into the sampling design.

(3) When verifying groundwater cleanup, sampling should be spaced temporally over at least two sampling rounds to check for rebound effects following cessation of heating. For example, at the Pinellas Science, Technology, and Research Center in Largo, FL, the work plan called for sampling groundwater from select wells every two weeks during the operational phase. After shutdown, additional rounds of sampling were to be conducted after remediation was completed (in 4 weeks, 12 weeks, and 24 weeks).

b. Sampling hot media.

(1) One of the problems encountered when attempting to confirm cleanup at ISTR projects is collecting samples of groundwater or soil that have not yet cooled to ambient temperatures. Characterizing soil and groundwater contaminated with VOCs is challenging because of the difficulties associated with minimizing VOC loss at ambient temperatures. At elevated temperatures, this problem is exacerbated as heat enhances

volatilization and the potential for VOC loss increases. Sampling hot media also presents a safety hazard, and extreme care should be taken to avoid burns from the unexpected formation and release of steam (steam flashing).

(2) The ISTR treatment needs to be shut down in advance of sampling to allow pressures in the subsurface to dissipate. Temperature monitoring as part of the remediation system operations indicates when sampling may be done. Extreme caution should still be exercised, especially when sampling wells screened below the water table. A sampling technician was seriously burned when trying to collect a groundwater sample with a bailer, and steam flashed out of the well onto the neck and face area at an ERH project in Portland, OR.

(3) The process of collecting and handling samples of hot media can be avoided by delaying the sampling effort until the subsurface cools to near ambient temperatures. However, delaying the sampling effort may not be possible, as it may require waiting up to 12 months for the subsurface to cool before verifying cleanup. At the Dynamic Underground Stripping/Hydrous Pyrolysis Oxidation demonstration project, steam injection conducted at the Savannah River Site in Aiken, SC, ceased in September 2001; however, more than 11 months of cooling were required before confirmation sampling could be done using conventional methods.

c. Collecting soil samples. A simple method of minimizing VOC losses during soil sampling was developed and tested at Launch Complex 34, Cape Canaveral Air Station, FL, during confirmatory drill-back sampling at the ERH demonstration site (Gaberell et al. 2002). The method involved collecting soil cores in metal or acetate sleeves and then placing the sleeves in an ice bath after capping both ends to cool the heated cores to ambient temperatures. The temperature of each core was monitored using a thermometer. Once ambient groundwater temperature, around 20 °C (68 °F), was reached, small aliquots of soil from each core sample were transferred to jars containing methanol (SW-846 Method 5030C).

d. Collecting groundwater samples. Sampling groundwater while it is hot can be dangerous but can provide another way of monitoring progress. Care must be taken to avoid injuries caused by flashing vapors emanating from monitoring wells. Groundwater samples should be obtained in a manner consistent with the discussions in paragraphs 8-1b and 10-1a and not be collected from subsurface zones that are not vented to prevent steam from building up and being released when a well cap is removed. Technicians should wear protective clothing/goggles when working in areas undergoing ISTR. To avoid contact with hot liquids and to reduce the loss of volatile contaminants from the water samples, samples should be collected using low-flow sampling methods. Permanent, dedicated tubing, accessible without opening the well cap, should be installed in each well and run through an ice bath before sample collection.

Chapter 10 Other Issues

10–1. Safety

a. *Thermal conductive heating.* Two specific areas of potential concern are exposure to high voltages and temperatures. These are addressed separately in the following paragraphs.

(1) Electrical work is performed in conformance with the NEC, NFPA 70. A licensed electrician must perform the electrical wiring (including connection to the high-voltage or primary power supply); wiring from the high-voltage supply to the transformer; wiring from the transformer to the electrical distribution panels; connecting power wiring to the off-gas treatment equipment; and wiring the heaters.

(a) To protect against worker injury in the event of an electrical fault with the heater elements, the heater cans, well screens, and metallic process piping are typically bonded together with an appropriately sized copper conductor that is connected to an earth ground (ground rod). Also, metal instrumentation ports for temperature and pressure monitoring installed in the soil are connected to a ground rod. The main transformer and electrical distribution gear must be connected to a ground rod as required by the NEC.

(b) To minimize the potential for worker exposure to energized electrical sources, access to the electrical distribution panel and the heater element electrical junction boxes should be restricted to authorized personnel only. Electrical components must be equipped with appropriate warning labels (such as high voltage) as required by the NEC.

(2) Appropriate measures must be taken to protect on-site workers from incidental contact with exposed hot surfaces. Exposed hot surfaces may include the process piping and certain components of the off-gas treatment equipment.

(a) Surfaces that exceed 60 °C (140 °F) are typically covered with insulation or otherwise protected with a guard where insulation cannot be used. In addition, personnel working in areas where incidental contact with hot surfaces at 60 °C (140 °F) may be possible should wear leather gloves.

(b) In some instances, exposure to hot material or components is unavoidable. Such circumstances may include, but are not limited to, collection of soil or groundwater samples during the ISTD heating process (if required) and replacement of ISTD heater elements (if required) during heating. In these instances, only trained personnel should be allowed in the work area. Worker protective measures are selected in conformance with the potential heat exposure.

(3) At sites having buried ordnance or sealed vessels that might generate explosive pressures when exposed to high temperatures, special precautions are needed to exclude personnel from the vicinity during heating. These precautions

include requiring that the removal of any UXO be conducted by a UXO-qualified contractor from the known subsurface footprint of the project prior to installing the equipment or having a UXO-qualified contractor on standby (see EM 385-1-97). An explosives safety submission is required for UXO contractor support when the probability of encountering a UXO is moderate to high (EM 385-1-97).

b. Electrical resistance heating.

(1) Safety precautions for working in an area undergoing treatment using ERH are like those involving TCH. All applications of ERH must follow OSHA requirements that surface voltages be less than 15 volts. This makes it possible for workers to enter the area undergoing treatment without the need for special protection. Lockout/tagout procedures are followed should there be any need to access or touch wells, electrodes, work with equipment, or perform any intrusive work. The surfaces are hot but can be safely accessed using work boots and leather gloves. Due to the presence of cables and piping to the various electrodes and recovery wells, slip, trip, and fall hazards are of particular concern, which may result in burns or scalds if unprotected parts of the body encounter hot surfaces.

(2) Subsurface intrusive activity can be safely performed during ERH treatment. Procedures followed involve coordinating with the technology vendor for shutting down the power 24 hours in advance of the intrusive activity. Electrical current quickly dissipates, but time should be allotted to dissipate pressures that may have built up in the soil because of heating. VR operations are typically maintained to promote dissipation of pressures in the soil. Vendor procedures for lockout/tagout are followed to ensure no startup of operations occurs during intrusive activities. Soil sampling equipment and soil cores are handled using leather gloves.

c. Steam enhanced extraction. Safety concerns in working in and around areas being treated with SEE methods are like TCH and ERH. The major difference is steam is distributed to wells rather than electricity being distributed to heater wells or electrodes. The steam distribution piping consists of additional hot surfaces that are pressurized, thereby increasing the risk of burns and scalds to workers in the area. Further, steam injections typically involve the use of steam traps in the distribution lines and blowdown points on the generators and piping to enhance distribution of high-quality steam to the subsurface. This requires workers to interact more with the equipment than is usually needed for either TCH or ERH operations. Site workers must adhere to local boiler code requirements, which may entail 24-hour oversight of activity. All piping should be labeled. Steam piping is typically insulated and jacketed.

10–2. Community acceptance and education

Implementation of ISTR at a site raises specific community concerns that are important to address as part of community outreach efforts. The responsibility for any outreach efforts rests with the project manager with support from the Public Affairs Office.

a. Specific concerns commonly expressed by local communities in relation to ISTR are listed here.

(1) Noise during construction and operation.

(2) Odor during construction and operation.

(3) Increased traffic in the vicinity of the site.

(4) Dust during construction and operation.

(5) Emissions from treatment units.

(6) Concerns about dioxin creation.

(7) Incomplete capture of contaminants.

(8) Uncontrolled mobilization of NAPL into previously clean areas (for example, “making it worse”) during thermal treatment.

(9) Uncertainties that are associated with the definition of DNAPL areas for treatment.

(10) On-site and off-site management of process wastes.

b. Under remedial authorities such as the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), a proposed plan or other decision document is typically released for public comment prior to selection of a thermal remedy. As a result, many community concerns related to implementation of the remedy may be known ahead of time. However, additional community outreach may be conducted during the design phase to address specific issues raised by the local community before the start of remedial action. Prevention and mitigation measures can then be targeted toward these concerns.

c. It is important to determine the most appropriate communication methods for the local community (if translation of ISTR technical information for non-English-speaking residents is necessary). It is useful to prepare a community relations plan, or update an existing one, that outlines a communication strategy specifically applicable for thermal technologies.

d. Standard community outreach tools that can be used before and during remedial action include community interviews, community meetings, workshops, and fact sheets. Updates to explain air monitoring results are especially important during ISTR implementation.

e. When appropriate, promptly distribute monitoring results to the community for ISTR applications. Site-specific websites are valuable in providing the community with timely updates and monitoring data.

f. A useful EPA resource provides a brief explanation of how thermal treatment methods work and defines terms associated with the process (USEPA 2001).

10–3. Contracting

ISTR services can be acquired in several ways. The appropriate approach depends on site conditions, funding, project goals, organizational capabilities, and facility requirements. Depth, volume, and required treatment temperature drive ISTR costs. The nature of funding (timing and availability) can determine whether a single contract covers construction and operation or if separate contracts are used. Facility needs may also affect schedules or sequencing.

a. *Planning for contracting.* Once ISTR becomes a likely remedy, acquisition planning should begin. The project manager should engage contracting specialists, legal counsel, and other staff to develop the acquisition plan, which is part of the project management plan (ER 5-1-11). Technical staff must help define treatment zones, performance metrics, uncertainties, risks, and schedule requirements. Facility representatives should also participate to communicate site constraints and confirm facility needs are met. The planning effort should define the appropriate contract type, vehicle, selection process, schedule, bidder pools, funding constraints, and sequencing of work.

b. *Contracting approaches.*

(1) *Invitation for bid versus request for proposal and performance.* Contracting may use either prescriptive specifications (Invitation for Bid) or performance specifications (Request for Proposal). Since ISTR involves multiple vendor-specific technologies, performance-based contracting is more common and generally preferable. A performance specification should clearly define depth, volume, target temperature, and operational endpoints, with measurable criteria to verify success. Failures in performance-based contracting often stem from gaps in the CSM, shifting excessive risk to the contractor, or unrealistic performance metrics.

(2) *Contracting tools.* ISTR services may be obtained through indefinite delivery-type contract pools or site-specific solicitations. Indefinite delivery-type contracts can speed up acquisition but add oversight costs from the prime contractor. Site-specific solicitations require careful evaluation of potential technologies and vendors. Sole-source awards may be possible but must be justified to avoid protest. Common contract types include firm-fixed-price, cost-plus-fixed-fee, and, in some cases, fixed-price-plus-incentive-fee. Firm-fixed-price contracts are best suited for well-defined projects but shift more risk to the contractor. Cost-plus-fixed-fee contracts provide more flexibility for uncertain sites but require closer government oversight.

(3) *Managing change.* Since ISTR is dynamic and site conditions may evolve, change management is critical. For firm-fixed-price projects, including bid schedule options for additional volumes, depths, or heating durations can reduce cost uncertainty. However, exercising options versus issuing contract modifications must be coordinated

with contracting specialists, as both approaches carry acquisition constraints that may affect the schedule.

(4) *Construction versus service contracts.* In many cases, ISTR operational costs exceed construction costs for fixed features such as wells and piping. Depending on the balance of activities, the contract may be issued as a service contract rather than a construction contract. Service contracts allow use of lower service labor rates (instead of Davis-Bacon wage rates) but can only be used where operations predominate. Contract clauses and bonding requirements differ between service and construction contracts, so selection must be coordinated with contracting officers, specialists, and legal counsel.

10–4. Equipment purchase, operations and maintenance

a. Aboveground ISTR equipment is usually provided by the contractor because it is only needed for a short time. However, when equipment is required after thermal treatment (such as long-term pump-and-treat), purchase by the government may be more cost-effective.

b. If the ISTR contract does not cover complete remediation or if operations are bid separately, the basis for operation costs must be established. Payment approaches include documented energy input, contaminant mass removed, actual operating time, successful operation, or actual cost. Each basis must be able to be quantified and clearly defined.

(1) *Successful operation.* This term can be difficult to define for thermal systems because elevated temperatures continue to drive treatment even when energy input has paused. Regardless, treatment processes must meet discharge requirements, typically expressed as concentration or mass discharge limits.

(2) *Time basis.* Using time alone is not recommended, as it provides no incentive for efficiency.

(3) *Mass removed.* While easy to measure, mass removal is not reliable as a sole cost basis because initial contaminant mass is uncertain, removal declines over time, and costs for heating the subsurface are not reflected.

(4) *Energy input.* Energy input provides a good measure of heating costs but may not correspond directly to treatment costs.

c. In practice, a combination of these measures is often the most reasonable approach for paying for O&M. Contracting for the entire project under a performance specification avoids many of the challenges of quantifying and compensating O&M costs.

10–5. Regulatory issues

a. Comprehensive Environmental Response, Compensation, and Liability Act authority.

(1) On-site activities of remedial projects conducted under CERCLA are exempt from permitting and other administrative requirements. However, CERCLA requires substantive compliance with all federal and state environmental standards identified as ARARs under Section 121(d) and the National Contingency Plan.

(2) Under CERCLA, state regulators propose state standards as ARARs, but the lead federal agency makes the final determination. The appropriate Office of Counsel must be consulted to determine which standards apply at a specific site and how substantive ARAR requirements should be implemented.

(3) Activities conducted off-site, such as disposal of waste at a landfill, remain subject to state and federal permit requirements. Remedial projects conducted under authorities other than CERCLA are also subject to applicable permitting requirements. The Office of Counsel should be consulted for guidance, as application of requirements can differ among Department of Defense programs.

b. Determination of applicable or relevant and appropriate requirements. ARARs and their substantive requirements are site-specific, depending on site characteristics, the remedial approach, and applicable environmental standards. Generally, the following regulatory programs are most relevant to ISTR.

c. Environmental discharges. For projects with discharges to the environment, ARARs typically set limits on contamination released to air, surface water, sewers, and groundwater. Both federal and state programs also regulate injection wells, which may apply to ISTR projects.

d. Air emissions. Depending on contaminant type and treatment methods, substantive requirements for air discharges may apply. For example, vapors extracted directly from the subsurface may require treatment before release. Emissions must be monitored for compliance, and modeling may be required to demonstrate that off-site air quality meets standards (Advanced Applied Technology Development Facility 1997).

e. Water discharges. Discharge of groundwater or process water to surface waters or municipal sewers must meet substantive state or federal water quality standards.

f. Underground injections. The Safe Drinking Water Act prohibits underground injections that may affect drinking water sources. States may impose additional restrictions. ISTR projects that involve injection of fluids, steam, or gas must comply with federal and state underground injection control requirements.

Appendix A References

Section I

Required Publications

Unless otherwise indicated, all U.S. Army Corps of Engineers publications are available on the USACE website at <https://publications.usace.army.mil>. Army publications are available on the Army Publishing Directorate website at <https://armypubs.army.mil>. DoD publications are available on the ESD website at <https://www.esd.whs.mil>. Federal Remediation Technologies Roundtable resources are available at <https://frtr.gov>.

