# CHAPTER 2

## Underlying Physical Principles and Technology Descriptions

2.1. Fundamental Principles. Organic chemicals released to the subsurface may exist in as many as four phases: the solid soil matrix, the gas phase, the aqueous phase, and a NAPL phase. Application of heat to the subsurface can mobilize NAPL phase contaminants from the soil matrix, allowing them to be removed in the fluid phases via groundwater recovery wells or vapor collection systems. This section presents a general overview of the processes of multiphase flow and multi-component mass transfer in the subsurface, and the manner in which elevated temperatures can enhance those processes for removal of contaminants.

2.1.1. *Chemical Principles*. Presented in the following sections are chemical, thermal, hydrogeological, and biological concepts to provide a basis of understanding of the changes that take place under ISTR.

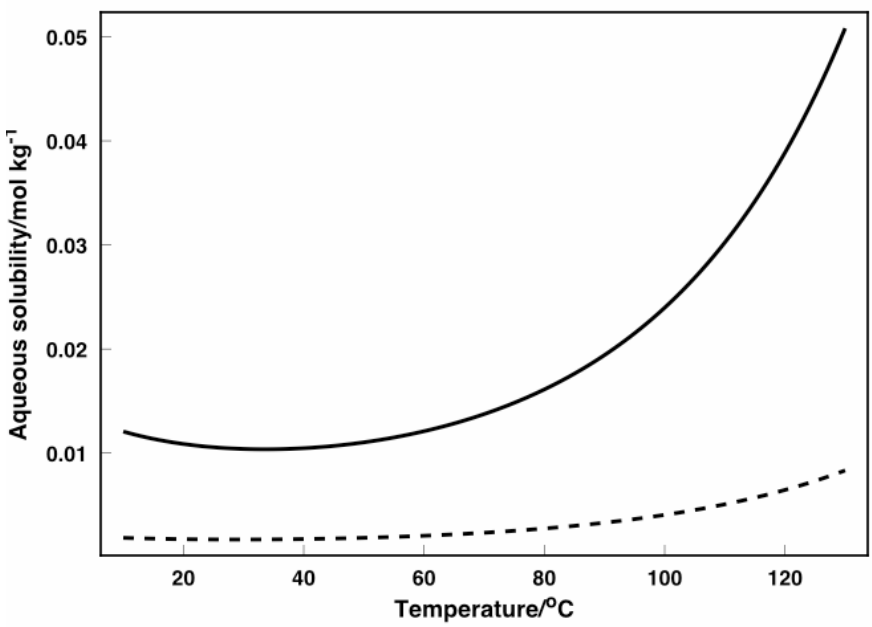



**Figure 2-1. Aqueous Solubilities of Trichloroethylene (solid line) and Tetrachloroethylene (dashed line) as a Fnction of Temperature. (From Knauss et al. 2000, copyright, Elsevier, used with permission.)**

2.1.1.1. *Aqueous Solubility*. For hydrocarbons, data on solubility at the temperatures used during ISTR are scarce. The aqueous solubilities of TCE and PCE as functions of temperature are presented in Figure 2-1. While the solubilities of the two compounds depicted increase exponentially with temperature, they do so only at temperatures above the conventional boiling point of water. A local solubility minimum around 30 to 50ºC has been observed in experimental studies for both TCE and PCE (Imhoff et al. 1997, Knauss et al. 2000, Heron et al. 1998a, b).

2.1.1.1.1. The temperature dependency for large molecules such as the PAH naphthalene is relatively strong. Figure 2-2 shows the aqueous solubility of solid naphthalene in the temperature range from 20 to 140$^{o}$C. The solubility increases about 45 times (from 31 to 1350 mg/L) by heating from 25 to 100$^{o}$C. The solubility of naphthalene when present in a mixture such as creosote increases by a factor of 5 to 10 at temperatures typically seen in ISTR (Davis 2003. This helps to explain the dramatic increases seen in dissolved PAH concentrations during field scale steam remediation at wood-treating sites such as Visalia Pole Yard, and Wyckoff-Eagle Harbor. An interesting result in investigating the temperature effect on the dissolution rate for NAPLs into water was that even if the aqueous solubility of PCE did not change dramatically with temperature, the dissolution rate for the DNAPL increased about five-fold (Imhoff et al. 1997). As a result, for systems with mass-transfer limitations, where the extracted water is below saturation, heating may increase the mass removal rate in the dissolved phase substantially.

2.1.1.1.2. Overall, the increased solubility of the contaminants can lead to enhanced dissolution, and for PAH's with low volatility, the aqueous phase removal can become a substantial component of the remedy. For example, during the SEE extraction at the Skokie, Illinois, site, it is estimated that 22% of the total hydrocarbon removed was in the dissolved phase (Smith 2003).

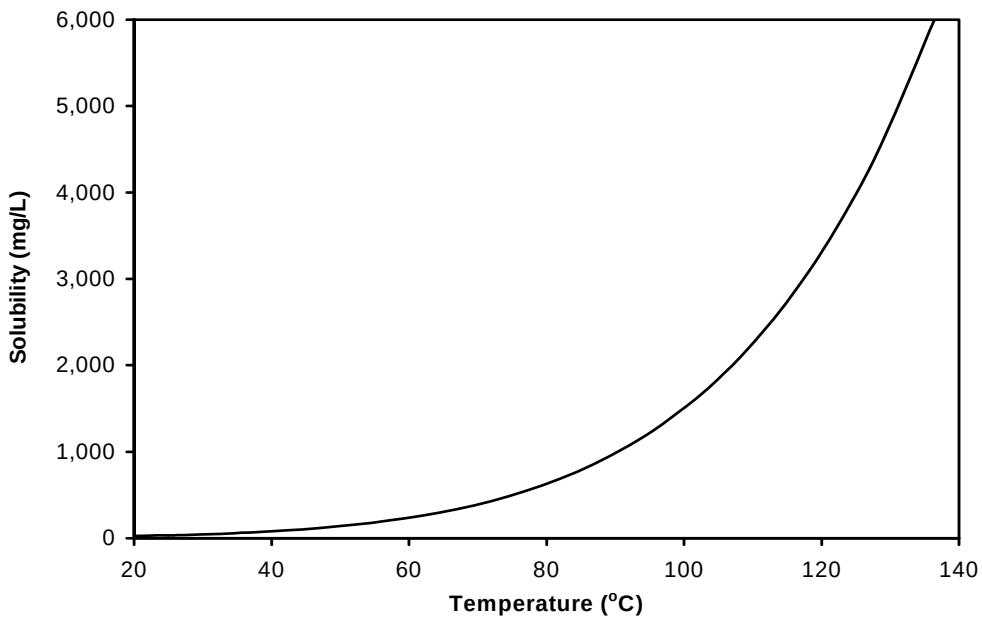



**Figure 2-2. Calculated Aqueous Solubility of Naphthalene as a Function of Temperature. (Based on equations from Reid et al.)**

2.1.1.2. *Sorption*. Soil-water sorption coefficients affect only the aqueous-phase transport of compounds. The temperature effect on soil-water sorption coefficients is likely to be most relevant to those ISTR systems that rely on aqueous-phase transport of the contaminants. In general, these sorption coefficients will decrease as a function of temperature, increasing the ability of hot fluids to remove contaminants from the soil. The effect of temperature is specific

to the contaminant, soil type, and water content. The soil-water sorption coefficient (saturated conditions) for TCE can theoretically decrease by 50% from 20 to 90°C, while the soil-gas sorption (dry soil) coefficient for TCE can decrease by an order of magnitude in the same temperature range (Heron et al. 1998a).

2.1.1.3. *Vapor Phase.* Volatilization of a chemical compound is controlled by its vapor pressure, which is the pressure exerted by the gas phase in equilibrium with its liquid or solid phase. The vapor pressure increases with temperature (see Figure 2-3), and boiling occurs when the vapor pressure exceeds atmospheric pressure. Evaporation or vaporization by steam distillation may occur below the pure-component boiling point.

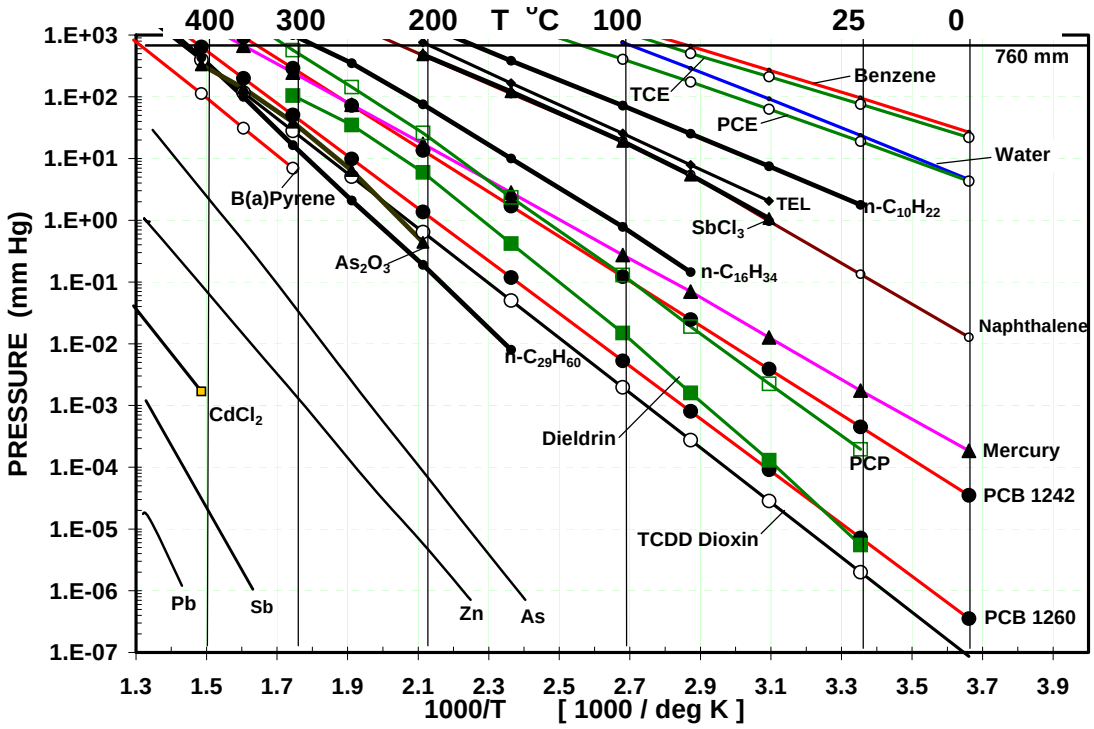



**Figure 2-3. Vapor Pressure of Selected Compounds vs. Temperature . Note that atmospheric pressure is 760 mm Hg. (From Stegemeier and Vinegar 2001, copyright, CRC Press, Used with permission.)**