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ER 1180-1-9

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Section III**Prescribed Forms**

This section contains no entries.

Appendix B Case Studies

Presented herein are case studies, organized by the ISTR technology applied at each location (see Table B–1 thru Table B–21). Some applications are better documented than others due to a lack of available information at the time this appendix was compiled. Dynamic underground stripping case studies are included with SEE case studies. Case studies for Skokie, Illinois, are presented under both SEE and ERH, since both technologies were applied sequentially at this site. The case studies do not cover every application of ISTR but are provided to illustrate the variety of applications that have been undertaken.

B–1. Thermal conductive heating

Table B–1
Thermal conductive heating case study at former Mare Island Naval Shipyard, Bay Area Defense Conversion Action Team¹

Field	Details
Location	Vallejo, California
Contaminants	PCB (Aroclor 1254 and Aroclor 1260) – maximum concentration of 2,200 mg/kg.
Regulatory Program	Navy Environmental Quality Research and Development Requirement
Remediation Scale	Demonstration Pilot Test
Site Owner	U.S. Navy
Consultant	Tetra Tech, Inc. (Environmental Management and Infrastructure Division)
Project Duration	September 1997 – December 1997

Note:

¹ Conley and Jenkins (1998), Navy (1998b).

a. Former Mare Island Naval Shipyard.

(1) *Site information.* The site was a 46.5 m² (500 ft²) area adjacent to a former electric shop located within the Mare Island Naval Complex.

(2) *Hydrogeology.* Fill and clay units overlying a siltstone and fine-grained sandstone. The Remedial Investigation report suggested that groundwater fluctuated seasonally from 4.57 m to 7.62 m (15 ft to 25 ft) below ground surface (BGS), well below the TTZ (the fill unit).

(3) *Remediation objectives.* Demonstration of ISTD to remove and destroy PCBs from all soils in situ. The cleanup goal was 2 ppm as prescribed by USEPA regulations at 40 CFR Part 761. Site-specific objectives were set in consultation with the Remediation Advisory Board at less than 1.0 ppm. Established target-soil treatment temperatures at 316 °C (600 °F) at the centroids between the thermal wells (for example, in the coldest regions). The particulate emissions rate could not exceed

2.83 grains/dry standard cubic meter (0.08 grains/dry standard cubic foot), corrected to 7 percent O₂, using the procedure given in 40 CFR 264.343 (c). The HCl emissions could not exceed the greater quantity of 1.81 kg/hr (4.0 lb/hr).

(4) *Approach.* The thermal well demonstration was conducted using a network of 12 heater-vacuum wells drilled to a depth of 4.27 m (14 ft). The thermal blanket test was conducted using 2 adjacent 2.44 m by 6.1 m (8 ft by 20 ft) heating units and treated soils to a depth of 30.48 cm (12 in.) over a period of 7 days.

(5) *Operation.* Mobilization to the site in July 1997. Site construction was performed from July 1997 through September 1997. Thermal treatment started in September 1997 and was completed in November 1997. Demobilization was completed by mid-December 1997.

(6) *Results.* After reaching an in situ soil temperature of at least 316 °C (600 °F) over a treatment period of 37 days, all post-treatment soil samples collected exhibited non-detectable total PCB concentrations (< 0.033 mg/kg). Prior to de-energizing the heater elements, the average soil temperature at the centroid of each thermal well pattern and at the base of each thermal blanket treatment cell exceeded 316 °C (600 °F). The emission rate limit of 1.81 kg/hr (4.0 lb/hr) was not exceeded during the demonstrations.

(7) *Cost.* The total demonstration cost for design, permitting, operation, demobilization, and reporting was \$912,500. Unit costs were not available.

Table B-2
Thermal conductive heating case study at Naval Facility Centerville Beach¹

Field	Details
Location	Ferndale, California
Contaminants	PCB (Aroclor 1254) – contamination ranging from 0.15 ppm to 860 ppm. PCDD/Fs – up to 3.2 parts per billion (ppb) 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD). Toxicity Equivalents (TEQs).
Regulatory Program	RCRA Corrective Action
Remediation Scale	Full Scale
Site Owner	U.S. Navy
Consultant	Tetra Tech, Inc. (Environmental Management and Infrastructure Division)
Project Duration	September 1998 – April 1999

Note:

¹ Conley and Lonie (2000), TerraTherm (1999).

b. Naval Facility Centerville Beach.

(1) *Site information.* The site was located on a 12.1-hectare (30-acre) military base used for oceanographic research and undersea surveillance that was

decommissioned in 1993. The site consisted of an area measuring 12.2 m x 9.14 m (40 ft x 30 ft) x 4.57 m (15 ft) deep (for an overall volume of 510 m³ or 667 yd³), with the contaminated soils under/adjacent to a former transformer/diesel generator building. The contamination under the building extended from 0.61 m to 4.57 m (2.0 ft to 15 ft) BGS. PCBs were found outside the building ranging from 1.52 m to 4.57 m (5 ft to 15 ft) BGS.

(2) *Hydrogeology.* Unsaturated, silty, and clayey colluvial soils. Groundwater was encountered at depths greater than 18.3 m (60 ft).

(3) *Remediation objectives.* Average PCB concentration of 1 ppm or lower, dioxins and furans (such as PCDD/Fs), total TCDD TEQ < 1.0 ppb.

(4) *Approach.* Heat the subsurface using a 3:1 ratio of heater-only to heater-vacuum thermal wells. Standard drilling techniques were used for the installation of 57 wells on a grid of equilateral triangles spaced 1.82 m (6 ft) apart, forming a hexagonal pattern. The heater-vacuum wells were located at the center of each hexagonal pattern of heater-only wells, with a resulting spacing between heater-vacuum wells of approximately 3 m (10 ft). Target treatment temperatures at centroids between wells (coolest regions) were 450 °C (840 °F). Treatment gases removed from the subsurface by the heater-vacuum wells were treated using a flameless thermal oxidizer and GAC before being discharged to the atmosphere.

(5) *Operations.* Mobilization to the site took place in September 1998. Construction occurred from September through October 1998. Treatment transpired between November 1998 and January 1999. Interim soil sampling and shutdown occurred in February 1999. Final confirmation sampling was conducted in early April 1999.

(6) *Results.* The target treatment area achieved the remedial objectives for all samples. The temperature in the center of the well patterns ranged from 357 °C (675 °F) at 2.1 m (7 ft) BGS to 510 °C (950 °F) at 4.57 m (15 ft) BGS. CO emissions were below 10 ppmV with a three-minute lag throughout the soil treatment and a mean concentration of 2 ppmV, approximately. CO₂ emissions were recorded by the CEM system and were observed generally at < 2 percent. THC readings observed during the treatment were generally below 10 ppmV or < 0.0023 kg/hr (< 0.005 lb/hr) as methane. An in situ destruction and removal efficiency (DRE) of two nines (99 percent) plus the four nines DRE of the AQC unit resulted in a combined DRE of approximately six nines (99.9999 percent).

(7) *Cost.* The total turnkey cost for design, permitting, operation, demobilization, and reporting was \$456,000, or approximately \$890/m³ (\$680/yd³).

**Table B-3
Thermal conductive heating case study at former Shell Bulk Storage Terminal¹**

Field	Details
Location	Eugene, Oregon
Contaminants	Benzene – 1,200 µg/L in groundwater. Gasoline Range Organics – 3,500 mg/kg in soil. Diesel Range Organics – 9,300 mg/kg in soil. NAPL (Free Product) – thickness ranged from trace to ~1 m (~3 ft).
Regulatory Program	Oregon Department of Environmental Quality
Remediation Scale	Full Scale
Site Owner	Shell Oil Products Company
Consultant	Hart Crowser, Inc.
Project Duration	June 1997 – September 1998

Note:

¹ Conley et al. (2000).

c. Former Shell Bulk Storage Terminal.

(1) *Site information.* The site was a 0.40-hectare (1-acre) site with buildings adjacent to railroad tracks in a residential and light commercial area of Eugene, Oregon. The site was a former bulk storage facility for middle and heavy hydrocarbon distillates. The remedial action was designed to enable closure under the risk-based corrective action underground storage tank program with the Oregon Department of Environmental Quality.

(2) *Hydrogeology.* The geological composition consisted of mainly consolidated and semi-consolidated marine as well as non-marine sediments, which were covered by unconsolidated alluvium. A gravel layer covers the surface of the site to a depth of 0.30 m to 1.22 m (0.9 ft to 4 ft) BGS. A silt layer underlies the gravel and extends to approximately 3.35 m to 4.88 m (11 ft to 16 ft) BGS. A second hydraulically permeable layer (4.76×10^{-2} cm/s) consisting of gravel in a sand-to-clay matrix was present beneath the impermeable (9.53×10^{-6} cm/s) silt layer. Two water-bearing zones are identified at the site. Perched groundwater was encountered in unconfined top gravel and silt layers. A confined groundwater zone was present in the lower gravel layer.

(3) *Remediation objectives.* Remove free-product LNAPL as well as smear zone hydrocarbons present in soil to a depth of 3.6 m (12 ft); attain groundwater cleanup standards in down-gradient areas; and enable closure of the site under the risk-based corrective action underground storage tank program with the Oregon Department of Environmental Quality through the application of the thermal well technology.

(4) *Approach.* The approach involved the installation of 277 heater-vacuum wells and 484 heater-only wells to treat approximately 11,430 m³ (14,950 yd³). The thermal wells were spaced on 2.13 m (7.0 ft) centers and installed to a depth of 3.05 m to 3.66 m (10.0 ft to 12.0 ft) BGS.

(5) *Operations.*

(a) Site construction was performed from September 1997 through May 1998. Thermal treatment lasted 120 days, from June 1998 through August 1998. Confirmatory soil samples were collected between September 1998 and October 1998. Demobilization was completed by early October 1998. Post-remediation groundwater samples were collected quarterly between December 1998 and September 1999 by monitoring wells located within and downgradient of the treatment area. Site characterization efforts indicated that the treatment zone was below the water table.

(b) A two-phase method was used to reduce the amount of water in the treatment zone at the start of the thermal treatment, as well as to limit the impact of recharge from both the surface and external sources outside the treatment area. First, ports were installed at the top of the heater-vacuum wells to allow liquid to be removed before thermal operation began. This step allowed the removal of 970,000 L (257,000 gal) from the treatment zone.

(c) Groundwater flow into the treatment area during operations was controlled through a set of 39 perimeter wells screened from 4.3 m to 4.6 m (14 ft to 15 ft) BGS. The perimeter groundwater control system depressed the water level by an estimated 1.2 m (4 ft) during operation and removed approximately 5.7×10^6 L (1.5×10^6 gal) of water over a 7-month period (December 1997 to July 1998).

(6) *Results.* The thermal well system achieved an average in situ temperature of approximately 282 °C (540 °F). An estimated 90,718 kg (200,000 lbs) of hydrocarbons were removed and treated during the 120-day heating cycle. The LNAPL was removed from the entire site. All confirmation (post-remediation) soil and groundwater samples were below the Department of Environmental Quality's Tier I risk-based concentrations for both soil and groundwater exposure pathways. Benzene concentrations in groundwater within the treatment area were reduced from 1,200 to 2.14 µg/L. All post-treatment off-site groundwater samples were below the analytical detection limit (< 0.5 µg/L). The Oregon Department of Environmental Quality issued a "no further action" letter for the site in March 2000.

(7) *Cost.* The total turnkey cost for design, permitting, operation, demobilization, and reporting was \$2,971,000, or approximately \$260/m³ (\$200/yd³).

Table B-4
Thermal conductive heating case study at chlorinated solvents manufacturing facility¹

Field	Details
Location	Portland, Indiana
Contaminants (Pretreatment concentrations)	PCE – 3,500 mg/kg. cis-1,2-Dichloroethylene – 39 mg/kg. TCE – 79 mg/kg.
Regulatory Program	Indiana Department of Environmental Management, Voluntary Remedial Program
Remediation Scale	Full Scale
Site Owner	Private – Voluntary Cleanup
Consultant	None
Project Duration	July 1997 – December 1997

Note:

¹ Vinegar et al. (1999).

d. Chlorinated solvents manufacturing facility.

(1) *Site information.* The site was an operating manufacturing facility with contaminants in two locations on the property, one of which ran alongside the building.

(2) *Remediation objectives.* The remediation objectives included 8 mg/kg for PCE, 25 mg/kg for TCE, and 0.08 mg/kg for cis-1,2-dichloroethylene.

(3) *Hydrogeology.* The site showed wide variances in permeability, ranging from tight clays to very permeable fill above the target zone. The fill was a combination of sand, clayey sand, gravel, and construction debris. The next layer was described as a till, which consisted of moist to damp silty clay that ranged from brown to gray in color and extended down to depths of 5.5 m to 5.8 m (18 ft to 19 ft) BGS. Running through some parts of the till were seams of sand that could become saturated during the wetter periods of the year. Below the tills was a sand and gravel layer, consisting of some sand ranging from fine to coarse, with some areas of gravel locally. Groundwater was encountered in the sand and gravel layer at depths of 6.7 m to 7.6 m (22 ft to 25 ft). The groundwater was not impacted by the vadose-zone contamination.

(4) *Approach.* Two areas were treated. The first area had 15 heater-vacuum wells that were each 3.66 m (12 ft) deep. The second area had 130 heater-vacuum wells that extended 5.8 m (19 ft) into the subsurface. Secondary and tertiary treatment was accomplished using a flameless thermal oxidizer and a carbon bed, both of which were situated on a process trailer.

(5) *Operations.* The process ran for approximately nine weeks.

(6) *Results.* The remediation goals were achieved for PCE, TCE, and cis-1,2-dichloroethylene. All soil samples were below 0.5 mg/kg, 0.057 mg/kg, and 0.2 mg/kg for PCE, cis-1,2-DCE, and TCE, respectively. The southern part of the well field reached 260 °C (500 °F), but an influx of water in the northern part of the field limited the temperature to 100 °C (212 °F). Steam stripping, however, caused the removal of the contaminants in the northern end, and the remediation goals were met despite not superheating the soil in that area.

(7) *Cost.* Not available.

Table B-5
Thermal conductive heating case study at Missouri Electric Works site¹

Field	Details
Location	Cape Girardeau, Missouri
Contaminants	PCB (Aroclor 1260) – NAPL.
Regulatory Program	CERCLA
Remediation Scale	Demonstration Pilot Scale
Site Owner	MEW site Trust Fund Donors
Consultant	Sverdrup, Inc.
Project Duration	March 1997 – June, 1997

Note:

¹ Vinegar et al. (1997); Haley and Aldrich (1997a); Haley and Aldrich (1997b); Franceœlsetts (1998).

e. Missouri Electric Works site.

(1) *Site information.* MEW used to sell, service, and remanufacture transformers, electric motors, and electrical equipment. The MEW site included all areas on and off the MEW property that were impacted with PCBs above the action limits of 10 ppm from 0 m to 1.22 m (0 ft to 4 ft) deep and 100 ppm below 1.22 m (4 ft) deep. It was located on a 2.59-hectare (6.4-acre) tract of land adjacent to Highway 61 in a commercial/light industrial area. Additional soil was contaminated in adjacent off-site areas.