2.1.1.3.1. Because the gas-phase concentration of a hydrocarbon compound strongly depends on its vapor pressure, a temperature increase will improve mass transport by increasing the concentration in the vapor phase, even if the temperature is below the boiling point. Figure 2-3 shows the vapor pressure of several compounds as a function of temperature. Figure 2-4 presents the predicted vapor-phase volumetric concentration of TCE and PCE as a function of temperature; the volumetric aqueous solubilities at room temperature are noted.

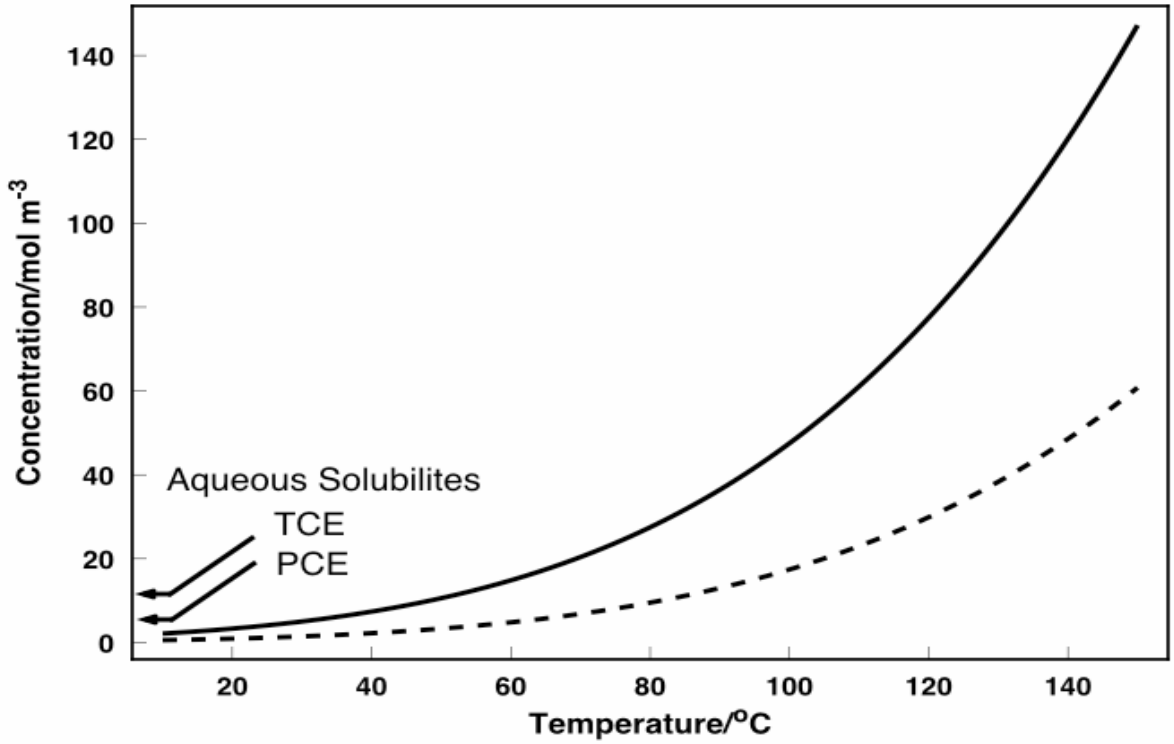



**Figure 2-4. Vapor-Phase Concentrations of Trichloroethylene (solid line) and Tetrachloroethylene (dashed line) as Functions of Temperature. Calculated with the Clapeyron equation assuming ideal-gas behavior. The arrows to the ordinate axis indicate the aqueous solubilities of the two compounds at 25°C.**

2.1.1.4. *Gas Mixtures*. Four fundamental laws of thermodynamics describe the composition of a gas mixture:

a. Dalton's Law states that the pressure exerted by a mixture of gases is the sum of the pressures that could be exerted by each individual gas occupying the same volume alone. The pressure that could be exerted by an individual gas is referred to as the partial pressure.

b. Raoult's Law states that the equilibrium gas-phase partial pressure of a compound isequal to the product of the vapor pressure of the pure compound and the mole fraction of the compound in the NAPL phase.

c. Henry's Law states that the equilibrium gas-phase partial pressure of a compound is equal to the mole fraction of the compound in the aqueous phase multiplied by a constant, known as the Henry's Law constant (see Figure 2-5).

d. The Ideal Gas Law predicts that the mole fraction of a compound in the gas phase is equal to the ratio of its partial pressure and the total pressure.

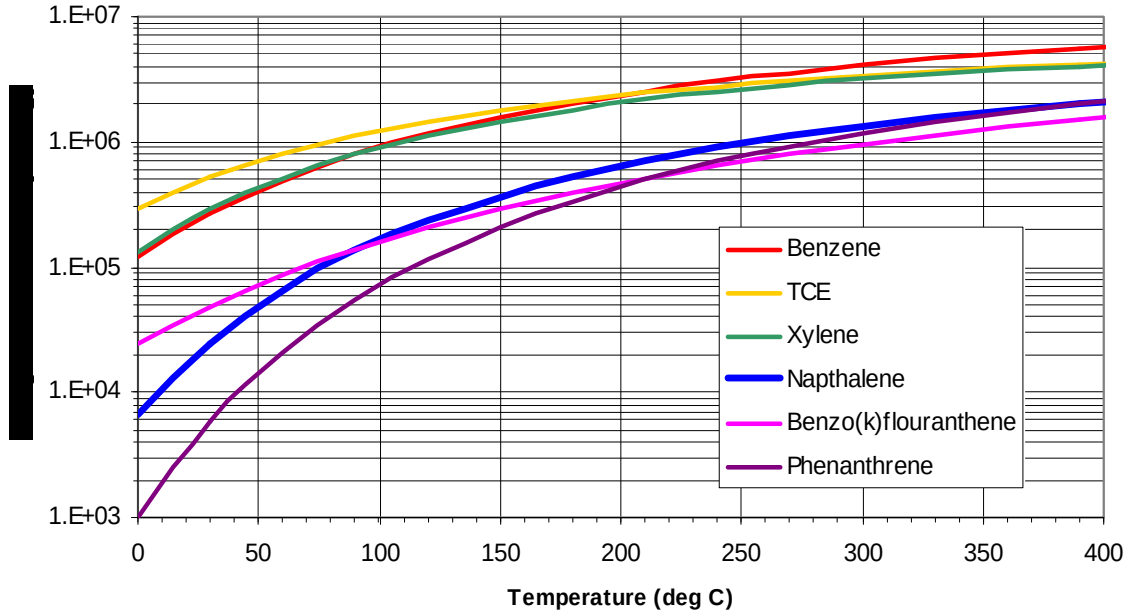



**Figure 2-5. Henry's Law Constants vs. Temperature for Various Compounds (From EPA 1984.)**

2.1.1.4.1. Based upon these four principles, the concentrations of hydrocarbon contaminants in vapor extracted from a thermal treatment zone will increase with temperature. Further, the relative proportion of each component in the vapor phase is dependent on its volatility (vapor pressure) and its concentration in the liquid phase.

2.1.1.5. *Hydrolysis, Pyrolysis, and Oxidation*. Hydrolysis is a process by which compounds decompose into simpler compounds while dissolving in, or reacting with, water. If oxygen or naturally occurring oxides are present in the soil, contaminants can also be altered or decomposed by oxidation. The potential for both hydrolysis and oxidation increases at with increasing temperatures. In addition, organic contaminants are subject to pyrolysis, or high-temperature decomposition with or without the presence of water or oxygen. These processes are often undifferentiated during ISTR, owing to the conditions and byproducts they have in common. Contaminant destruction under steam and liquid water conditions often relies on recharge of oxygenated groundwater to the treatment zone, and may be referred to as hydrous pyrolysis and oxidation. Thermal destruction at these temperatures is slow but significant, and has accounted for as much as 17% of the apparent contaminant destruction during steam injection treatment of creosote-contaminated soil (Subsurface Contaminants Focus Area, 2000). The rate of hydrolysis varies by compound and with temperature as shown in Table 2-1.