(2) *Hydrogeology.* The MEW site is underlain by a weathered and unweathered loess that sits on Ordovician-aged sedimentary formations. The surficial loess deposits are typically brown, firm, silty clays. The shallow water-bearing zone occurs between 9.14 m and 18.29 m (30 ft and 60 ft) BGS.

(3) *Remediation objectives.* Demonstration of TerraTherm Inc.'s ISTD process through the application of thermal wells and blankets to achieve a cleanup goal for PCBs of 2 ppm.

(4) *Approach.* Installation of 12 heater-vacuum wells in a triangular pattern spaced on 1.52-m (5-ft) centers. Wells were installed to a depth of 3.6 m (12 ft). To account for heat losses out of the top and bottom of the system, the bottom 0.61 m (2 ft) and top 0.3048 m (1 ft) of the heaters were run with a 57 percent higher power input. Application of 2 thermal blankets was used to treat contaminated soil to a depth of 45.7 cm (18 in.), and the demonstration of an ex situ blanket application for stockpiled soil.

(5) *Operations.* Mobilization of the site took place in March 1997, with site construction beginning during the same month. Thermal treatment lasted between 10 to 45 days, depending on the thermal configuration for the 3 different processes, and was completed in June 1997. Demobilization from the site was in July 1997.

(6) *Results.*

(a) All cleanup goals were met for the thermal well and thermal blanket applications, and pertinent information was produced for the continued development of the ISTD ex situ operations.

(b) PCBs were reduced from a maximum concentration of about 20,000 ppm and a mean concentration of 782 ppm ($n = 88$) to less than 2 mg/kg in all 90 post-treatment samples within the treatment zone. PCB concentrations were considered non-detect (< 0.033 ppm) in 84 of the post-treatment soil samples and less than 0.302 mg/kg in the 6 soil samples with detectable levels.

(c) Stack testing showed 99.9999998 percent DRE. CEM showed the average stack composition contained about 20,000 ppm CO₂, 2 ppm CO, and 1 ppm THC. The peak HCl concentration in the stack was 60 ppm from the decomposition of the PCBs. All emissions standards were met during the project.

(d) There was no evidence of horizontal/vertical contaminant migration. Dioxins in treated soil were below background level for North American soil (< 6 parts per trillion). A soil temperature of 482 °C (900 °F) was reached in the center of all the triangular patterns, with the center of the pattern reaching a temperature of 593 °C (1,100 °F).

(e) A comparison of pre- and post-treatment soil hydraulic characteristics indicated that the soil porosity increased from 30 percent to 40 percent and the horizontal and vertical hydraulic conductivities increased by over 4 orders of magnitude (1×10^{-3} to 30 m/day) following treatment.

(7) *Cost.* Demonstration costs for design, permitting, operation, demobilization, and reporting totaled \$2,038,000. Unit costs were not available.

Table B-6
Thermal conductive heating case study at Tanapag Village site remediation

Field	Details
Location	Tanapag Village, Saipan, Northern Mariana Islands (Western Pacific)
Contaminants	PCB (Aroclor 1254 and Aroclor 1260) – average concentration 500 ppm, individual samples beyond 10,000 ppm.
Regulatory Program	–
Remediation Scale	Full Scale
Site Owner	U.S. Army Corps of Engineers
Consultant	Environmental Chemicals Corporation
Project Duration	July 1997 – August 1998

f. Tanapag Village site remediation.

(1) *Site information.* A site with an area of approximately 1,858 m² (20,000 ft²) was designated as the area for the staging of stockpiled soils and the installation of TerraTherm, Inc.'s treatment cells and associated batch process equipment.

(2) *Hydrogeology.* The treated soils were gathered from multiple sites on the island of Saipan. The soil consisted of silty sand and crushed coral. There was no groundwater impact during the project duration. Stockpiled soils and the treatment cell were subjected, however, to surface-level water saturation due to five typhoons and additional seasonal rainstorms.

(3) *Remediation objectives.* Ex situ treatment of 765 m³ (1,000 yd³) of PCB-contaminated soil through the application of thermal blankets to achieve cleanup criteria of 10 ppm.

(4) *Approach.* Construction of four treatment cells to accommodate the placement of seven thermal blankets each; soil was simultaneously placed in two treatment cells and thermally treated. Each cell was sized to handle approximately 30.6 m³ to 34.4 m³ (40 yd³ to 45 yd³) each. Treatment cells consisted of a thermal blanket beneath and another above each batch of soil.

(5) *Operations.* Mobilization of the site occurred in July 1997. Site construction was performed from July 1997 through August 1997. Thermal treatment began in September 1997 and was completed in August 1998. Demobilization was completed by the end of September 1998.

(6) *Results.* The results for 765 m³ (1,000 yd³) of PCB-impacted soil were treated to 10 ppm or less. The project received a 1998 Merit Award from the USACE Chief of Engineers Design and Environmental Awards Program.

(7) *Cost.* The total turnkey cost for design, permitting, operation, demobilization, and reporting was \$2,805,000.

Table B-7
Thermal conductive heating case study at former wood-treatment area (area of concern-2)

Field	Details
Location	Alhambra, California
Contaminants	PAHs. PCP. Dioxins and Furans. Petroleum Hydrocarbons.
Regulatory Program	California Department of Toxic Substances Control – Expedited Remedial Action Program
Remediation Scale	Full Scale
Site Owner	Southern California Edison
Consultant	None
Project Duration	Ongoing: May 2002 – March 2003

g. Former wood-treatment area.

(1) *Site information.* Southern California Edison’s Alhambra Combined Facility occupies approximately 13.3 hectares (33 acres) and is currently used for storage, maintenance, and employee training. The former wood-treatment area (area of concern-2) occupies a 0.81-hectare (2-acre) portion of the western third of the site. Treating wood with creosote occurred in the area from approximately 1921 to 1957. The total treatment volume is approximately 11,500 m³ (15,000 yd³) of vadose zone soil. The treatment area includes a range of buried subsurface features, including treatment tanks, the structural remains of the former boiler house and tank farm, and various buried utilities.

(2) *Hydrogeology.* Soil within the treatment area is comprised of surficial fill and silty sands, interbedded with sands, silts, and clays. The average treatment depth is approximately 6.1 m (20 ft) BGS; in some areas, the depth extends to 27.4 m (90 ft) BGS. The depth of the water table is 82.3 m (270 ft) BGS.

(3) *Remediation objectives.* The soil remediation standards for PAHs expressed as benzo(a)pyrene [B(a)P] TEQ, PCP, and dioxins expressed as TCDD TEQ are 0.065 mg/kg, 2.5 mg/kg, and 1 µg/kg, respectively.

(4) *Approach.* Using a 3:1 edge-centered hexagonal pattern with 2.13 m (7.0 ft) well spacing, a minimum target temperature of 325 °C (617 °F) is maintained for 3 days; 780 total wells are used, with 128 of them being heater-vacuum wells and the other 652 being heater-only wells.

(a) In situ thermal oxidation and pyrolysis are predicted to result in an in situ destruction efficiency of between 95 percent and 99 percent, with the remaining contamination being treated above ground. The off-gas treatment consists of a thermal oxidizer, heat exchanger, and GAC. The estimated dioxin emission rate calculated for the air discharge permit is 0.311 billionths of a kg (0.685 billionths of a lb) TCDD TEQ/hr.

(b) This is equal to 0.896 millionths of a kg (1.97 millionths of a lb) of TCDD TEQ over the 120-day life of this project. This is a very low amount and less than one-thousandth of the annual TCDD TEQ emission from a typical hazardous waste incinerator. California's Department of Toxic Substances Control is overseeing the project, which is being conducted under California's Expedited Remedial Action Program.

(5) *Operations.* Two phases of operation. Simulation predicted 60- to 70-day heating time per phase; 90 days per phase were allotted.

(6) *Cost.* The total turnkey cost for design, permitting, operation, demobilization, and reporting is projected to be \$5,343,500, or approximately \$480/m³ (\$370/yd³).

B-2. Electrical resistivity heating

Table B-8
Electrical resistance heating case study for thermal treatment of viscous specialty fuel

Field	Details
Location	Atlanta, Georgia
Contaminants	Viscous specialty fuel comprised of jet and diesel fuels.
Regulatory Program	–
Remediation Scale	Full Scale
Site Owner	–
Consultant	Brown & Caldwell
Project Duration	December 1999 – November 2000

a. *Thermal treatment of viscous specialty fuel.*

(1) *Site information.* Viscous specialty fuel released to soil and groundwater largely beneath a manufacturing facility.

(2) *Hydrogeology.* Structural fill with moderate permeability beneath a large manufacturing building, underlain by candy-clay saprolite with low permeability. Groundwater was 7.3 m (24 ft) BGS.

(3) *Remediation objectives.* Reduce LNAPL thickness from 3.048 m (10 ft) to less than 0.3175 cm (0.125 in.) on the water table.

(4) *Approach.* ERH operating in a six-phase mode was used to treat the soils at this site. Vapors were recovered and treated by thermal oxidation.

(5) *Operation.* Operations lasted from 14 weeks to 16 weeks.

(6) *Cost.* Overall costs were \$223/yd³.

Table B-9
Electrical resistance heating case study at Lucent Technologies

Field	Details
Location	Skokie, Illinois
Contaminants	TCE, 1,1,1-TCA and associated biodegradation and hydrolysis daughter compounds.
Regulatory Program	Illinois Site Remediation Program
Remediation Scale	Full Scale
Site Owner	Lucent Technologies
Consultant	ENSR International Corporation
Project Duration	June 1998 – April 1999

b. Lucent Technologies.

(1) *Site information.* The site was a former Teletype Corporation manufacturing facility closed after the breakup of the Bell System in 1984. TCE and TCA were discovered beneath the plant floor with DNAPL measured as thick as 2.43 m (8 ft) in several monitoring wells. From 1991 to 1998, a combined SEE and enhanced biodegradation system was operational. This system was successful in removing DNAPL and secured a “no further remediation” letter from the Illinois EPA for a portion of the treatment area. Manmade subsurface features short-circuited the steam injection, which limited SEE’s effectiveness in treating the areas using ERH.

(2) *Hydrogeology.* Site lithology consists of heterogeneous silts to 5.48 m (18 ft) BGS and a dense silty clay till from 5.48 m to 7.62 m (18 ft to 25 ft) BGS. The groundwater table was at 2.13 m (7 ft) BGS, and hydraulic conductivity through the remediation zone ranges from 10⁻⁴ cm/s to 10⁻⁸ cm/s. At the start of six-phase heating, most of the remaining solvent mass was pooled on top of the clay till at 5.48 m to 6.09 m (18 ft to 20 ft) BGS.

(3) *Remediation objectives.* Reduce concentrations of organic compounds below site-specific Tier III criteria. Lucent modified this goal to treat concentrations so that after the system was turned off and intrinsic biodegradation became the dominant fate of the residual organic compounds, rebound remained below levels of concern.

(4) *Approach.* A network of 107 six-phase heating electrodes was installed, covering just over 1 acre. To treat directly beneath the plant, 85 of those electrodes were constructed through the floor of the building. The electrically conductive zone was

from 3.35 m to 6.4 m (11 ft to 21 ft) BGS, resulting in the ERH electrodes actively heating the depth interval from 1.52 m to 7.31 m (5 ft to 24 ft) BGS. Once subsurface temperatures reached boiling, steam laden with chlorinated solvents was collected by 37 soil-vapor extraction wells screened to 1.52 m (5 ft) BGS. Full-scale operations of the system began on June 4, 1998. Initially, the system operated in six-phase mode. It was observed that previous treatment had elevated chloride levels in the water, resulting in lower applied voltages than anticipated. The system was modified to operate in three-phase mode in August 1989.

(a) Within 60 days, temperatures throughout the 18,349 m³ (24,000 yd³) of the first treatment volume had reached the boiling point of water. With another 70 days of heating, separate-phase DNAPL in this area had been removed, and groundwater concentrations of both TCE and TCA were reduced to below the targeted Tier III risk-based cleanup levels.

(b) Due to the success of the first phase of six-phase heating, a second 6,499 m³ (8,500 yd³) treatment volume was cleaned to Tier I cleanup levels in 90 days using 85 new electrodes.

(5) *Operation.* The project timeline is listed here.

(a) In March 1998, construction began.

(b) In June 1998, startup of operations.

(c) In August 1998, the operation was converted from six-phase to three-phase mode.

(d) In October 1998, a major system malfunction occurred, and operations were down for the entire month.

(e) In December 1998, constructed an expanded treatment system.

(f) In January 1999, treatment of the expanded area was brought online, with a phase-out of treatment in the initially treated area.

(g) In April 1999, monitoring shows a very low hydrocarbon removal rate and system shutdown.

(h) In May 1999, post-treatment sampling shows soils at residential standards, with 4 out of 13 monitoring wells below Tier I standards.

(i) In June 1999, system demobilization begins.

(j) In July 1999, the Illinois EPA issued no further remediation for the site.

(k) In August 1999, site redevelopment begins.

(l) In December 1999, 11 out of 13 wells were below Tier I standards.

(m) In May 2000, the Illinois EPA approved no further monitoring required and site redevelopment complete.

(6) *Results.* Concentrations in groundwater were reduced from indications of residual DNAPL (the prior SEE applications had removed observable DNAPL in the wells) to less than Tier III criteria, and through intrinsic biodegradation, to less than Tier I standards.

(7) *Cost.* Approximately \$1.2 million.

Table B-10
Electrical resistance heating case study at Avery-Dennison

Field	Details
Location	Waukegan, Illinois
Contaminants	Methylene Chloride.
Regulatory Program	Illinois Site Remediation Program
Remediation Scale	Full Scale
Site Owner	Avery-Dennison
Consultant	Clayton Environmental
Project Duration	December 1999 – November 2000

c. Avery-Dennison.

(1) *Site information.* Methylene chloride was used in film coating operations from 1975 to 1992. In 1985, an inventory check indicated that 6,000 L (1,585 gal) of methylene chloride were released from an underground pipe.

(2) *Hydrogeology.* Silty clay glacial till to a depth of approximately 54.8 m (180 ft) BGS. Discontinuous silty sand stringers are also present. Water encountered at depths of 1.82 m to 7.62 m (6 ft to 25 ft) BGS.

(3) *Remediation objectives.* Reduce methylene chloride concentrations to less than 24 mg/kg.

(4) *Approach.* ERH operating in a six-phase mode was used to treat the soils at this site. An area of 1,580 m² (17,000 ft²) was treated to a depth of 7.62 m (25 ft). A total of 95 copper electrodes were installed with 34 wells for vapor and steam recovery. The goal of the remediation was to heat the soil to 24 °C (75 °F).

(5) *Operation.* The project timeline is listed here.

(a) In December 1999, ERH treatment began.

(b) In November 2000, ERH treatment was complete.

(6) *Results.* Methylene chloride concentrations reduced from a maximum of 40,000 mg/kg and a mean of 1,400 mg/kg to a mean of 2.51 mg/kg.

(7) *Cost.* Not Available.

Table B–11
Electrical resistance heating case study at Area A, Young-Rainey Science, Technology, and Research Center, Largo, Florida

Field	Details
Location	Largo, Florida
Contaminants	TCE, cis-1,2-DCE, methylene chloride, toluene, and petroleum hydrocarbon.
Regulatory Program	–
Remediation Scale	Full Scale
Site Owner	DOE
Consultant	–
Project Duration	October 2002 – February 2003

d. Area A, Young-Rainey Science, Technology, and Research Center, Largo, Florida.

(1) *Site information.* This site was a former DOE facility. The treatment area was approximately 929 m² (10,000 ft²).

(2) *Hydrogeology.* Moderately permeable sand to 9.14 m (30 ft), underlain by a tight (Hawthorn) clay aquitard.

(3) *Remediation objectives.* Operational targets included achieving and maintaining a minimum temperature of 84 °C (183.2 °F) throughout the entire treatment volume and operating until NAPL was no longer observed to be recovered from the extraction wells. Numerical goals for this site can be found in Table B–12.

Table B–12
Area A, Young-Rainey Science, Technology, and Research Center, Largo, Florida numerical goals

Compound	Groundwater Goal (mg/L)	Soil Goal (mg/kg)
TCE	11	20.4
cis-1,2-DCE	50	71
Methylene chloride	20	227
Toluene	3.3	15
TPH	50	2,500

(4) *Approach.* A combination of steam and three-phase ERH was used, consisting of 36 steam injection wells, 51 electrodes (21 in the upper sands, 30 in the Hawthorn clay), and 28 extraction wells. Wells were spaced approximately 4.57 m to 6.09 m (15 ft to 20 ft). Steam was injected at depths of 6.09 m to 9.14 m (20 ft to 30 ft), near the base of the aquifer. ERH was conducted from depths of 3.04 m to 4.57 m (10 ft to 15 ft) and from 9.14 m to 10.66 m (30 ft to 35 ft).

(5) *Operation.* Hydraulic and pneumatic control was documented after one week of operation, and heating began on October 1, 2002, and was completed on February 28, 2003, after a cool-down mode beginning on February 17, 2003. The deep electrodes were activated first, forming a heated floor to the aquifer. After one week of heating the floor, steam injection was initiated in the perimeter wells. After this hot steam barrier was formed (around three weeks) around the treatment zone, steam injection, and ERH began in the central and upper portions of the treatment volume.

(a) Once the desired temperature was reached, pressure cycling was induced for a period of approximately one month.

(b) On January 13, 2003, an area containing sap-like resin was found, requiring a modification in the treatment involving additional injections and extraction wells.

(6) *Results.* Screening and analytical sampling show that after recovery of 2,268 kg to 4,082 kg (5,000 lbs to 9,000 lbs) of VOCs, an asymptotic level of 2.27 kg/day (5 lbs/day) removal of VOCs was observed. Approximately 757 L (200 gal) of DNAPL was recovered. Groundwater concentrations were reduced by three to four orders of magnitude in most wells. Effluent vapor and water concentrations had been reduced to less than 0.5 percent of their peak values during treatment.

(7) *Cost.* Turnkey remediation costs, including power, were \$1.3 million, or \$118/yd³. The contract includes a performance guarantee.

Table B-13
Electrical resistance heating case study at dry cleaner site

Field	Details
Location	Western Suburbs of Chicago, Illinois
Contaminants	PCE – 12,000 mg/kg, average 1,400 mg/kg.
Regulatory Program	Illinois Site Remediation Program
Remediation Scale	Full Scale
Site Owner	Privately Owned
Consultant	Clayton Group
Project Duration	November 2002 – March 2003

e. *Dry cleaner site.*

- (1) *Site information.* The dry cleaner site was in the western suburbs of Chicago. A ruptured sewer line released PCE 91.44 m (300 ft) down gradient from the dry cleaner. Soil contaminated from 1.21 m to 6.09 m (4 ft to 20 ft) deep.
- (2) *Hydrogeology.* Glacial silty clay.
- (3) *Remediation objectives.* Remove DNAPL to 529 mg/kg.
- (4) *Approach.* Initially involved 70, 4-inch diameter SVE wells that operated for 4 years.
- (5) *Operation.* The project timeline is listed here.
 - (a) On November 19, 2002, startup began.
 - (b) On January 8, 2003, interim sampling revealed 44 out of 58 samples below the remediation objective.
 - (c) On March 21, 2003, shutdown (final mean concentration 50 mg/kg).
- (6) *Results.* The project removed 1,085 kg (2,392 lbs) of VOC.
- (7) *Cost.* Fixed price and guaranteed remediation cost totaled \$695,000.

Table B-14
Electrical resistance heating case study at manufacturing site

Field	Details
Location	Northwest Suburbs of Chicago, Illinois
Contaminants	TCE – 2,400 mg/kg.
Regulatory Program	Illinois Site Remediation Program
Remediation Scale	Full Scale
Site Owner	Privately Owned (confidential)
Consultant	United Research Services Corporation
Project Duration	Two Phases: July 2002 – September 2002, and January 2003 – April 2003

f. Manufacturing site.

- (1) *Site information.* The manufacturing of computer-related equipment occurred in the northwest suburbs of Chicago, Illinois. TCE was released at the site because of degreasing operations that were performed on a loading dock.
- (2) *Hydrogeology.* Glacial silty clay.
- (3) *Remediation objectives.* The minimum goal was to remove TCE to less than C_{sat} concentrations of 1,200 mg/kg; the revised goal (achieve Illinois EPA Tier I residential soil ingestion criteria) was 5 mg/kg.

(4) *Approach.* Initially, the approach involved seven electrodes with a horizontal VR system. The project operated from July 15, 2002, to September 21, 2002. Sampling confirmation indicated that groundwater contaminated from a previously undiscovered source north of the treatment area was seeping into the area already treated through granular sub-base. The second phase involved adding seven additional electrodes with integrated VR to treat the previously undiscovered source and then to treat the initial treatment area again. TCE volatilized from the soil beneath the catch basin and then recondensed in the soil immediately below it due to seepage from treatment. To complete the remediation, 5.35 m³ (7 yd³) of soil was excavated from beneath the catch basin and disposed of off-site.

(5) *Operation.* The project timeline is listed here.

(a) On July 15, 2002, startup began.

(b) On September 21, 2002, interim shutdown.

(c) In November 2002, the system was expanded.

(d) On January 10, 2003, operations were started again.

(e) On April 8, 2003, the system was shut down.

(6) *Results.* The project removed 133 kg (292 lbs) of VOC.

(7) *Cost.* Including electricity, costs totaled \$919,000.

Table B-15
Electrical resistance heating case study at manufacturing site

Field	Details
Location	Northwest Suburbs of Chicago, Illinois
Contaminants	TCE – 1,500 mg/kg.
Regulatory Program	Illinois Site Remediation Program
Remediation Scale	Full Scale
Site Owner	Privately Owned (confidential)
Consultant	United Research Services Corporation
Project Duration	September 2002 – January 2003

g. Manufacturing site.

(1) *Site information.* The manufacturing of computer-related equipment occurred in the northwest suburbs of Chicago, Illinois. TCE was released at the site because of degreasing operations that were performed on a loading dock.

(2) *Hydrogeology.* Glacial silty clay.

(3) *Remediation objectives.* The minimum goal was to remove TCE to less than a C_{sat} concentration of 1,200 mg/kg; the revised goal (achieve Illinois EPA Tier I residential soil ingestion criteria) was 5 mg/kg.

(4) *Approach.* The project involved nine electrodes with a horizontal VR system and was operated from September 2, 2002, until January 6, 2003.

(5) *Operation.* The project timeline is listed here.

(a) On September 9, 2002, startup began.

(b) On January 6, 2003, the system was shut down.

(6) *Results.* The project removed 76.2 kg (168 lbs) of VOC.

(7) *Cost.* Including electricity, costs totaled \$552,000.

Table B-16
Electrical resistance heating case study at Fort Richardson

Field	Details
Location	Anchorage, Alaska
Contaminants	TCE, PCE, 1,1,2,2-tetrachloroethane.
Regulatory Program	–
Remediation Scale	Full Scale
Site Owner	U.S. Army Corps of Engineers
Consultant	United Research Services Corporation
Project Duration	December 1999 – November 2000

h. Fort Richardson.

(1) *Site information.* Disposal pit for wastes from practice decontamination of chemical munition-exposed equipment.

(2) *Hydrogeology.* Dense, relatively impermeable, poorly sorted silty sandy gravel with some dense sand, silt, or silty sand. Groundwater was located at 2.43 m (8 ft) BGS.

(3) *Remediation objectives.* Reduce LNAPL thickness from 3.04 m (10 ft) to less than 0.3175 cm (0.125 in.) on the water table.

(4) *Approach.* ERH operating in a six-phase mode was used to treat the soils at this site. Heating extended from 2.43 m to 12.19 m (8 ft to 40 ft) BGS.

(5) *Operation.* Three six-phase arrays were used. The time to install and reach the desired temperature was three weeks per array. The treatment time per array was 6 weeks, 18 weeks total.

(6) *Results.* Initial and final concentrations (mg/kg) can be found in Table B–17.

Table B–17
Results of electrical resistance heating case study at Fort Richardson

Compound	Initial (mg/kg)	Final (mg/kg)
TCE	21.53	1.6
PCE	2.0	0.08
1,1,2,2-tetrachloroethane	82.34	1.17

(7) *Cost.* Costs totaled \$185/yd³.

Table B–18
Electrical resistance heating case study at International Chemical and Nuclear Corporation Pharmaceuticals Incorporated

Field	Details
Location	Portland, Oregon
Contaminants	TCE – 150 mg/L, DCE – 370 mg/L, and vinyl chloride – 24 mg/L.
Regulatory Program	Unilateral Order, Oregon Department of Environmental Quality Oversight
Remediation Scale	Full Scale
Site Owner	–
Consultant	AMEC Earth and Environmental, Incorporated
Project Duration	May 2000 – December 2001

i. International Chemical and Nuclear Corporation Pharmaceuticals Incorporated.

(1) *Site information.* Wastes from laboratory operations were disposed of in a 6.09 m (20 ft) deep dry well. Concentrations of TCE in groundwater were indicative of the presence of DNAPL southwest of the dry well. Groundwater plume size was estimated at 36.57 m (120 ft) by 24.38 m (80 ft).

(2) *Hydrogeology.* Silt and sand are discontinuously interlayered by overbank deposits up to a thickness of 18.28 m (60 ft). The overbank deposits are underlain by the Troutdale Gravel Aquifer, measuring approximately 53.34 m (175 ft) thick at the site. The water table was found at a depth of 2.43 m (8 ft) BGS. The DNAPL appeared to have been restricted to the overbank deposits.

(3) *Remediation objectives.* There were no numerical goals for the pilot test. The following performance objectives were established.

- (a) Contaminants must be extracted from the target zone.
- (b) The target zone must be heated to the applied boiling point.
- (c) Air to support HPO must be injected into the treatment area.

(4) *Approach.* Treatment was performed using ERH. Initially 60 electrodes were installed to a depth of 17.67 m (58 ft) in a six-phase heating pattern. Each electrode could direct power to three zones in the overbank: 6.09 m to 9.14 m (20 ft to 30 ft) BGS, 10.36 m to 13.41 m (34 ft to 44 ft) BGS, and 14.63 m to 17.67 m (48 ft to 58 ft) BGS. In December 2000, 50 electrode vents were installed along the perimeter and throughout the treatment area to help control migration of steam and hot water outside this area. The system was expanded in May 2001 with the installation of nine electrodes, four electrode vents, and two monitoring wells to address areas where contaminated steam appeared to have migrated beyond the treatment area.

(5) *Operation.* The project timeline is listed here.

(a) In May 2000, startup of the system began.

(b) In December 2000, the system was expanded with the addition of 50 electrode vents.

(c) The system was expanded with 13 electrodes and 19 electrode vents in May 2001.

(d) In December 2001, the system was shut down.

(6) *Results.* As of June 2002, TCE concentrations reduced from 150 mg/L to 0.008 mg/L; DCE reduced from 370 mg/L to 1.3 mg/L; and vinyl chloride from 24 mg/L to 0.050 mg/L.

(7) *Cost.* Not Available.

B-3. Steam enhanced extraction

At the time of preparation of this manual, individual write-ups were only available for the Visalia Pole Yard project. Table B-22 and Table B-23 provide a summary of other SEE projects.

a. *Site.* The SCE Company, Visalia Pole Yard National Priorities List site in Visalia, California.

(1) *Contaminants.* Contaminants found at the site included PAHs (creosote), diesel, PCP, polychlorinated dibenzo-p-dioxins, and polychlorinated dibenzo-p-furans.

(2) *Technology.* In situ SEE with supplemental air injection to enhance in situ chemical and metabolic oxidation.

(3) *History.* The SCE Company operated a wood treating plant from 1925 to 1980, during which the subsurface soil and groundwater were infiltrated to a depth of 36.6 m (120 ft) with PAHs, PCP, polychlorinated dibenzo-p-dioxins, polychlorinated dibenzo-p-furans (TCDD TEQ), and diesel (wood preservative chemicals). Since 1975, SCE has pumped and subsequently treated approximately 2.5 billion gallons of

groundwater to control the gradient and minimize the plume volume of these DNAPLs and the dissolved constituents.

(4) *Project goals.* The general project objective was to remove the source of contamination from the subsurface and allow “natural attenuation” to degrade the remaining aqueous-phase plume. Specific goals are listed in Table B–19.

Table B–19
Groundwater remediation standards for Visalia steam remediation project

Parameter	Concentration
- PCP	1 µg/L
- B(a)P	0.2 µg/L
- TCDD	30 µg/L

(5) *Engineered systems.* SCE started with 11 steam injection wells, 7 liquid/vapor extraction wells, 4 steam boilers, a vacuum system, a two-stage heat exchange system, a vapor treatment system, and a tertiary water treatment system. ERT and thermocouples were deployed via 29 wells to image the subsurface heated zone.

(6) *System capacity.* The steam generation system had the capability of 200,000 lb/hr, with nominal injection rates of 80,000 lb/hr to 120,000 lb/hr. Recovery wells and treatment systems could remove approximately 140,000 lb (H₂O/min), maintaining overall hydraulic control of the site at nominal injection rates. Recovered liquids (groundwater and condensate) and vapors were separated and pumped to respective treatment systems. The non-condensable gases (vapors) were piped to the steam generators and thermally destroyed in the firebox of the boiler. Groundwater and condensate were pumped to the headworks of the tertiary water treatment system. This system consisted of serial separation (gravity and air flotation), parallel dual media and polish filtration, and serial treatment by GAC. The treated effluent was discharged to the local sewer under an industrial waste discharge permit.

Table B–20
Major design parameters and specifications for Visalia steam remediation project

Design Parameter	Specification
- Well Field Dimensions	145 ft x 2 acres
- Contaminated Material Volume	375,000 yd ³
- Heated Material Volume	>1,000,000 yd ³
- Water Treatment Plant Capacity	400 gpm
- Vapor Extraction System Capacity	2,500 scfm
- Steam Injection System	120,000 lb/hr (+ 80% Reserve)

(7) *Preliminary results.* From May 1997 to June 2000, approximately 660 million pounds of steam were injected into the subsurface formation. Approximately 1.33 million pounds of wood preservative chemicals in the formation were mobilized and

removed/destroyed. The following table depicts the wood-treating chemical mass removed by free phase, aqueous and vapor phase, and chemical oxidation.