2.1.1.5.1. .As can be seen from Table 2-1, the hydrolysis rates for halogenated alkenes (e.g., TCE and PCE) tend to be very slow, even at steam temperatures. However, the hydrolysis rates for halogenated alkanes (e.g., TCA and carbon tetrachloride) tend to be very fast. These compounds tend to be destroyed as quickly as they dissolve.

**Table 2-1. Rate of Hydrolysis by Compound and Temperature (Weintraub et al. 1986, Barbash and Reinhard 1989, Jeggers et al. 1989, ETC8 1993).**

| Compound | Half-life at 25°C (years) | Activation Energy (kJ/mol) | Hydrolysis Product | Half-life (days) Temperature (°C) | | |
|---|---|---|---|---|---|---|
| | | | | 80 | 100 | 120 |
| chloroform | 1850 | 123 | mineralizes | 294 | 31 | 4 |
| carbon tetrachloride | 41 | 115 | mineralizes | 11 | 1.3 | 0.2 |
| 1,1-DCA | 61 | 110 | Vinyl chloride | 22 | 3 | 0.5 |
| 1,1-DCE | $1.2\times10^{8}$ | 130 | insignificant | $1\times10^{7}$ | $1\times10^{6}$ | $1\times10^{5}$ |
| 1,2-DCE | $2.1\times10^{10}$ | 130 | insignificant | $2\times10^{9}$ | $2\times10^{8}$ | $2\times10^{7}$ |
| 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 | $1.3\times10^{6}$ | 127 | insignificant | $2\times10^{5}$ | $2\times10^{4}$ | 1960 |
| 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 | $9.9\times10^{8}$ | 123 | insignificant | $2\times10^{8}$ | $2\times10^{7}$ | $2\times10^{6}$ |
| EDB (ethylene dibromide) | 2.5 | 92 | mineralizes | 3 | 0.5 | 0.1 |
| methylene chloride | 1.6 | 119 | mineralizes | 0.3 | 0.04 | 0.01 |
| 1,2-DCA | 5.9 | 104 | ethylene glycol | 3 | 0.5 | 0.1 |

2.1.2. *Thermal Principles*.

2.1.2.1. *Heat Transport (Conduction, Advection and Convection*. Energy transport in the subsurface is attributable to heat conduction in the porous matrix as well as heat transport by fluid motion. In the absence of fluid movement, energy flow by conduction only is described by the relationship:

$$q''_x = -k(dT/dx) \tag{2-2}$$

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 ($K \cdot m^{-1}$).

The terms “convection” and “advection” are often used interchangeably to describe energy transport due to movement of heated fluids. Convection actually includes heat diffusion as well as advection; however heat transport by fluid diffusion tends to be minor compared to advection and conduction. In general, heat convection is the most effective transport mechanism in materials with moderate to high permeability, such as sand and gravel, while conduction is the dominant process in materials with lower permeability such as silt and clay (Figure 2-6).

2.1.2.2. *Thermal Conductivity and Thermal Diffusivity*. Thermal conductivity is a measure of the ability of a material to conduct heat. Thermal diffusivity is a measure of material’s ability to conduct heat relative to its ability to store heat (i.e., thermal conductivity divided by heat

capacity; see next section). Heat can migrate relatively quickly through a material with high thermal conductivity, while heat flow into a material with high thermal diffusivity will result in a relatively rapid temperature increase. Typical values of thermal conductivity are shown in Table 2-2.

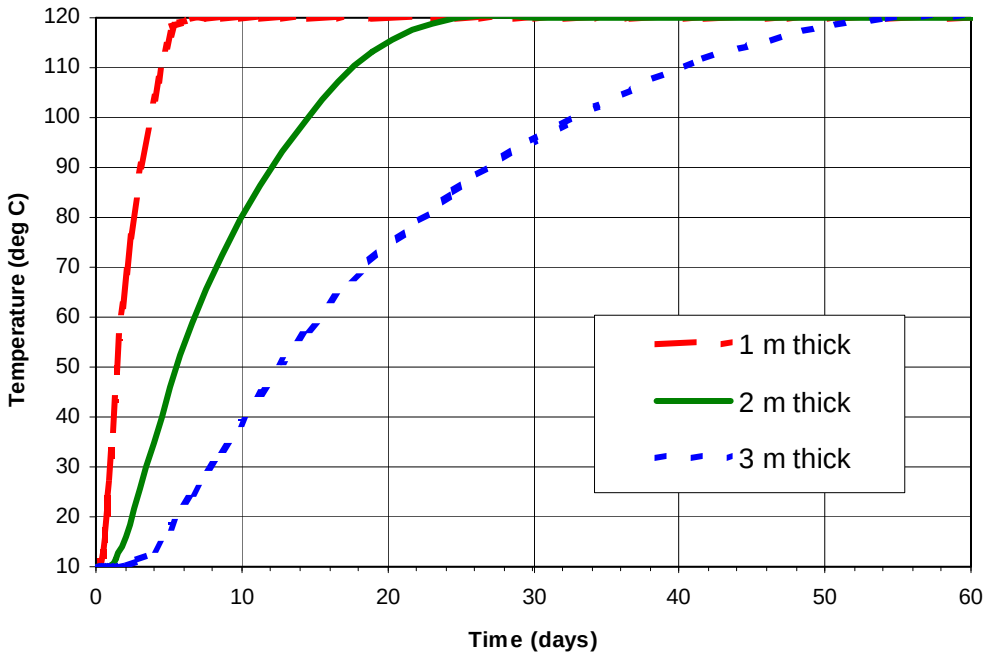



**Figure 2-6. Conductive Heating of 1-, 2-, and 3-m-thick Impermeable Layers From Both Sides. Steam temperature above and below the layer is 120°C, ambient temperature = 10°C, soil diffusivity is 5.82 ×10$^{-7}$ m$^2$/s.**

**Table 2-2. Thermal Properties of Representative Materials and Fluids (de Vries 1963, Incropera and De Witt 1996, USEPA 2002).**

| Material | Thermal conductivity (W/m K) | Heat capacity (KJ/m$^3$ K) | Diffusivity (m$^2$/s) | Density (g/cm$^3$) |
|---|---|---|---|---|
| Quartz[1] | 8.79 | 2008 | $4.38\times10^{-6}$ | 2.66 |
| Clay minerals[1] | 2.93 | 2008 | $1.46\times10^{-6}$ | 2.65 |
| Organic matter[1] | 0.25 | 2510 | $9.96\times10^{-8}$ | 1.30 |
| Silty sand (dry)[2] | 1.23 | 1906 | $9.76\times10^{-7}$ | 1.52 |
| Silty sand (wet)[2] | 1.41 | 4359 | $5.82\times10^{-7}$ | 1.80 |
| Silt (dry)[2] | 0.96 | 1078 | $1.29\times10^{-6}$ | 1.44 |
| Silt (wet)[2] | 1.26 | 5030 | $4.77\times10^{-7}$ | 1.90 |
| Water[1] | 0.57 | 4184 | $1.36\times10^{-7}$ | 1.00 |
| Air[1] | 0.0218 | 1.3 | $1.68\times10^{-5}$ | 0.0013 |
| Engine oil[3] | 0.15 | 1669 | $7.71\times10^{-8}$ | 0.89 |

2.1.2.2.1. The thermal conductivity of solids and fluids can vary with temperature, and representative values should be selected for the temperature range of interest (Figure 2-7). Measured thermal conductivity of porous materials is a combination of conduction and convection occurring within the pore fluids. The change in measured thermal conductivity may be influenced by increased convection with temperature. Additional thermal conductivity values are available in the published literature, for soil materials (Johansen 1997, Sundberg 1988) and for fluids (Poling et al. 2001). Note that the bulk thermal conductivity ($k_{bulk}$) for a soil is the combined thermal conductivity of the soil particles and the fluid contained in the pore space:

$$k_{bulk} = k_{particle}(1-n) + k_{fluid}(n) \tag{2-3}$$

Where $n$ = soil porosity [unitless].

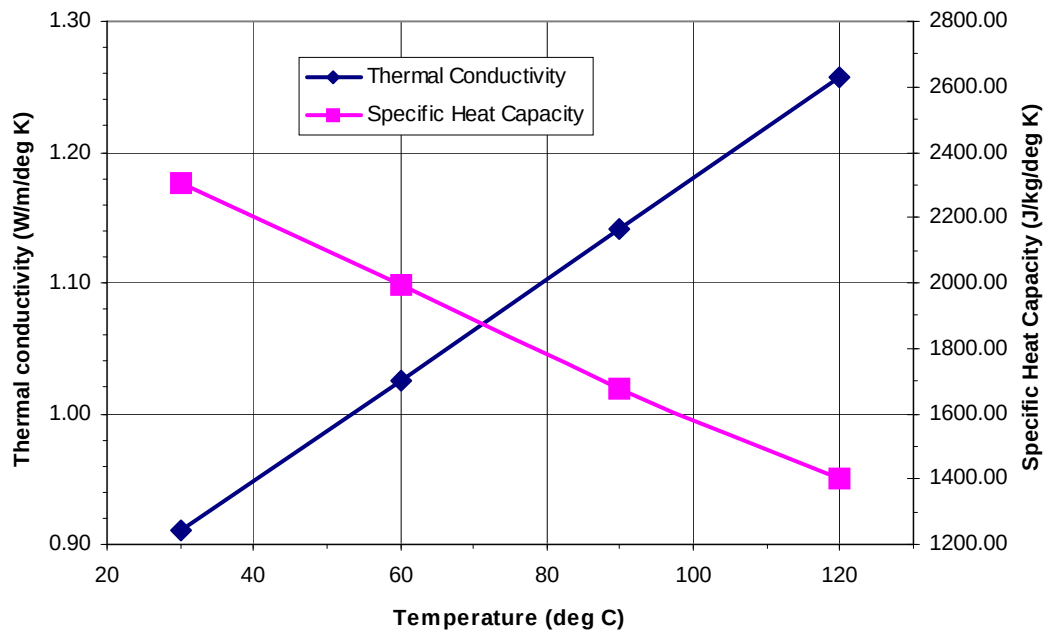



**Figure 2-7. Thermal Conductivity and Specific Heat Capacity of Dry Silty Sand vs. Temperature (EPA 2002a).**

2.1.2.3. *Heat Capacity*. The specific heat of a material ($KJ \cdot kg^{-1} \cdot K^{-1}$) is the energy required to raise the temperature of a unit mass by one degree (Figure 2-7). The product of the specific heat and density is referred to as the heat capacity ($KJ \cdot m^{-3} \cdot K^{-1}$), and provides a measure of the material's ability to store heat. The heat capacity of soils and fluids change with temperature; however the range of variation for heat capacity of different soils is generally small compared to the variability of other parameters such as permeability. Similar to thermal conductivity, the bulk heat capacity of a soil is the combined heat capacity of the soil particles and the fluid in the pore space.