Table B-21
Removed mass by phase category for Visalia steam remediation project

Phase	Mass Removed (lb)	Total Removed (%)
- Free	678,300	51
- Vapor	239,400	18
- In Situ Oxidation	212,800	16
- Aqueous	199,500	15
Total	1,330,000	100

(a) SCE designed and built a “carbon tracking” system, which on a real-time basis accounted for the mass removed in the aqueous and vapor phases.

(b) Oxidation in place was determined from the increase in CO₂ and dissolved carbonate over the native groundwater and injected steam, taking temperature/solubility relationships into account.

(c) Free-phase wood-treating chemicals were measured daily from the skimmed volumes emanating from the gravity separators.

(8) *Operational considerations.* The system components must be robust and have inherent flexibility to maintain operational integrity. Strength and material compatibility, if not addressed properly, result in many unforeseen events ranging from significant project delays to catastrophic failures. The Visalia design was robustly designed and constructed. It maintained a 96 percent operational-capacity factor during 36 months of steaming operations.

(a) The initial target of steam injection focused on the intermediate aquitard, which is a heterogeneous saturated zone typified by interbedded coarse sand and cobble-sized material. This aquitard is about 24.38 m to 30.48 m (80 ft to 100 ft) below the ground level.

1. The steam injection wells were installed in a circular array around the contaminant mass. The steam was injected to mobilize wood preservative chemicals into centrally located liquid- and vapor-extraction wells. This operation scheme was a classic “steam flood” of the intermediate aquitard, which relies on the integrity of the confining formations (shallow and intermediate aquitards) to drive the “steam chest” horizontally across the intermediate aquifer.

2. Under this scenario, the aquifer is primarily heated by convection. Portions of the confining shallow and intermediate aquitards are conductively heated. Heat transfer modeling indicated that the first 4.57 m (15 ft) of the intermediate aquitard would achieve the desired thermal treatment threshold of 100 °C (212 °F) if the leading surface of this confining layer was exposed to steam temperatures for 140 days.

(b) This operational mode continued for approximately 10 months. The recovery rates of contaminants ranged from 907 kg (2,000 lbs) to a record high of about 6,350 kg (14,000 lbs) in one day. The subsurface thermal signature resembled a “donut-shaped” plume of elevated temperatures approaching the apparent formation boiling point of water.

(c) The original design called for three of the extraction wells to be adapted to inject steam. The second phase of steam injection, which was still based on aquifer steam flood, was initiated to inject steam in the center of the contaminant mass. The ERT proved to be a valuable tool in managing the duration of steam injection from the center of the contaminant mass. The treatment of the intermediate aquitard based on steam flood techniques continued for an additional eight months. The typical formation heat signature indicated temperatures approaching the apparent water boiling point from about 29 m (95 ft) below the ground level virtually to the surface.

(d) Steam flood techniques were not fully successful at conductively heating the intermediate aquitard. This method suffered from the persistent problem of “steam override,” which has been well documented by the enhanced oil recovery industry.

1. There were two additional factors that added a cooling effect in the lower reaches of the intermediate aquifer. The material at 29 m (95 ft) below the ground level is described as a 1.52 m (5 ft) deposit of cobble-sized material with an estimated horizontal groundwater velocity of greater than 0.914 m (3 ft) per day. The second factor was a vertical connectivity of the “deep aquifer” into the intermediate aquifer. The vertical flux rate was measured at approximately 3 gal/day per ft².

2. The introduction of native groundwater at ambient temperature (~16 °C or ~60 °F) both laterally and vertically imparted sufficient cooling capacity to prevent the desired heating of this part of the formation.

(e) An alternative method relying on injecting steam below the intermediate aquitard was conceived and subsequently approved by the Department of Toxic Substances Control. This aquitard is about 30.48 m to 38.1 m (100 ft to 125 ft) below the ground level and is characterized as interbedding of sand, fine sand, and silts. This aquitard had been shown, during the 1991 remedial investigation, to have been significantly penetrated with the wood-treating chemicals. It was also obvious that the intermediate aquitard was not impervious to permeation, based on the stated flux rates from the deep water-bearing unit into the intermediate aquifer.

(f) Three injection wells were drilled into the “deep” aquifer to a depth of 44.19 m (145 ft) below the ground level. Heating the intermediate aquitard from below employed the natural physical character of the “buoyancy” of steam.

1. Steam injected below this aquitard takes the “path of least resistance” and travels to the bottom edge of this formation, propagating in a radial fashion across the bottom of the aquitard. The steam also takes the same pathways through the aquitard that the native groundwater utilized in the vertical ascent from the deeper unit into the

intermediate aquifer. As the steam ascended, the contaminant mass was mobilized ahead of the steam front and delivered to the extraction wells in the intermediate formation.

2. Steam injection cycles were virtually continuous to uniformly heat the intermediate aquitard and provide a thermal barrier for downward migration of the chemicals of concern. More extraction wells were installed into the deep aquifer as a precautionary measure.

(g) An additional phenomenon was observed at Visalia that greatly reduced the possibility of downward migration of the wood-treating chemicals. The specific gravity of the mixture of wood-treating chemicals was measured at 1.11. Thus, the free-phase mass within the formation was DNAPL.

1. The first 13,258 L (3,500 gal) of recovered product resembled the original mixture in terms of color, odor, and density. When the wood-treating chemicals were exposed to temperatures beyond 50 °C (122 °F), and most probably in the presence of water, there was a dramatic change in the physical and chemical characters of this mixture. The original mixture was black in color and had a distinct coal-tar odor. After the thermal soak, the extracted mass changed in appearance to a tight gray emulsion while retaining a coal-tar odor, albeit reduced in intensity.

2. Of primary importance, the density of the recovered mass was lighter than water. Assays performed at LLNL indicate that the mixture of wood-treating chemicals was saponified, essentially changing a DNAPL into an LNAPL.

(h) Injecting steam into the “deep” aquifer continued for 18 months, with approximately an additional 199,580 kg (440,000 lbs) of wood-treating chemical recovered from the intermediate aquitard.

b. *Groundwater quality.* PCP was considered as the target compound to be removed in the source area, considering that it was the most soluble chemical in the suite of wood preservative chemicals used at the Visalia facility. Historically, PCP was detected in monitoring wells located about 914.4 m (1,000 yd) from the Visalia Pole Yard’s western property boundary. Through an aggressive pumping program from 1975 to 1990, the PCP aqueous phase plume was reduced to the area roughly within the property boundary (Figure B–1).

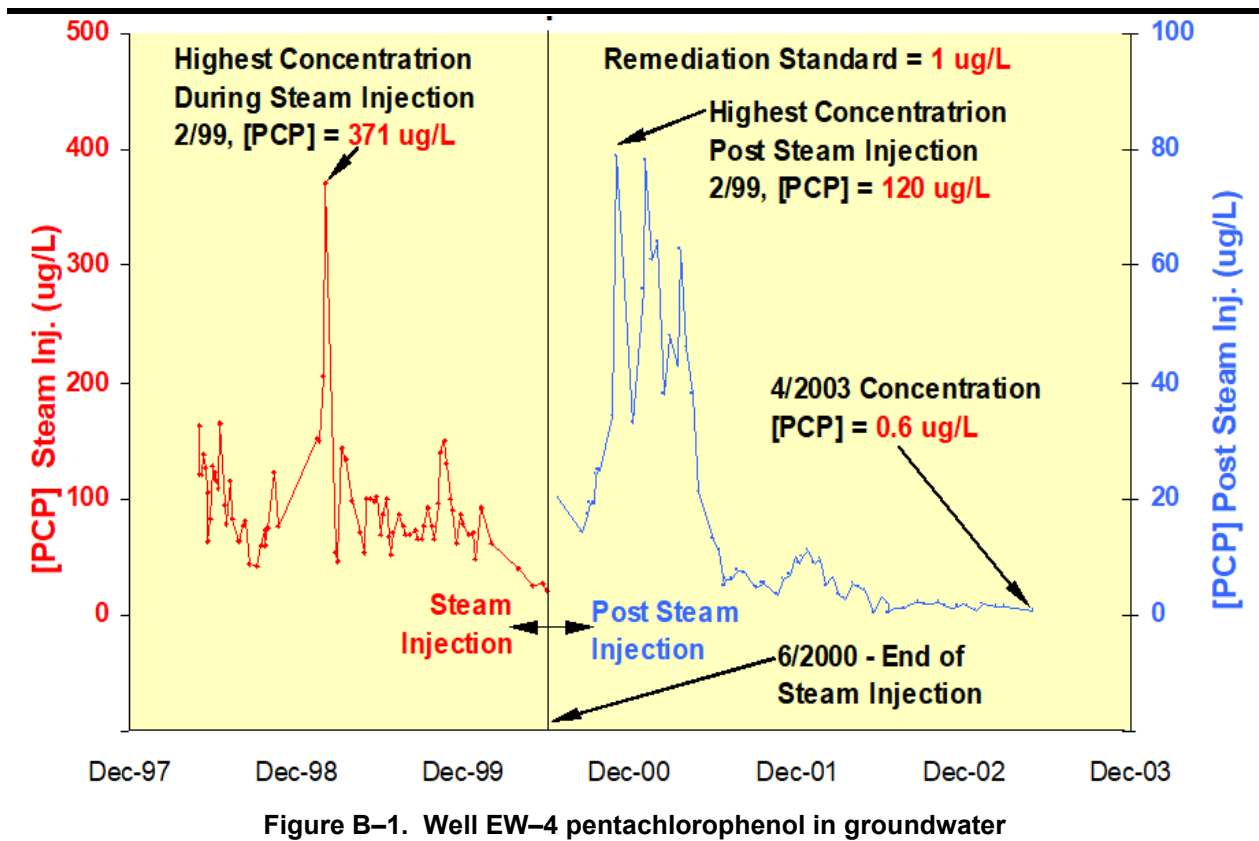
(1) The following graphs (Figure B–1 thru Figure B–5) describe the groundwater quality for the parameters listed in Table B–19. Figure B–1 and Figure B–2 present the analytical results in groundwater extracted from a well in the vicinity of the “point of compliance.” Figure B–4, Figure B–5, and Figure B–6 present similar groundwater assays from a production well in a former free-phase hydrocarbon plume (source area). In general, the graphs for PCP and B(a)P contain approximately 150 data points, and the TCDD TEQ graphs contain about 20 data points. The data comprehensively describes the trend of improving groundwater quality from the initiation of steam injection to the present. Similar data sets exist for 12 additional production wells, all of

which exhibit similar trends. The data selected for this appendix are representative of the improvement of groundwater quality at the Visalia Pole Yard.

(2) The groundwater extracted from well EW-4 has shown two orders of PCP mass reduction since May 1997, which was the onset of steam injection activities. The May 2003 PCP assay is lower than the remediation standard of 1 µg/L. This trend is encouraging; however, the data may not be entirely representative, considering that these results are from an extraction well.

(3) The B(a)P and dioxins data indicate that these parameters do not adversely impact the groundwater in the vicinity of the “compliance point.” During three years of active steam injection cycles and the subsequent three years of post-steaming activities, these organic chemical species have not been detected at concentrations that exceed the remediation standards.

(4) In reviewing the quality of the groundwater pumped from the “source area” (see Figure B-3, Figure B-4, and Figure B-5), it becomes evident there was a considerable mobilization of PCP, B(a)P, and dioxins that occurred during steam injection cycles.



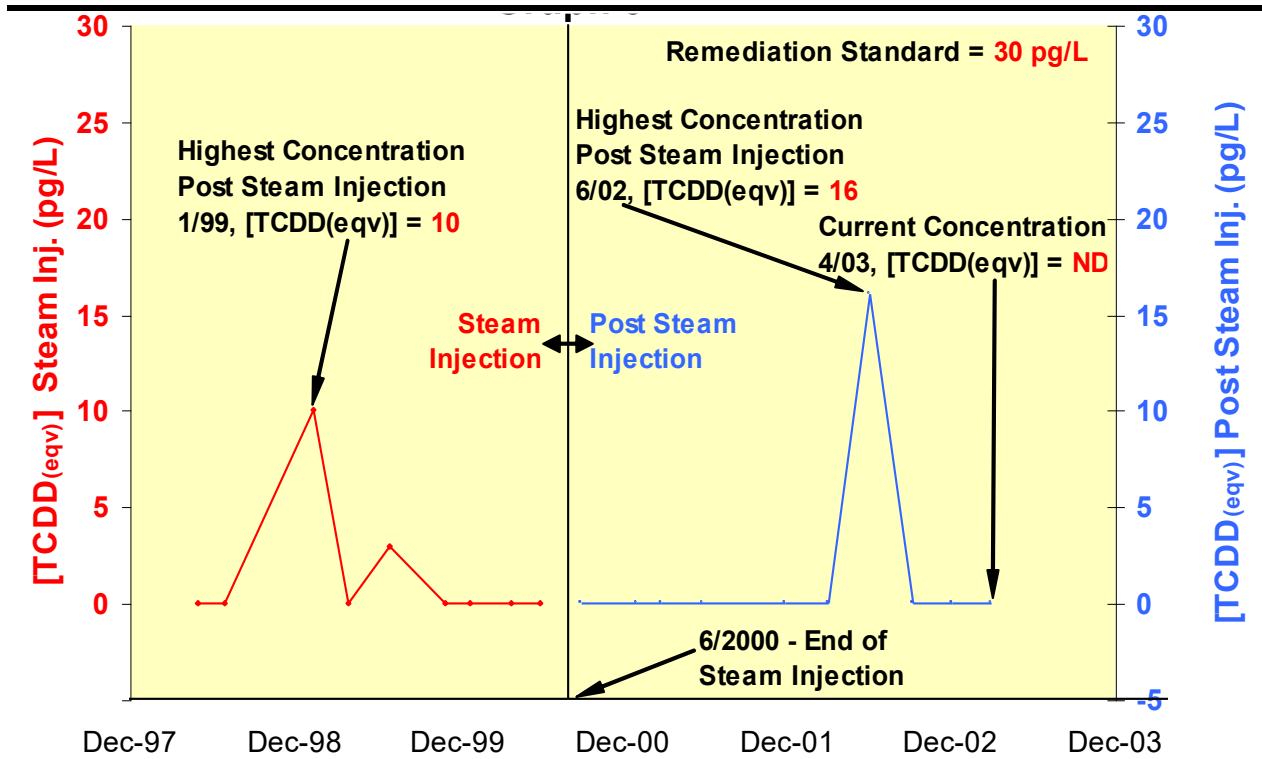


Figure B-2. Well EW-4 tetrachlorodibenzo-p-dioxin toxicity equivalents in groundwater