2.1.2.4. *Heat of Vaporization*. The heat of vaporization ($KJ \cdot kg^{-1}$) is the amount of energy required to vaporize a unit mass of material, i.e., to boil a kilogram of liquid until it is entirely converted to gas. If the conversion takes place at the liquid boiling point, the energy input does

not result in a temperature increase. The total heat required to vaporize a liquid that is originally at ambient temperature will be the sum of the heat required to raise the liquid to its boiling point (product of specific heat, temperature increase, and mass) and the total heat require to vaporize the liquid (product of heat of vaporization and mass).

2.1.2.5. *Thermodynamics of NAPL/Water "Boiling."* The boiling temperature of a liquid mixture is the temperature at which its total vapor pressure is equal to atmospheric pressure. Since the total vapor pressure is the sum of partial pressures of all of the components of the mixture, the boiling point of the mixture (eutectic point of the azeotropic mixture) can be achieved at a lower temperature than any of the boiling points of any of the separate components (Lupis 1983). This phenomenon is called co-distillation or steam distillation (Davis 1998). The implication for ISTR is that many contaminants can be easily removed in vapor at steam temperatures, even if their boiling temperatures are greater than 100°C. Table 2-3 provides select NAPL compounds and steam co-distillation boiling points.

**Table 2-3. Select NAPL Compounds and Steam Co-Distillation Boiling Points (Lide 1999).**

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

2.1.2.6. *Thermodynamics of Steam Stripping via In Situ Steam Generation.* Steam stripping is a process whereby contaminants partition from soil, water, or NAPL phases into the vapor (steam) phase and are carried away (stripped) from their source areas by vapor flow. The removal of the vaporized contaminants prevents the liquid or solid phases from reaching equilibrium with the vapor phase, allowing vaporization to continue at maximum rates. The stripped contaminants are condensed along with the steam at the edge of the steam zone (condensation front). When the concentration of a condensing contaminant exceeds its solubility, NAPL or solid compounds are deposited near the steam front, forming a "contaminant bank."

2.1.3. *Hydrogeological Principles*.

2.1.3.1. *Fluid Flow Fundamentals and Impact of Elevated Temperatures.* The rate of liquid flow in a saturated porous medium is proportional to the hydraulic gradient across the medium. For the one-dimensional case, this relationship is written symbolically as:

$$Q/A = -K(\mathrm{d}h/\mathrm{d}L) \tag{2-4}$$

Where:

$Q/A$ = volumetric flow rate of water per unit of surface area [$L \cdot T^{-1}$]
$K$ = hydraulic conductivity [$L \cdot T^{-1}$]
$\mathrm{d}h/\mathrm{d}l$ = hydraulic gradient [$L \cdot L^{-1}$].

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.

2.1.3.1.1. *Hydraulic Conductivity*. Hydraulic conductivity in liquid-saturated porous media is dependent on liquid density, liquid viscosity, and soil characteristics including grain size (Hubbert 1956); that is, hydraulic conductivity ($K$) is separable into distinct contributions due to the fluid properties and porous media permeability:

$$K = k\rho g/\eta \tag{2-5}$$

Where:

$\rho$ = density of the liquid [$M \cdot L^{-3}$]
$\eta$ = 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 [$L^2$] (Table 2-2).

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, i.e., in the vadose zone, or when various combinations of air, steam, liquid water, or NAPL are present (see Paragraph 3-1.3.2). In general, the permeability of granular soil is not significantly affected by 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 from drying at temperatures above the boiling point of groundwater.

2.1.3.1.2. *Viscosity*. Figure 2-8 shows the temperature dependence of viscosity for different fluids. NAPL-recovery during ISTR is enhanced by the reduction of liquid viscosities at higher temperatures. In general, the viscosity of most liquid organic chemicals decreases by about one percent for a temperature increase of 1ºC (Davis 1997, Poling et al. 2001). Gas viscosities tend to be one to two orders of magnitude less than liquid viscosities, but increase proportionally with temperature. Typically, the viscosity of a gas will increase about 30% with a temperature increase of 100°C (Davis 1997).

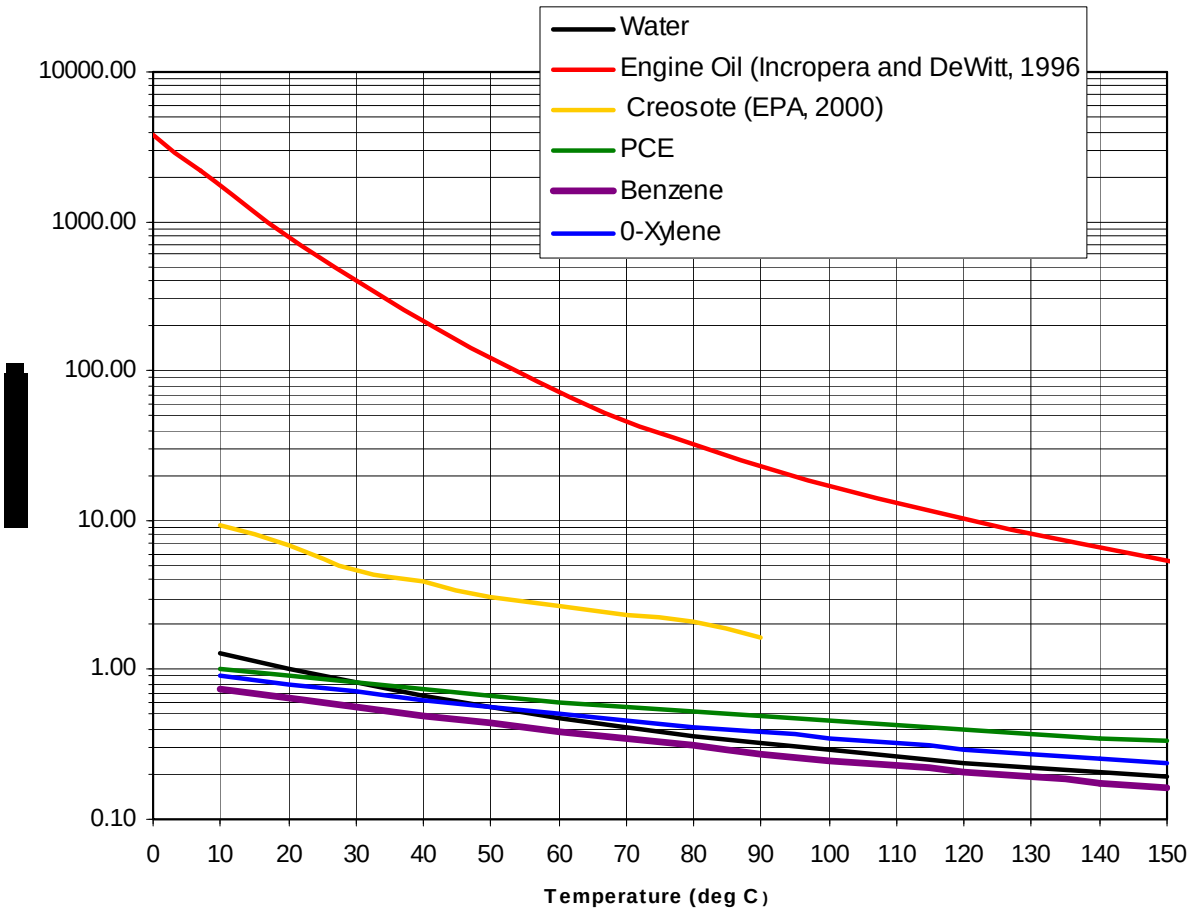



**Figure 2-8. Viscosity vs. Temperature for Liquids (Incropera and DeWitt 1996, EPA 2000a, Poling 2001).**

2.1.3.1.3. *Density*. Figure 2-9 shows the variation of density with temperature for different fluids. In general, hydrocarbon compound densities will decrease about 10% for a temperature change of 100°C (Davis 1997). The density of water decreases about 4% over the temperature range from 0 to 100°C. Although these changes are small, they can affect contaminant migration

because of the more rapid change of NAPL density relative to groundwater density. DNAPLs with densities close to the density of water, such as creosote or halogenated hydrocarbon and oil and grease mixtures, can become LNAPLs at elevated temperatures.

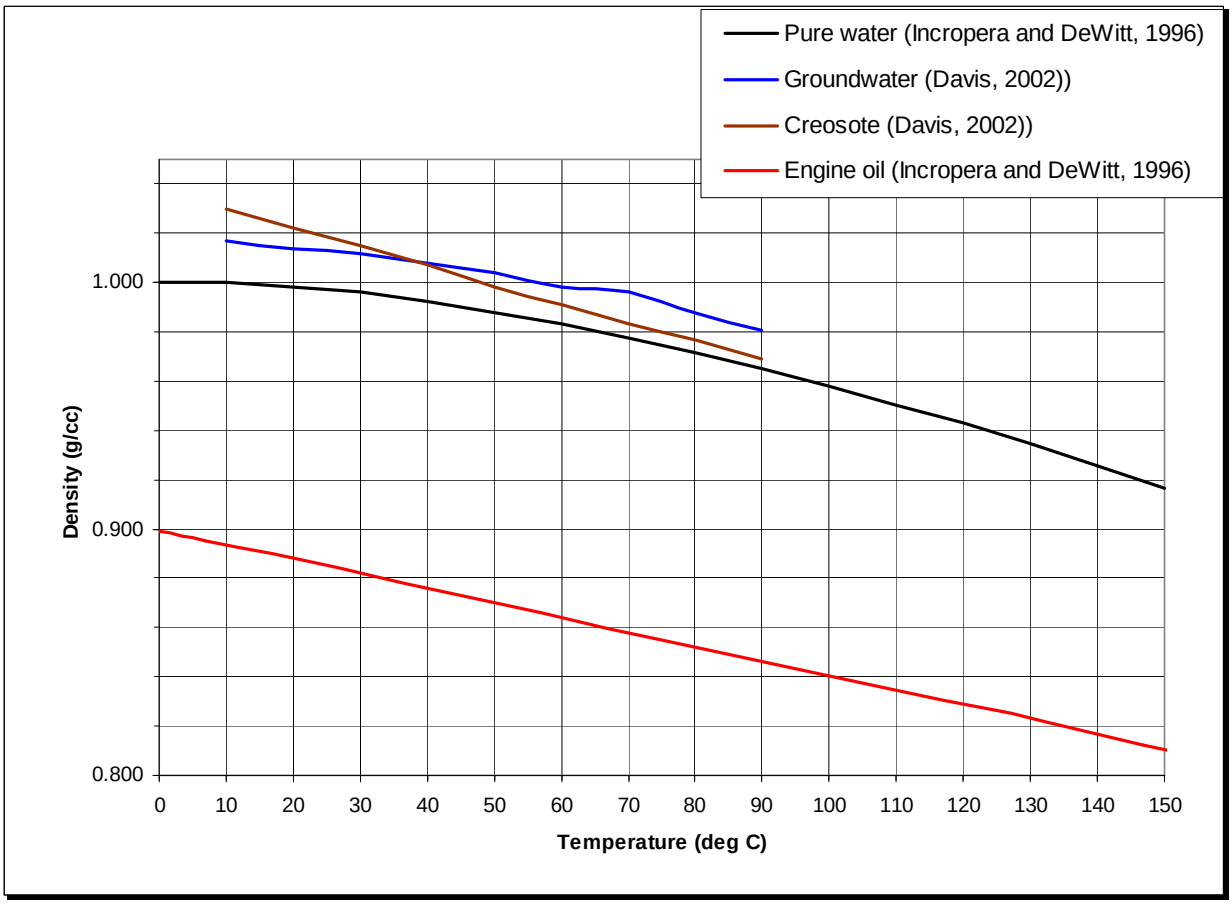



**Figure 2-9. Density vs. Temperature for Liquids (Incropera and DeWitt 1996, Davis 2002).**

2.1.3.2. *Multi-Phase Flow*. The performance of in situ thermal remediation systems is strongly affected by the simultaneous flow of two (gas and water) or three (gas, water and NAPL) phases through a porous matrix at elevated temperatures. The following paragraphs summarize the principles that control the interactions of immiscible fluids in the subsurface. Figure 2-10 shows a conceptual diagram of fluid movement during steam injection.

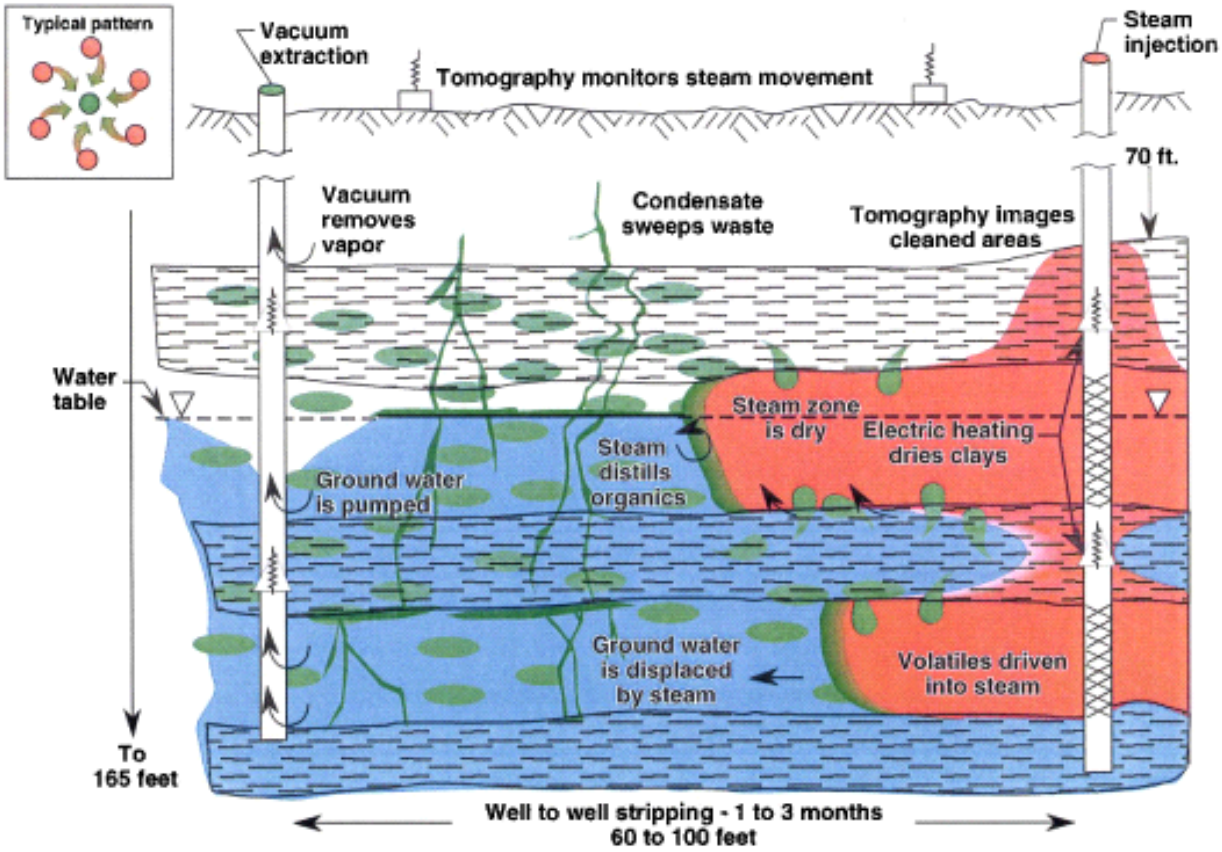



**Figure 2-10. Conceptual Diagram of Multiphase Flow at a Dynamic Underground Stripping Project (Lawrence Livermore National Laboratory 1994).**

2.1.3.2.1. *Residual Saturation.* Residual saturation is the amount of a fluid that remains in a porous medium after displacement by another fluid. In an air-water system, residual water content is the amount of water retained after draining the soil. In the context of ISTR, residual NAPL saturation is the amount of NAPL remaining after drainage of the NAPL by recovery wells, or displacement of the NAPL by steam, air, or groundwater. Residual NAPL saturations in unconsolidated sands at ambient conditions typically range from 14 to 30% (Wilson et al. 1990). This has important implications for ISTR because, once residual saturation is achieved, contaminant recovery can continue only in the dissolved or vapor phases. Experimental studies have found consistently that residual NAPL saturation decreases with increasing temperature (Sinnokrot 1969, Sanyal 1972, Davis 1994). The estimated residual saturation of PCE has been shown to decrease linearly by 67% as the temperature is increased from 20 to 80°C (She and Soppe 1998. These data indicate favorable conditions for recovery of NAPL contaminants by ISTR.

2.1.3.2.2. *Interfacial Tension and Capillary Pressure.* If two immiscible fluids occupy the voids of a porous medium, the pressure of the fluid that wets the porous matrix is less than that of the non-wetting fluid. This pressure difference is made possible by the tension in the meniscus between the two fluids (interfacial tension), similar to the pressure difference between

the inside of a balloon and the surrounding atmosphere. Capillary pressure increases as the non-wetting fluid displaces the wetting fluid, and the degree of saturation by the wetting liquid decreases (Figures 2-11 and 2-12). Gas and NAPL are expected to be the non-wetting fluids in most soils; however, geochemical conditions can cause a soil to become NAPL-wet over time. Because retention of immiscible fluid in soil pore space is partially the result of capillary pressure, mobility and potential recovery of NAPL could be improved by reducing interfacial tensions. Although the air-water interfacial tension is known to decrease with increasing temperature, available data indicate that temperature has only a minor effect on oil-water interfacial tensions (Davis 1994, 1997 2003).