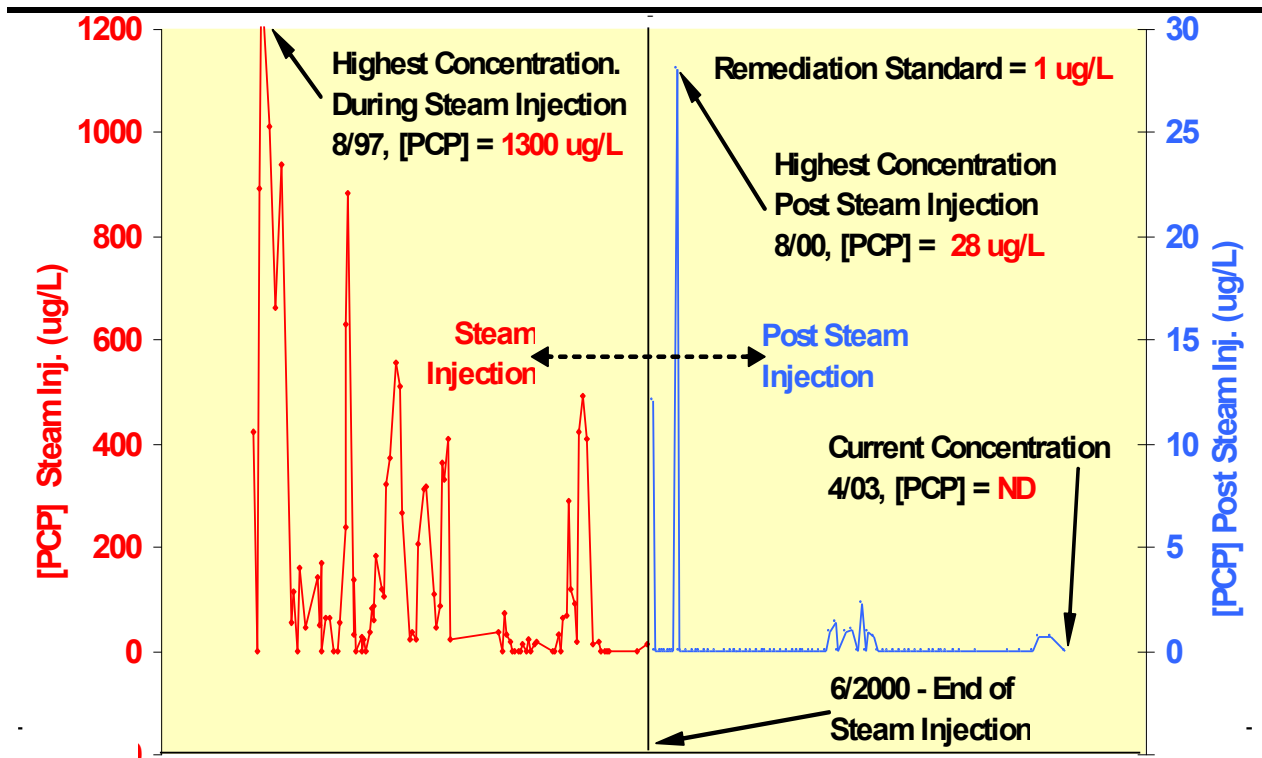


Figure B-3. Well S-14i pentachlorophenol in groundwater

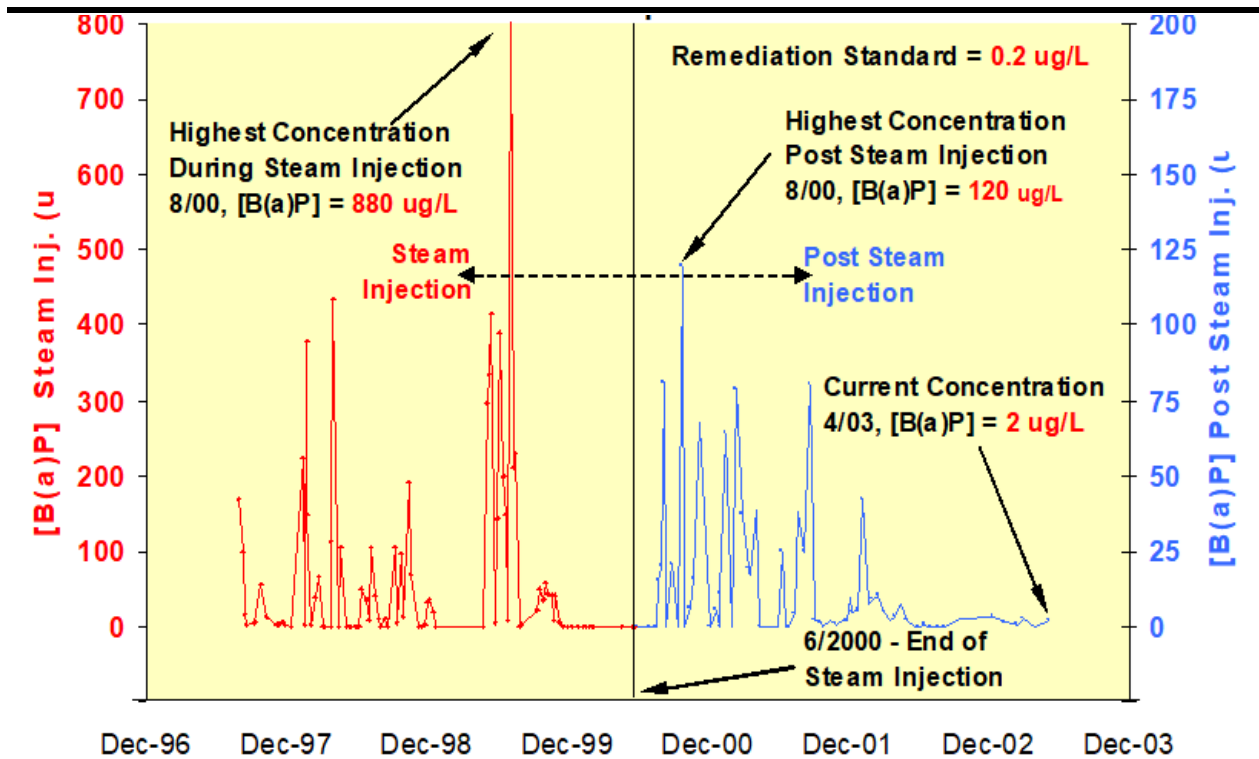


Figure B-4. Well S-14i benzo(a)pyrene in groundwater

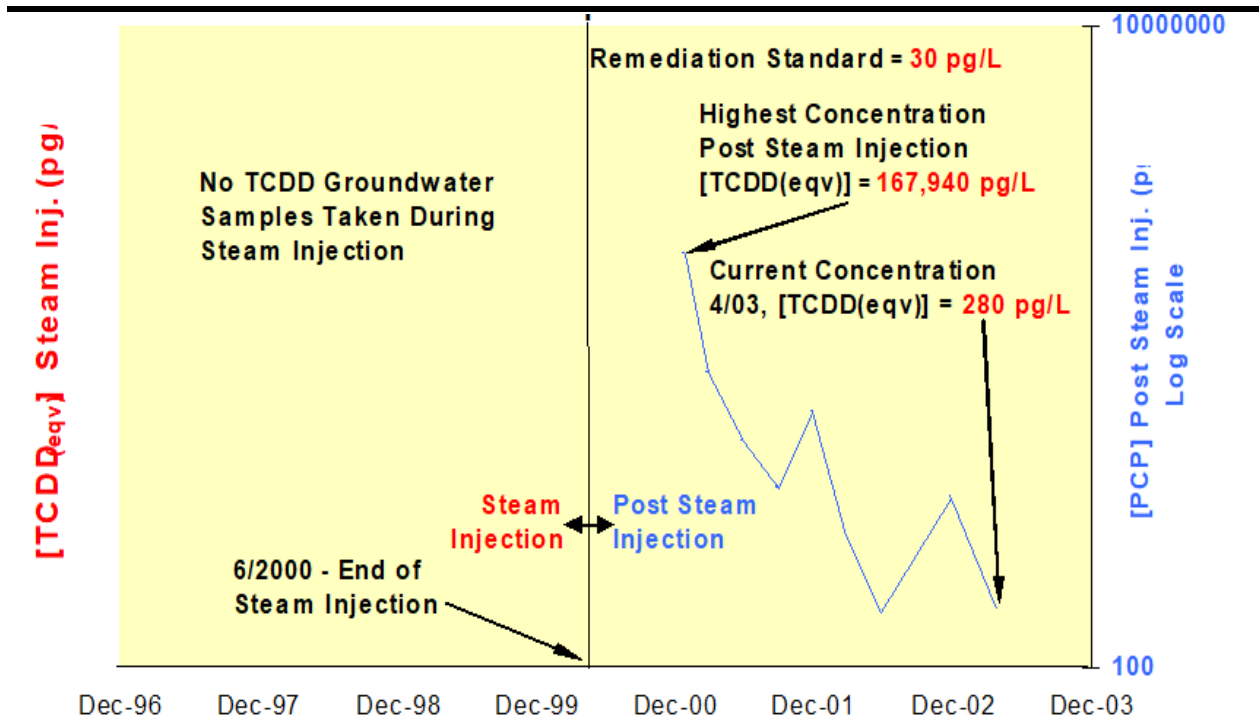


Figure B-5. Well S-14i tetrachlorodibenzo-p-dioxin toxicity equivalents in groundwater

(5) The highest recorded initial PCP concentration (1,300 µg/L) in the groundwater has been reduced to a concentration below the method detection limit (not detected at < 1 µg/L). Since December 2000, there has been one period in which the level of PCP in the groundwater was assayed in concentrations above the remediation standard. During this event (around December 2000), a cluster of assays recorded concentrations above the detection limit; however, only two of the results were recorded above the remediation standard (1.3 µg/L and 2.1 µg/L, respectively). Since December 12, 2001, all assays' results were reported at concentrations below the regulatory limit (1.0 µg/L). The two data points above the detection limit in early 2003 were measured at concentrations of about 0.7 µg/L.

(6) Pumping of well S-14i still produces groundwater with B(a)P concentrations beyond the regulatory limit of 0.2 µg/L. However, looking at the body of this data, it becomes clear that thermal treatment of the groundwater matrix in the vicinity of S-14 has resulted in a measurable improvement in quality in terms of B(a)P. The B(a)P concentration has steadily decreased from a maximum of 880 µg/L to 2 µg/L.

(7) The same conclusion drawn for B(a)P concentrations in well S-14i can be made for the dioxin concentrations represented in Figure B-5. The highest dioxin concentration was measured beyond 160,000 µg/L. The groundwater dioxin content has progressively reduced in mass to the current measured amount of 280 picograms per liter.

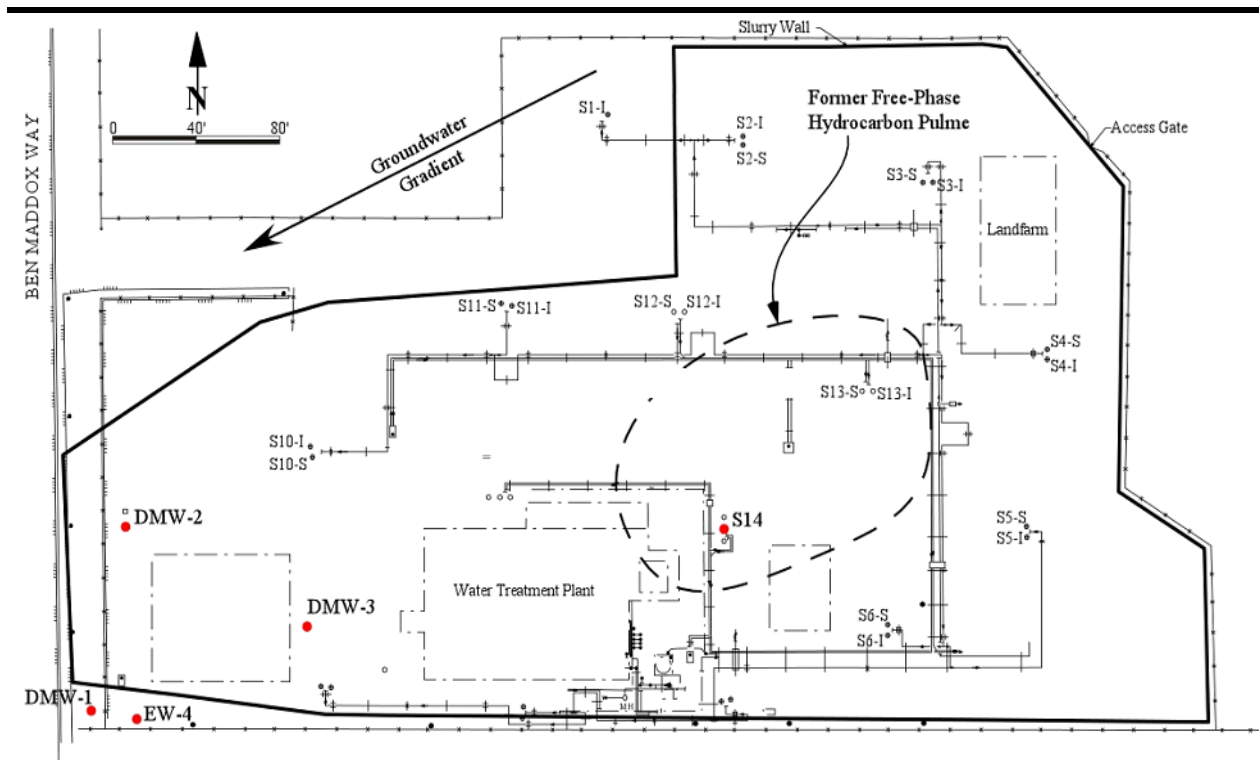


Figure B-6. Site map

(8) Observations over the past 60 months of the groundwater quality in other wells located at the site suggest B(a)P and dioxins have not been mobilized to any degree beyond the original source area. The observations may not be entirely representative; however, in the ensuing time since the project initiation, the empirical observations of the groundwater quality have produced encouraging results, and achieving the stated goals appears to be certain.

c. *Future objectives.* The compliance plan negotiated with the California EPA, Department of Toxic Substances Control, calls for the demonstration of compliance at a point along the western boundary of the Visalia Pole Yard property. Three monitoring wells were to be dedicated as the “compliance point” and are scheduled for completion by the third quarter of 2003. On completion of these wells, SCE enters a regulatory demonstration phase to show compliance with the remediation standards as listed above. The details of the monitoring program and data reduction methods have yet to be determined and subsequently approved by the Department of Toxic Substances Control.

(1) The groundwater quality in well EW–4 continues to improve, and as of May 2003, the quality meets all the regulatory objectives. On completion of the monitoring wells, SCE continues with monthly assays of each of the wells.

(2) A representative database is to be collected, and a final decision is to be made to discontinue the operation of the Visalia Water Treatment Plant. The water treatment plant is held in a “wet” standby status to ensure a “backup” remedy is available. The duration of the standby status of the water treatment plant has yet to be determined.