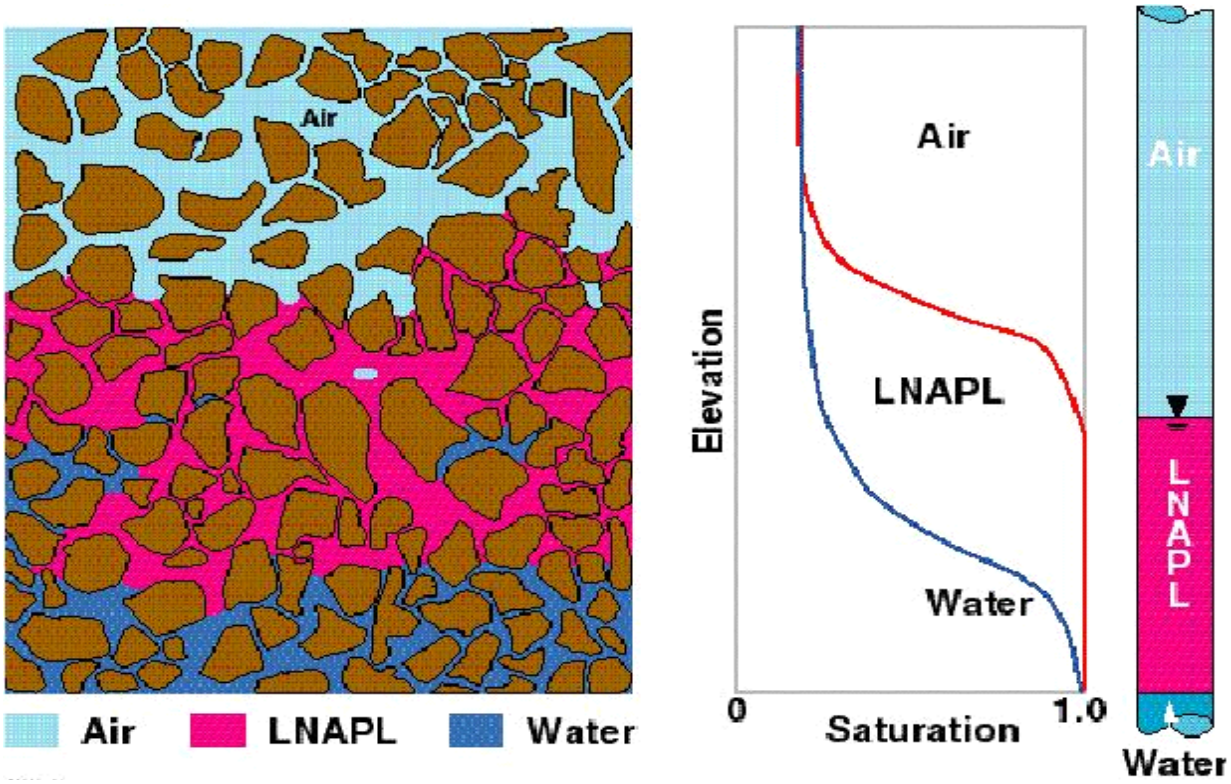



**Figure 2-11. LNAPL in Soil, Saturations vs. Elevation, and Level in a Well. Figure courtesy of Dr. Ralph Baker, TerraTherm, Inc. Used with permission.**

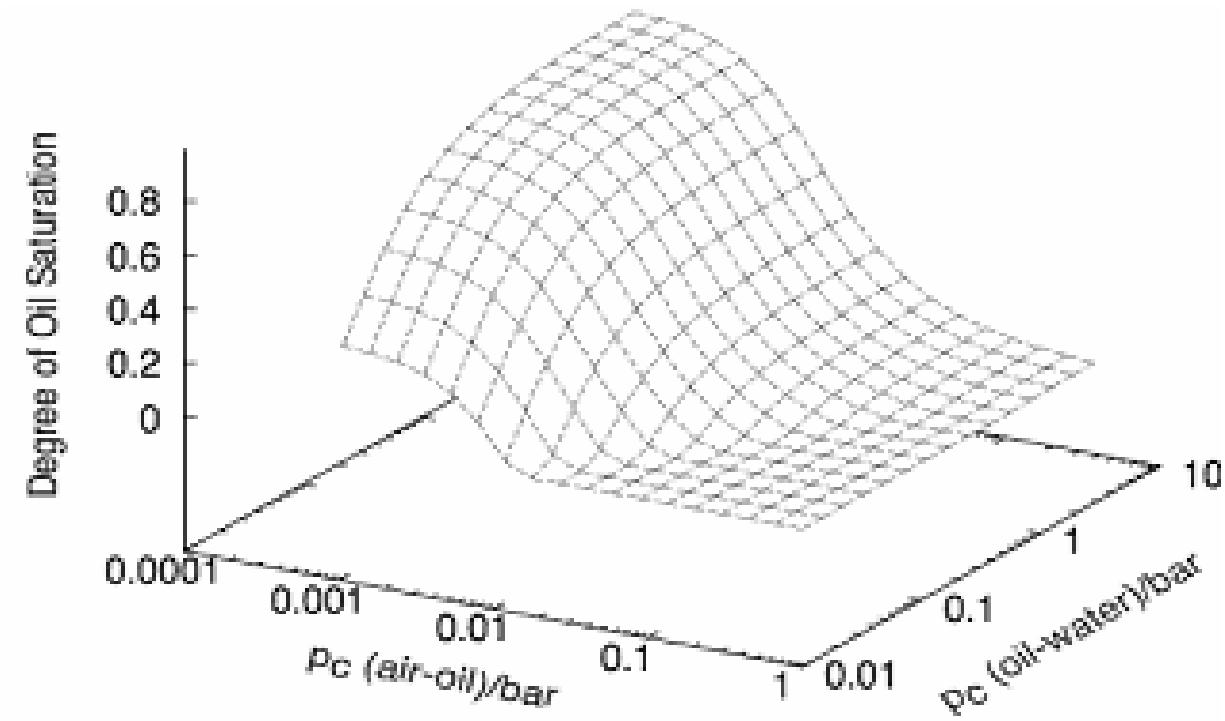



**Figure 2-12. Example of Oil Saturation as a Function of Air-NAPL Capillary Pressure and NAPL-Water Capillary Pressure. The total (water + oil) saturation is determined by the air-NAPL capillary pressure. The water saturation is determined by the oil-water capillary pressure. (From Lenhard and Parker 1987, copyright, Elsevier, used with permission.)**

2.1.3.2.3. *Relative Permeability.* Saturated and partially saturated hydraulic conductivities are related by the following relationship:

$$k_r = K/K_s \tag{2-6}$$

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).

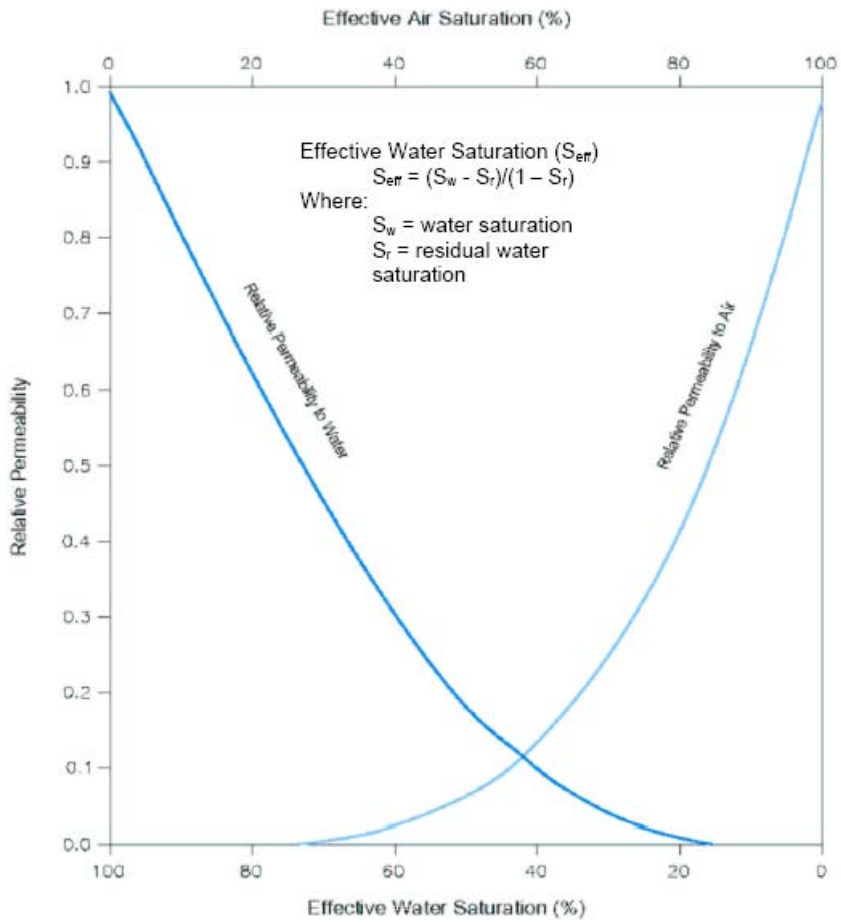



**Figure 2-13. Typical Relationship of Relative Permeability and Saturation, in a Soil Partially Saturated with Air and Water. As the water saturation increases, the relative permeability of the soil with respect to water increases, but the relative permeability to air decreases.**

2.1.3.3. *Fluid and Energy Transport.*

2.1.3.3.1. *Effect of Fluid Transport on Energy Transport*. Energy may be conveyed in the subsurface by convective or advective flow, or by fluid-phase changes (e.g., condensation of steam) in the porous matrix. Hot fluid transfers heat to soil particles, raising the temperature of the soil according to its heat capacity. When hot gases condense in soil, however, the heat of vaporization is also transferred to the soil particles, resulting in an additional temperature increase. Since the heat of vaporization of a liquid is many times larger than its heat capacity, the condensation accompanying fluid flow has the potential to deliver much more energy to the subsurface than fluid flow alone.

2.1.3.3.2. *Flow of Condensate from Steam Zone*. One of the important features of energy transport associated with ISTR is the horizontal flow of hot condensate away from the steam zone. Injection of non-condensable gas in the saturated zone (i.e., air sparging) typically results

in a conical zone of gas channels extending from the injection screen to the ground surface (USACE 1997). Introduction of steam into the subsurface, however, from injection wells or the propagation of steam resulting from in situ electrical or conductive heating, can create a gas-saturated zone of relatively greater horizontal extent owing to the horizontal flow of condensate. The condensate heats the media along its flow path toward extraction wells or away from the heated zone, creating a near-horizontal warm zone that can achieve steam temperature with less heat input than would be required for steam temperatures at ambient conditions. For typical ISTR arrays of vertical wells and electrodes installed at similar elevations, the condensate-heated zone is likely to be elongated in the horizontal direction, and can impart a significant horizontal component to the expansion of the steam zone. A potential goal in system design might be to optimize horizontal steam propagation, allowing maximum well spacings to be used (see Chapter 6).

2.1.3.4. *Biological Processes at Elevated Temperatures*. It is generally recognized that dissolved-phase plumes of contaminated groundwater are stabilized or reduced at least to some extent by natural attenuation processes (biodegradation, dispersion, dilution, sorption, volatilization, and abiotic degradation mechanisms). Of these mechanisms, biodegradation is perhaps the most important because it represents actual reduction in contaminant mass. While in situ biodegradation may have limited impact on NAPL source removal, there is the potential for biologically mediated contaminant reduction to assist thermal remediation projects, both during treatment and as a polishing step, resulting in the reduction of downgradient contaminant plumes both during and after active thermal remediation.

2.1.3.4.1. There are several possible effects of thermal remediation on the in situ biodegradation at a contaminated site. These range from complete inhibition within the heated zone to enhancement during and after thermal treatment. Neither effect is fully supported by current research, while there is only anecdotal indirect evidence of enhancement. There exist several lines of reasoning suggesting that in situ biodegradation should be enhanced by thermal remediation. It does seem clear, that based on existing data, thermal remediation does not result in permanently sterile soil conditions. Thermal remediation likely alters the consortia of microorganisms present and active at a site undergoing thermal treatment.

2.1.3.5. *Temperature Tolerance of Microorganisms*. The occurrence and abundance of microorganisms in a particular environment is controlled by the complex interaction of nutrients with physical and chemical factors (temperature, redox, pH, etc.) present in the environment through time. Consequently, the presence and success of a specific organism or consortia of microorganisms responsible for degrading hydrocarbons in a contaminated subsurface ecosystem depends on both nutrient requirements and tolerance for the range of physical and chemical conditions present. Temperature is considered to be one of the most important physical factors controlling the distribution and abundance of organisms. Bacteria, in particular, have adapted to a wide variety of environments, including habitats characterized by extreme temperatures, and can be sorted into descriptive groups based on the temperatures at which optimum growth has been observed (Table 2-4).

**Table 2-4. Generally Recognized Optimum Growth Range for Various Groups of Microorganisms.**

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

2.1.3.5.1. Thermophiles and extreme thermophiles have made several adaptations to membrane and enzyme systems that allow them to function at temperatures that would otherwise inhibit cellular transport and metabolic activity. These adaptations include high proportions of saturated lipids in cell membranes to prevent melting, enzyme systems that remain stable at high temperatures, and high proportions of the amino acids guanine and cytosine in nucleic acids to raise the melting point of DNA (Atlas and Bartha 1993).

2.1.3.5.2. Generally, higher environmental temperatures that do not kill microbes or exceed the temperature tolerance of the microbial consortia will result in higher metabolic activity. The increased metabolic activity of enzymatic systems with temperature (Q10) continues up to the temperature where the enzymes denature or lose the structural stability that enables them to function. Mesophiles are more efficient at degrading hydrocarbons at temperatures from 30 to 40°C (86 to 104°F) (Bossert and Bartha 1984). Thermophiles actively degrade hydrocarbons and recalcitrant NAPL constituents (PAHs and high-molecular-weight hydrocarbons) at temperatures up to 70°C (158°F) (Huesemann et al. 2002). Even though biocatalytic reactions proceed faster at higher temperatures, the growth rate of thermophiles is often slower than mesophiles at their optimum growth temperatures. Consequently, degradation reactions at elevated temperatures found at an ISTR site may progress more rapidly as thermophiles are capable of mediating degradation reactions at a faster pace without diverting energy to increasing biomass.

2.1.3.6. *Bioavailability at Elevated Temperatures*. In addition to increased metabolic activity that can be attributed to increased temperature, biodegradation at an ISTR site can also be enhanced by a temperature-induced increase in bioavailability. For example, the persistence of PAHs in the environment is attributed to the hydrophobicity of these compounds and their tendency to strongly sorb onto soil or sediment particles. Generally, NAPL constituents not in the dissolved phase are not available for microbial degradation, although there is some recent evidence that NAPL contaminants may be degraded by specially adapted bacteria (Wattiau 2002). However, increases in temperature have been shown to increase the solubility of both PAHs and the rate of dissolution of chlorinated compounds (Hulscher and Cornelissen 1996, Imhoff et al. 1997, Bonten et al. 1999, Jayaweera et al. 2002). Consequently, increased subsurface temperatures should increase the concentration of contaminants in the dissolved phase and increase the availability of these compounds to degrading microorganisms.

2.1.3.6.1. As discussed in Paragraph 2.1.1, the solubility of NAPL constituents increases at increased temperatures. At increased temperatures, the solubility of TCE and PCE increases,

resulting in greater mass of contaminant in the dissolved phase and, therefore, greater potential availability to degrading microorganisms. Preliminary data have also shown that the increased solubility of selected PAHs at temperatures up to 60°C enables thermophiles to degrade the PAHs at a rate of up to 8 times faster than mesophiles at lower temperatures (Viamajala et al. (2007).

2.1.3.7. *Microorganism Population Changes and Ability to Degrade Contaminants.* The combination of increased metabolic activity and greater bioavailability allows for enhancing in situ biodegradation at ISTR sites. During active thermal treatment, in situ degradation may be temporarily inhibited once subsurface temperatures increase above the tolerance range of indigenous mesophiles. Microorganisms have several mechanisms for surviving unfavorable conditions, however, including the formation of non-vegetative structures (i.e., spores or cysts) that are metabolically less active and allow the organism to survive until environmental conditions improve. Bacterial cells in bench-scale tests of creosote-contaminated soil have demonstrated the ability to rapidly become metabolically active following steam injection (Richardson 2000).

2.1.3.7.1. Further studies have also demonstrated that thermophilic degradation of PAHs and non-volatile hydrocarbons increased at temperatures likely to occur adjacent to the active treatment zone of an ISTR site (Huesemann et al. 2002). This observation is likely the result of shifts in the population of microorganisms from predominantly mesophilic to predominantly thermophilic. This type of community shift is usually associated with a reduction in the diversity of microorganisms, as the number of different types of organisms is smaller in extreme environments. As subsurface temperatures cool after active thermal treatment, the consortia within the heated zone will again shift as conditions become less favorable for thermophiles and return to the optimum temperatures for mesophiles. The effect these population shifts may have on the actual make-up of the community of microorganism at an ISTR site, and the resulting impact on the rate of in situ biodegradation, has not been well quantified. This question remains an important research topic that needs to be addressed for a more complete understanding of the fundamental processes that occur following ISTR.

2.1.3.7.2. While there are limited data to support claims of enhanced bioremediation at thermal remediation sites, it is possible to infer that in situ biodegradation rates are likely to increase both following thermal remediation (as the site cools) and adjacent to an ISTR site as groundwater passes through a heated zone, carrying heat and increased contaminant concentrations downgradient. The EPA Technology Innovation Office has published a more detailed review of this topic, available at the website www.clu-in.org (USEPA 2002b).

2.1.3.8. *Redox Theory of Biodegradation*. Established natural attenuation protocols may be used to document evidence of in situ biodegradation after active thermal treatment. Most biologically mediated degradation activity is conducted by enzymatic systems that carry out oxidation-reduction reactions. In these reactions, microorganisms obtain energy for growth and synthesis of proteins and other cellular components by transferring electrons from electron donors to electron acceptors. In the context of aerobic degradation reactions, organic contaminants in the dissolved phase act as electron donors, giving up electrons to electron

acceptors such as oxygen, nitrate, Fe(III), Mn (IV) sulfate, or carbon dioxide. In some cases, such as the reductive dechlorination reactions responsible for the degradation of chlorinated solvents, the organic contaminant acts as an electron acceptor.