Table B–22
Summary of steam injection projects

Site	LLNL Gas Pad, Livermore, CA	Visalia Pole Yard, Visalia, CA	Lemoore Naval Air Station, CA	Alameda Naval Air Station, CA	DOE, Portsmouth, OH
DATA					
Status:	- Complete	- On going, full scale.	- Full scale cleanup complete.	- Pilot project complete.	- Pilot project complete.
Target Chemicals:	- Gasoline	- Creosote - PCP	- JP-5	- TCE - Diesel - Motor oil	- TCE
Geology:	- Sand, gravel, silt, and clay (K=2E-4 to 5E-2 cm/s).	- Sand, silt, and sand/silt mixture (high pumping rates suggest K ~1E-1 cm/s).	- Silt and clay (shallow); sand (deeper, K=4E-3 to 1E-2 cm/s).	- Fill, silty sand, and clay.	- Sand, gravel (K=5E-3 cm/s), and shale.
Treated Depth Interval (BGS):	- 21 m to 47 m (70 ft to 155 ft).	- 24 m to 30 m (80 ft to 100 ft).	- 3 m to 6 m (10 ft to 20 ft).	- 0.9 m to 3 m (3 ft to 10 ft).	- <6 m (<20 ft).
Water Table Depth (BGS):	- 30 m to 36 m (100 ft to 120 ft).	- 10 m (35 ft).	- 4.8 m (16 ft).	- 1.7 m (5.5 ft).	- 3.6 m to 4.5 m (12 ft to 15 ft).
Saturated Zone:	- Partial	- Yes	- Partial	- Yes	- Yes

Site	LLNL Gas Pad, Livermore, CA	Visalia Pole Yard, Visalia, CA	Lemoore Naval Air Station, CA	Alameda Naval Air Station, CA	DOE, Portsmouth, OH
Treated Area (Acres):	- 0.3 acres	- 3.6 acres	- 0.2 acres	- 0.08 acres	- 0.5 acres
Treated Volume m³ (yd³):	- 34,659 m ³ (45,333 yd ³)	- 87,923 m ³ (115,000 yd ³)	- 4,814 m ³ (6,296 yd ³)	- 713 m ³ (933 yd ³)	- <12,233 m ³ (<16,000 yd ³)
Duration:	- November 1992 to December 1993.	- June 1997 to June 2000.	- July 5 to September 23, 1994.	- 20 days in 1999.	- 4 months in 1999.
Containment Mechanism:	- SVE	- SVE - Pumping Wells	- SVE	- SVE	- SVE
Pumping Rate (Water/Vapor Steam):	-	- 350 gpm to 400 gpm groundwater. - 2,500 scfm vapor.	- 260 scfm for vapor. - 9 gpm for liquid.	-	- 8 gpm to 15 gpm water. - 100 scfm to 500 scfm vapors.
Number of Wells:	- 23 Total (6 steam injection wells, 3 electrical heating wells, 3 extraction wells, 1 SVE well, and 10 monitoring wells).	- 48 Total (29 ERT and thermocouple, 11 injection wells, and 8 extraction wells).	- 31 Total (11 injections and extraction wells, 16 temperature monitoring wells, and 4 sample boreholes).	- 7 injection well and extraction well clusters, 11 thermocouple wells, 11 sampling wells.	- 24 wells + 23 sample bore holes.
Well Spacing:	- 7.62 m (25 ft)	- 17 m (57 ft)	- 5.1 m (17 ft)	- <3.3 m (<11 ft)	- 6.7 m (22 ft)
Wells per Acre:	- 70 acres	- 14 acres	- 155 acres	- >362 acres	- 94 acres
Mass Removed:	- 115,000 lbs	- 1.3 million lbs Total (1 million lbs in first 1.5 years, 0.3 million lbs in next 1.5 years).	-	- >600 gals	- Estimated at ~80% of initial mass (375 kg or 828 lbs).
Volume Removed:	- 7,600 gals gasoline.	-	- 78,500 gals to 98,000 gals (due to conflicting reports).	-	- 6.5 million liters of water extracted.
Groundwater Concentration (Initial):	- Several thousand ppb benzene.	-	- >20,000 ppm	-	- ≤970 ppm TCE.
Groundwater Concentration (Remediation Target):	- CA MCLS: 1 ppb benzene; 680 ppb ethyl benzene; 1,750 total xylenes.	-	-	-	-
Groundwater Concentration (Final):	- 200 ppb to 300 ppb benzene.	- ≤2,300 ppb total creosote compounds.	- >20,000 ppm	-	-
Soil Concentration (Initial):	- 5,100 ppm	-	- 89,200 mg/kg (maximum).	-	- ~1,600 (maximum).
Soil Concentration (Remediation Target):	-	-	-	-	-
Soil Concentration (Final):	-	-	- 20,000 mg/kg (maximum).	-	- ~450 mg/kg (maximum).

Site	LLNL Gas Pad, Livermore, CA	Visalia Pole Yard, Visalia, CA	Lemoore Naval Air Station, CA	Alameda Naval Air Station, CA	DOE, Portsmouth, OH
Concentration In Extracted Vapor:	-	- 1,100 ppm total organics.	-	-	- 50 to 600 lbs/hr vapor per well (total average of 2,500 lbs/hr).
Concentration In Extracted Condensate:	-	- 10% of solubility.	- >7.8% JP-5 (based on 0.76 gpm JP-5 and 8.95 gpm water).	-	-
Temperature Achieved:	- >93 °C (>200 °F)	- 138 °C (280 °F) maximum. - Average 60 °C (140 °F).	-38 °C to 60 °C (100 °F to 140 °F) in most extraction wells.	-	- ~107 °C (~224 °F) maximum.
Electrical Power Requirement:	-	-	-	-	-
Additional Findings:	- Dynamic underground stripping = steam flushing + electric heating + ERT.	- Some soil is still contaminated below treatment zone. - Continuing to pump-and-treat and sparge without SVE.	- Saturated zone JP-5 concentration not reduced. - Vapor condensation increased concentration in previously clean areas of unsaturated zone.	-	- 4 pre- and post-treatment soil samples in "most contaminated zone" result in one 60% decrease, one no change, two increases.
Total Cost (Demonstrated):	- \$10.4M	- \$22.5M	-	-	- \$6.2M
Cost/Unit Volume (Demonstrated):	- \$230/yd ³	- \$197/yd ³	-	-	- >\$390/yd ³
Total Cost (Vendor Estimate):	- Estimated future cost \$6.4M for "same site."	-	-	-	-
Cost/Unit Volume (Vendor Estimate):	- \$140/yd ³	-	-	-	-
Vendor:	- LLNL/University of CA-Berkeley	- Steam Tech Environmental Services	- University of CA-Berkeley/OHM Corporation	- Steam Tech Environmental Services	- Steam Tech Environmental Services
Vendor Comments/Status:	-	-	-	-	-
Owner:	- LLNL	- SCE	- U.S. Navy	- U.S. Navy	- DOE
Owner Comments:	-	- 2 of 6 monitoring wells stay above cleanup goal. Expect 2 years of pump-and-treat plus sparging to clean site "enough." Trusts compliance point may be ~1/2 mile off-site. Expect K=1.0E-3 cm/s to be lower limit of steam feasibility.	-	-	-

Table B-23
Summary of additional steam injection projects

Site	Solvent Services, San Jose, CA	Lucent Technologies, Skokie, IL	AG Communication Systems, Northlake, IL	Amoco, Minneapolis, MN
DATA				
Status:	- Pilot project complete.	- Full scale cleanup complete.	- Full scale cleanup complete.	- Full scale cleanup complete.
Target Chemicals:	- Chlorinated solvents	- TCE - TCA	- TCE - Mineral spirits	- Fuel Oil
Geology:	- Silt and clay ($K10^{-5}$ to 10^{-6} cm/s).	- Fine sand, silt, and clay (Clay till: 10^{-9} cm/s; sand and gravel 10^{-3} cm/s).	- Clay till with sand and gravel seams.	- Sand
Treated Depth Interval (BGS):	- 0 m to 1.5 m (0 ft to 5 ft), roughly.	- 1.5 m to 6.4 m (5 ft to 21 ft).	- 1.5 m to 24 m (5 ft to 80 ft).	- 1.5 m to 5.4 m (5 ft to 18 ft).
Water Table Depth (BGS):	-	- 2.1 m (7 ft).	- 3.6 m (12 ft).	- 4.3 m (14 ft).
Saturated Zone:	- No	- Yes	- Yes	- Both vadose and saturated.
Treated Area (Acres):	- 0.002 acres	- 3 acres	- 3 acres	- 3 acres
Treated Volume m^3 (yd^3):	- 11.5 m^3 (15 yd^3)	- 61,664 m^3 (80,000 yd^3)	- 152,911 m^3 (200,000 yd^3)	- 50,996 m^3 (66,700 yd^3)
Duration:	- 140 hours in August 1988.	- 7 years.	- 5 years.	- 1 year.
Containment Mechanism:	- SVE	- Well point system - SVE	- Vacuum-enhanced groundwater pumping/SVE.	- Groundwater pumping/SVE.
Pumping Rate (Water/Vapor Steam):	-	- 3 gpm to 5 gpm. - 250 ft^3/min . - 300 lbs/hr.	- 8 gpm to 10 gpm. - 350 ft^3/min . - 450 lbs/hr.	-
Number of Wells:	- 7 wells.	- ~115 well points, 15 thermistors, 96 steam injection, 115 vapor, 15 sampling wells.	- ~120 (combined vapor and groundwater recovery), 90 steam injection, 120 vapor, 8 thermocouple, groundwater extraction doubled as sampling.	-
Well Spacing:	- 1 m (3.4 ft)	- 6.7 m (22 ft)	- 6.7 m (22 ft)	-
Wells per Acre:	- 3,860 acres	- 70 acres	- 70 acres	-
Mass Removed:	- >146 kg (321 lbs)	- >17,236 kg (>38,000 lbs)	- 14,968 kg (>33,000 lbs)	-
Volume Removed:	-	-	-	-
Groundwater Concentration (Initial):	-	- Up to 2.4 m (8 ft) of DNAPL measured in wells.	- Up to 0.9 m (3 ft) of DNAPL measured in wells.	-

Site	Solvent Services, San Jose, CA	Lucent Technologies, Skokie, IL	AG Communication Systems, Northlake, IL	Amoco, Minneapolis, MN
Groundwater Concentration (Remediation Target):	-	- Illinois: Class II	- Illinois: Class II	-
Groundwater Concentration (Final):	-	- Illinois: Class II	- Illinois: Class II (1 area exceeded).	-
Soil Concentration (Initial):	- >1,000 ppm	-	-	-
Soil Concentration (Remediation Target):	-	-	-	-
Soil Concentration (Final):	-	- Illinois: Residential Criteria	-	-
Concentration In Extracted Vapor:	-	-	-	-
Concentration In Extracted Condensate:	-	-	-	-
Temperature Achieved:	-	- 80 °C to 105 °C (176 °F to 221 °F).	- Soil: 29 °C to 40 °C (84 °F to 104 °F). - Groundwater: 20 °C to 74 °C (68 °F to 165 °F).	-
Electrical Power Requirement:	-	-	-	-
Additional Findings:	- Downward mobilization observed, post- treatment concentration in underlying low permeability zone higher than pretreatment concentration.	- Enhanced bioactivity achieved.	- Enhanced bioactivity achieved.	-
Total Cost (Demonstrated):	-	- \$8M	- \$4.9M	-
Cost/Unit Volume (Demonstrated):	-	- \$100/yd ³	- \$15/yd ³	-
Total Cost (Vendor Estimate):	-	-	-	-
Cost/Unit Volume (Vendor Estimate):	-	-	-	-
Vendor:	- Steam Injection Vacuum Extraction Services	- ENSR International Corporation	- ENSR International Corporation	- Steam Injection Vacuum Extraction Services
Vendor Comments/Status:	-	- Lucent Technologies/Bell Laboratories Patent	- Lucent Technologies/Bell Laboratories Patent	-

Site	Solvent Services, San Jose, CA	Lucent Technologies, Skokie, IL	AG Communication Systems, Northlake, IL	Amoco, Minneapolis, MN
Owner:	-	- Lucent Technologies	- AG Communication Systems	-
Owner Comments:	-	- No further remediation determination received from Illinois EPA. Achieved Teir I criteria: no rebound, no ongoing monitoring. Site has been redeveloped into movie cinema.	- No further remediation determination from Illinois EPA. Achieved Tier III criteria. Site redeveloped into warehouse distribution center with soft drink bottling operations. Ongoing monitoring.	-

Appendix C Example Checklists

C-1. Design review checklist

a. *Site physical data.*

- (1) Existing conditions site plan.
- (2) Existing facilities, historic facilities.
- (3) Subsurface utilities.
- (4) Representative boring logs.
- (5) Stratigraphic cross sections.
- (6) Depth to groundwater.
- (7) Soil physical properties (such as grain size distribution, porosity, vapor phase permeability, and water content).

b. *Chemical data.*

- (1) COC and other organic matter distribution and concentration.
- (2) COC physical properties (such as boiling point and vapor pressure).
- (3) TOC data.
- (4) Presence of NAPL.
- (5) Contaminant-specific clean-up goals.
- (6) Anion and cation concentrations (particularly for chlorinated sites).

c. *Bench/pilot test data.* May include some or all the following items listed here, depending on the site.

- (1) Confirm successful application of ISTD.
- (2) Select the target treatment temperature.
- (3) Predict vapor stream contaminants and loading.
- (4) Determine acid neutralization/buffering capacity.
- (5) Evaluate potential coke formation.

d. *Simulation results (where applicable)*. May include some or all the following, depending on the site.

- (1) Verify selected target treatment temperature.
- (2) Verify vapor stream contaminants and loading projections.
- (3) Project duration of heating.
- (4) Recommend well spacing and well field pattern.
- (5) Recommend power input for each well.
- (6) Evaluate coke formation and suggest preventative/corrective measures.
- (7) Determine adjustments/modifications required to address edge effects.

e. *Subsurface design*.

- (1) Lay out a well-field pattern over contaminated area(s).
- (2) Design heater(s) to deliver required power.
- (3) Select controlled or controllerless heater elements.
- (4) Identify subsurface obstructions/conduits to be removed or plugged.
- (5) Detail heater elements.
- (6) Detail heater-only and heater-vacuum wells (coordinate with heater design).
- (7) Calculate thermal expansion (heaters and wells); cross-check versus details and revise as needed.

(8) Specify materials of construction and fabrication methods for thermal wells and heaters.

- (9) Specify thermal well installation methods based on site data.
- (10) Specify the location and configuration of well field temperature and PMPs.
- (11) Evaluate the need for groundwater control measures; design if required.

f. *Civil/site design*.

- (1) Evaluate/modify site grading to control runoff/run-on into the treatment area.
- (2) Lay out sediment and erosion control measures.

(3) Lay out the site operations area (well field, off-gas treatment components, material laydown area, decontamination area, job trailer/temporary facilities, water supply, etc.).

(4) Design and detail surface seal/insulation; coordinate with simulation results and well details.

(5) Design and detail surface seal penetrations; coordinate with well and monitoring point details.

g. Process design.

(1) Estimate vapor production from the thermal well field.

(2) Develop a PFD.

(3) Perform heat and material balance on process equipment.

(4) Size and select off-gas treatment components.

(5) Develop a process and instrumentation diagram.

(6) Develop control loops and interlocks.

(7) Specify requirements for the programmable logic controller program (where applicable).

(8) Select monitoring instrumentation.

(9) Water or condensate treatment.

h. Mechanical design.

(1) Thermal design (total and rate of consumption).

(2) Layout vapor collection pipe manifold, valves, expansion joints, etc.

(3) Calculate vapor-conveyance piping sizes (head loss).

(4) Calculate pipe manifold thermal expansion; adjust layout as required.

(5) Detail vapor conveyance piping manifold and supports.

(6) Specify pipe materials of construction, including valves, expansion joints, etc.

(7) Calculate manifold pipe supplemental heat and insulation requirements.

(8) Specify pipe heating measures and insulation requirements.

- (9) Design a condensate collection and conveyance system (where applicable).
- (10) Detail off-gas treatment system interconnecting piping.

i. Electrical design.

- (1) Potential for presence of explosive vapors and fire hazards.
- (2) Consult with the utility supplier regarding power availability.
- (3) Calculate well field circuits based on individual heater design.
- (4) Develop a field wiring strategy to balance circuits.
- (5) Calculate the manifold pipe heater electrical load; select heaters.
- (6) Calculate additional system loads (manifold pipe heating, motors, etc.).
- (7) Specify main transformer size and power requirements.
- (8) Develop a wiring strategy for off-gas treatment components (motor control center or remote).
- (9) Select variable frequency drives or soft starts when appropriate.
- (10) Develop an electrical one-line distribution diagram.
- (11) Select distribution panels/switchboards and breakers to accommodate design.
- (12) Specify overcurrent protection requirements, trip settings, etc. (include allowances for continuous duty).
- (13) Select well field and system component conductor and ground wire sizes (account for voltage drop).
- (14) Calculate emergency generator load; select generator and transfer switch.
- (15) Specify site-lighting (nighttime) requirements and select lights.

j. Cost.

- (1) Estimate material costs.
- (2) Estimate construction costs.
- (3) Estimate operating costs, including supplemental fuel for the oxidizer and electricity.
- (4) Estimate decontamination and decommissioning costs.

- (5) Compare projected costs with budget allowance.

C-2. Checklist for review of models for in situ thermal destruction/desorption

a. Domain.

- (1) Is the horizontal domain large enough to simulate stable background temperature and pressure conditions outside the treatment area?
- (2) Does the vertical domain extend far enough to include relevant influences (such as soil caps, leaky lower aquifers, etc.)?

b. Grid.

- (1) Is the horizontal grid size or node spacing small enough to provide proper definition of heat flow, fluid flow, and steam-zone propagation between electrodes, injection wells, and extraction wells?
- (2) Is the layer thickness or vertical node spacing small enough to allow proper definition of steam override, saturation changes in the vadose zone, stratigraphic layers, soil caps, and vapor collectors?
- (3) If a variable node spacing is used, is each increase in node spacing limited to 50 percent of the adjacent smaller node spacing?

c. Boundaries.

- (1) Are the lateral boundaries distant enough to prevent the boundary conditions from constraining modeled stresses within the treatment zone?
- (2) Do the boundaries properly represent influences of lateral features such as barrier walls or shorelines?
- (3) Does the upper model boundary accurately simulate the effects of atmospheric pressure and temperature?
- (4) If the model simulates only a portion of a well field or array, are the boundaries properly aligned with axes of symmetry (fluid flow divides)?
- (5) Does the lower model boundary accurately reflect recharge from or discharge into aquifers below the treatment zone?

d. Sources and sinks.

- (1) Do the simulated wells accurately account for well efficiency?
- (2) For pressure-controlled wells, do the input parameters account for the difference between well diameter and model cell width?

(3) Is the vacuum in multiphase extraction wells appropriately applied only above the pumping water level?

(4) Are injected steam temperatures correctly derived from steam table data for anticipated injection pressures?

e. Initial conditions.

(1) Are representative initial soil and groundwater temperatures used, based on site measurements?

(2) Is the average air temperature for the anticipated treatment period used for the upper model boundary?

(3) Do the initial pressures accurately portray anticipated fluid levels at the beginning of thermal treatment?

f. Media properties.

(1) If permeability data is obtained from hydraulic conductivity testing, have the proper conversions been made to obtain intrinsic permeability values for model input?

(2) Has the vertical anisotropy of the soil materials been carefully evaluated and properly simulated? Steam propagation and override are sensitive to this parameter.

(3) Is the proper conversion being made between wet versus dry thermal coefficients (heat capacity and conductivity) prior to model input or in the model computations?

(4) Does the model utilize appropriate thermal coefficients for the anticipated temperature range? Heat capacity and conductivity can both vary as much as 50 percent between ambient and operating temperatures.

(5) Are representative pressure-saturation-permeability relationships used for the site soils?

g. Fluid properties.

(1) Is the temperature dependency of density and viscosity properly simulated for both liquid and vapor forms of water? Steam tables should be used for data input or should be included in the numerical modeling code.

(2) Is the temperature dependence of density and viscosity properly simulated for NAPL? Input values for analytical solutions, or temperature-dependent coefficients for model input, need to be derived from available test data.

h. Contaminant properties.

(1) Is the temperature dependency of both solubility and other partitioning coefficients accurately portrayed?

(2) Are the effects of non-equilibrium partitioning adequately considered? Most modeling codes assume equilibrium, and the resulting uncertainty should be recognized during interpretation of the results.

(3) Is the selection of pseudocomponents suitable for existing site contamination? Have the contaminants been grouped appropriately for combining into pseudocomponents (aliphatic compounds, halogenated hydrocarbons, high molecular weight PAH, low molecular weight PAH, etc.)?

i. System operations.

(1) Is the anticipated operations strategy based on a consensus within the project team, and is it properly portrayed in the model?

(2) Are the modeled well and electrode flows, pressures, and energy inputs within the capabilities of the existing or proposed energy conveyance and treatment systems?

(3) Are allowances being made for potential system malfunctions, maintenance, and downtime?

j. Uncertainties and sensitivity.

(1) Are uncertainties in the model input values properly addressed? Sensitivity runs can be performed to test the effect of input values on model results.

(2) Can the treatment strategy be altered to accommodate uncertainties in underground conditions? Reasonable maximum and minimum input values can be used in the model to evaluate operational changes that might be required.

(3) Can the energy conveyance and treatment systems be designed to allow uncertainties in underground conditions? Model input values can be varied to establish ranges of flow rates, energy requirements, temperatures, or contaminant loads that the systems may need to accommodate.

Appendix D

Example Table of Contents for Operations Manual

Volume 1

- 1 Introduction**
 - 1.1 Site Description
 - 1.2 Process Description
 - 1.3 Intent of O&M Manual
 - 1.4 Overview of O&M Manual

- 2 Communications**
 - 2.1 Organization Chart
 - 2.2 Vendor Phone List
 - 2.3 Client/Facility Contact List

- 3 Process Equipment Description**
 - 3.1 Process Systems
 - 3.1.1 In Situ Heating System
 - 3.1.2 Piping Manifold and Insertion Heaters
 - 3.1.3 Off-Gas Treatment System Control Unit
 - 3.1.4 Electrical Distribution Equipment
 - 3.1.5 Emergency Generator and Automatic Transfer Switch
 - 3.1.6 Well Field Pressure and Temperature Monitoring Equipment
 - 3.1.7 CEM System
 - 3.2 Process equipment (identify components with unit numbers that match PFD)
 - 3.2.1 Cyclone Separator (optional)
 - 3.2.2 Thermal Oxidizer (optional)
 - 3.2.3 Heat Exchanger and Cooling Fan
 - 3.2.4 Fume Reheater/Dehumidifier (if needed)
 - 3.2.5 Carbon Vessels
 - 3.2.6 Main Blowers
 - 3.2.7 Stack
 - 3.2.8 Natural Gas Supply Line and Appurtenances (optional)
 - 3.2.9 Instrument Air Compressor (optional)
 - 3.2.10 CEM System
 - 3.2.11 CEM Calibration Gases, Bottles, and Regulators

- 4 Operational Limits**
 - 4.1 In Situ Heating System
 - 4.2 Piping Manifolds and Insertion Heaters
 - 4.3 Cyclone Separator
 - 4.4 Thermal Oxidizer
 - 4.5 Heat Exchanger
 - 4.6 Carbon Adsorbers

- 4.7 Stack Gas Analyzers (Air Emission Limits)
- 4.8 Process Control Alarms and Interlocks

- 5 Pre-start Commissioning**
 - 5.1 Overview
 - 5.2 Pre-Start Safety Orientation
 - 5.3 Pre-Start Checklists
 - 5.4 Testing, Balancing, Commissioning
 - 5.4.1 Test System Components for Proper Operation
 - 5.4.2 Test Off-Gas Treatment System Piping for Leaks
 - 5.4.3 System Startup
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- 6 Operations**
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 - 6.2 Daily Operations Review
 - 6.3 Outdoor Lighting (optional)
 - 6.4 Process Monitoring and Control
 - 6.4.1 Temperature and Pressure Monitoring Instruments
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 - 6.4.6 Carbon Beds
 - 6.4.7 Main Blowers
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 - 6.5 Performance Monitoring
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 - 6.6 General Record Keeping
 - 6.6.1 Personnel Training and Qualifications
 - 6.6.2 Log Books
 - 6.6.3 Electronic Data Backup
 - 6.7 Monitoring Groundwater Elevations
 - 6.8 Unit Shutdown Procedure
 - 6.9 Emergency Shutdown Policy and Procedure
 - 6.10 Unit Restart Procedure
 - 6.11 Job Shutdown Procedure

- 7 Safety**
 - 7.1 Overview
 - 7.2 Safety Procedures

- 7.3 Process and Equipment Safety Checklists
- 7.4 Lockout/Tagout
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- 8 Maintenance**
- 8.1 Overview
- 8.2 In Situ Heating Maintenance
- 8.3 Maintenance of Vacuum Piping and Manifolds
- 8.4 Maintenance of Insertion Heaters
- 8.5 Maintenance of Process Trailers
 - 8.5.1 Cyclone Separator
 - 8.5.2 Thermal Oxidizer
 - 8.5.3 Gas Rack
 - 8.5.4 Heat Exchanger and Cool Air Blower
 - 8.5.5 Carbon Adsorbers
 - 8.5.6 Control Room
 - 8.5.7 Air Compressor
 - 8.5.8 Process Skid Piping System
 - 8.5.9 CEM Samplers
 - 8.5.10 CEM Instrumentation
- 8.6 Seismic Bracing (if required)
- 8.7 Emergency Generator and Automatic Transfer Switch
- 8.8 Natural Gas Supply Line and Appurtenances
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- 9 System Troubleshooting Procedures**
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- 9.2 Natural Gas Supply Troubleshooting
- 9.3 Heater Element Troubleshooting
- 9.4 Well Field Manifold Piping Troubleshooting
- 9.5 Well Field Temperature and Pressure Instrument Troubleshooting
- 9.6 Insertion Heater Troubleshooting
- 9.7 Off-Gas Treatment System Troubleshooting
 - 9.7.1 Cyclone Separator Troubleshooting
 - 9.7.2 Thermal Oxidizer
 - 9.7.3 Heat Exchanger
 - 9.7.4 Carbon Beds
 - 9.7.5 Main Process Blowers (Vent Fans)
 - 9.7.6 CEM Sampler and CEM Instrumentation

- 10 Operating Contingency Plans**
- 10.1 Grid Power Interruption
- 10.2 Loss of Well Field Vacuum
- 10.3 Well Field Surface Cover Failure

- 10.4 Insufficient Subsurface Heating
- 10.5 Heater Can or Vacuum Screen Failure
- 10.6 Manifold Piping Failure
- 10.7 Inadequate Oxygen Levels to Oxidizer
- 10.8 Excessive CO Levels at Stack
- 10.9 Excessive THC Levels at Stack
- 10.10 Excessive Toxic Emissions (if source testing is required)
- 10.11 Heater Element Failure
- 10.12 Heat Exchanger Failure
- 10.13 Main Blower (Vent Fan) Failure
- 10.14 Thermal Oxidizer Overheat
- 10.15 Thermal Oxidizer Shutdown

Appendixes

Appendix A: Checklists

Volume 2

Vendor Manuals and Product Data Sheets

Section II

Prescribed Forms

This section contains no entries.

Glossary of Terms

Acronyms and Abbreviations

Term	Definition
¹³ C	Carbon-13
³⁷ Cl	Chlorine-37
AQC	Air Quality Control
ARAR	Applicable or Relevant and Appropriate Requirement
AS	Air Sparging
ASTM	American Society for Testing and Materials
B(a)P	Benzo(a)pyrene
BGS	Below Ground Surface
BTU	British Thermal Unit
CEM	Continuous Emission Monitoring
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CFR	Code of Federal Regulations
cm/s	Centimeters per Second
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COC	Compound (contaminant or constituent) of Concern
CPVC	Chlorinated Polyvinyl Chloride
CSM	Conceptual Site Model
dBA	A-weighted Decibels
DCE	Dichloroethene
DNAPL	Dense Non-Aqueous Phase Liquid
DOE	U.S. Department of Energy
DRE	Destruction and Removal Efficiency
DTS	Distributed Temperature Sensor
EM	Engineer Manual
EPA	Environmental Protection Agency
ER	Engineer Regulation
ERH	Electrical Resistance Heating
ERT	Electrical Resistance Tomography
ESTCP	Environmental Security Technology Certification Program
ft ²	Square Foot
GAC	Granular Activated Carbon
gpm	Gallons per Minute
HCl	Hydrochloric Acid
HPO	Hydrous Pyrolysis Oxidation

ISTD	In Situ Thermal Desorption or In Situ Thermal Destruction
ISTR	In Situ Thermal Remediation
ITRC	Interstate Technology and Regulatory Council
kJ/mol	Kilojoules per Mole
Ldn	Day-Night Average Sound Level
LLNL	Lawrence Livermore National Laboratory
LNAPL	Light Non-Aqueous Phase Liquid
m ²	Square Meter
m ³	Cubic Meter
mg/kg	Milligrams per Kilogram
mg/L	Milligrams per Liter
MCL	Maximum Contaminant Limit
MEW	Missouri Electric Works
NAPL	Non-Aqueous Phase Liquid
NEC	National Electrical Code
NFPA	National Fire Protection Association
NO ₃	Nitrate
O&M	Operations and Maintenance
O ₂	Oxygen
ORP	Oxidation-Reduction Potential
OSHA	Occupational Safety and Health Administration
PAH	Polycyclic Aromatic Hydrocarbon
PCB	Polychlorinated Biphenyl
PCDD/F	Polychlorinated Dibenzodioxin and Dibenzofuran
PCE	Perchloroethylene
PCP	Pentachlorophenol
PCU	Power Control Unit
PFD	Process Flow Diagram
pH	Potential of Hydrogen
PMP	Pressure Monitoring Point
ppb	Parts per Billion
ppm	Parts per Million
RAO	Remedial Action Objective
RCRA	Resource Conservation and Recovery Act
redox	Reduction-Oxidation
scfm	Standard Cubic Feet per Minute
SCE	Southern California Edison
SEE	Steam Enhanced Extraction
SO ₄	Sulfate
STAR	Self-Sustaining Treatment for Active Remediation
SVE	Soil Vapor Extraction

SVOC	Semi-Volatile Organic Compound
TCA	Trichloroethane
TCDD	2,3,7,8-tetrachlorodibenzo-p-dioxin
TCE	Trichloroethene
TCH	Thermal Conductive Heating
TEQ	Toxicity Equivalent
THC	Total Hydrocarbon
TMP	Temperature Measuring Point
TOC	Total Organic Carbon
TPH	Total Petroleum Hydrocarbon
TTZ	Target Treatment Zone
µg/L	Micrograms per Liter
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
UXO	Unexploded Ordnance
VOC	Volatile Organic Compound
VR	Vapor Recovery
yd ³	Cubic Yard