2.1.3.8.1. The release of organic compounds to the subsurface and groundwater flow systems results in changes to the oxidation-reduction (redox) conditions in groundwater. Under natural conditions, infiltrating groundwater interacts with soil organic and mineral compounds, oxidizing the organic material, and, in turn, reducing the minerals. The consortium of microorganisms present catalyzes these reactions. Oxygen in the groundwater is utilized first as a terminal electron acceptor in biocatalyzed degradation reactions, because the use of oxygen is thermodynamically more favorable for aerobic microbes. Once oxygen concentrations decrease, oxidation can still occur, but the oxidizing agents are $NO_3$, $MnO_2$, $Fe(OH)_3$, and $SO_4$. The normal progression is from nitrate reducing, to manganese or iron-reducing conditions, to sulfate-reducing conditions; and may eventually progress to methanogenic conditions, resulting in the production of methane. As these oxidizing agents are consumed, the groundwater environment becomes increasingly reduced to the point where methanogenic conditions may result, if there are: 1) sufficient oxidizeable organics, 2) sufficient nutrients, and 3) temperature conditions conducive to bacterial growth. These processes are shown in Table 2-5.

2.1.3.8.2. The role of in situ biodegradation may be evaluated through both primary and secondary field evidence. Primary evidence includes quantitative evaluation of plume stability, or whether it is shrinking or growing, based on historical data trends. Secondary evidence includes indirect indicators of biodegradation such as variations in geochemical parameters discussed below.

**Table 2-5. Redox Processes that Consume Organic Matter and Reduce Inorganic Compounds in Groundwater (Freeze and Cherry 1979).**

| Process | Equation* |
|---|---|
| Aerobic Respiration | $CH_2O + O = CO_2 + H_2O$ |
| Denitrification | $CH_2O + {}^4/_5NO_3^- = {}^2/_5N_2(g) + HCO_3^- + {}^1/_5H^+ + {}^2/_5H_2O$ |
| Manganese Reduction | $CH_2O + 2MnO_2(s) + 3H^+ = 2Mn^{2+} + HCO_3^- + 2H_2O$ |
| Iron (III) Reduction | $CH_2O + 4Fe(OH)_3(s) + 7H^+ = 4Fe^{2+} + HCO_3^- + 10H_2O$ |
| Sulfate Reduction | $CH_2O + {}^1/_2SO_4^{2-} = {}^1/_2HS^- + HCO_3^- + {}^1/_2H^+$ |
| Methane Fermentation | $CH_2O + {}^1/_2H2O = {}^1/_2CH_4 + {}^1/_2HCO_3^- + {}^1/_2H^+$ |

* $CH_2O$ represents organic matter; other organic compounds can also be oxidized and substituted in the equations.

2.1.3.8.3. When oxidizeable organic compounds are released to the subsurface, these compounds result in the consumption of oxygen. During aerobic respiration, oxygen is the favored terminal electron acceptor. Anaerobic respiration requires an alternative electron acceptor to be present, such as nitrate, sulfate, or iron(III). Denitrification, the chemical reduction of nitrate, occurs once the dissolved oxygen concentrations have been depleted to an anaerobic level and the nitrate is used as the terminal electron acceptor. Organic carbon may be biodegraded by anaerobic respiration, if the concentration of nitrate is less than 1.0 mg/L.

2.1.3.8.4. Sulfate is another terminal electron acceptor used in anaerobic respiration. Depleted levels of sulfate or elevated levels of sulfide are good indicators of sulfate reduction. Areas of lower sulfate concentrations likely indicate that anaerobic respiration has progressed from denitrification, through iron reduction, to sulfate reduction. As sulfate is reduced, methane fermentation occurs. At this redox level, mineral sources of oxygen become very limited and the oxidative capacity of the aquifer is said to be depleted.

2.1.3.8.5. The oxidation-reduction (redox) potential of the groundwater is a good indication of the type of electron activity present. Anaerobic microbial processes, such as denitrification and sulfate reduction, occur at and result in negative redox potentials. Redox potentials under these conditions have been measured in the field and reported primarily as negative. The negative redox potentials indicate that available dissolved oxygen has been consumed and that the bacteria are scavenging mineral sources of oxygen.

2.1.3.8.6. Several guidance documents published by EPA (1999a) and DoD (U.S. Department of the Navy 1998) are available, describing in greater detail the physical, chemical and biological process involved in situ biodegradation and monitored natural attenuation. These documents should be consulted during the design and review phases of an ISTR project, and incorporated into the project's monitoring program.

2.2. Technology Descriptions. Three main classes of ISTR technologies are discussed in this EM:

a. Conductive heating

b. Electrical resistivity heating

c. Steam enhanced extraction

Experienced vendors, suppliers, and practitioners contributed information for the following paragraphs. As such, the mention of trade names or commercial products may be made in the technology descriptions. This EM is intended to assist a project team considering ISTR applications for a site and does not constitute endorsement or recommended use of a particular vendor, supplier, or practitioner. Patent issues regarding technologies are further discussed in Chapter 10.

The three technologies have differing ranges of applicability for contaminants and soil and groundwater conditions, treatment efficiencies, and cost. While one technology may have the ability to attain a higher temperature than another, it may not be an efficient form of heating in a particular range. Table 2-6 shows a general range of upper bound temperatures that can be used as a preliminary screening to identify an appropriate ISTR technology.

**Table 2-6. Nominal Upper Bound Temperatures Achieved for Various ISTR Technologies.**

| Class of ISTR Technology | Nominal Upper Bound Temperature Range |
|---|---|
| Conductive Heating | 750 – 800°C (1,400 – 1,500°F) |
| Electrical Resistivity Heating | 100°C (212°F)* |
| Steam Injection | 170°C (300°F) * |

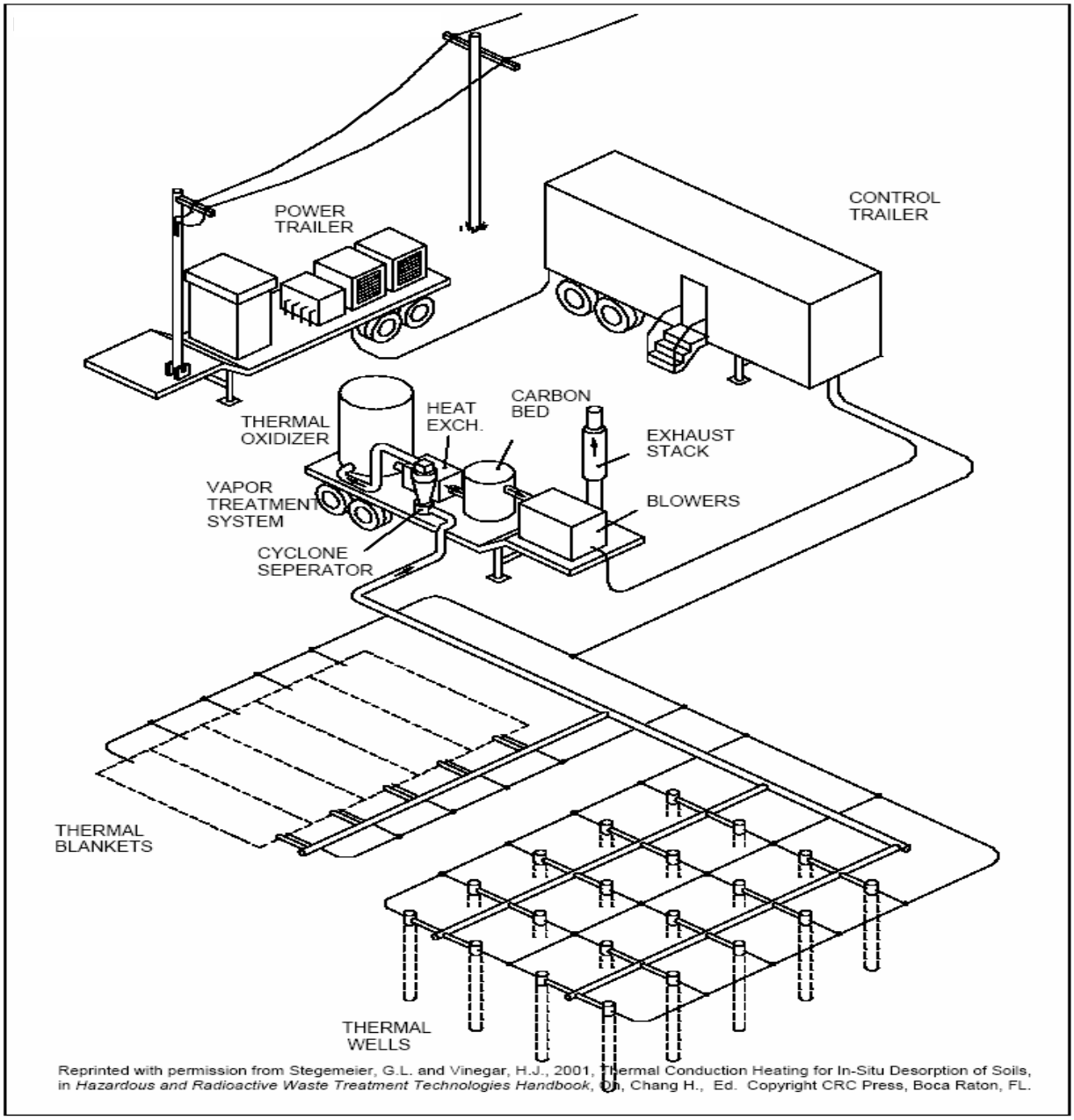
* Temperatures are dependent on depth below the water table. Increased depth corresponds to increased local pressure, and as a result, increased boiling point of water at local pressures. With water boiling at higher temperatures, higher treatment temperatures can be achieved.

2.2.1. *Thermal Conductive Heating.*

2.2.1.1. *General Description of Treatment Process and Layout.* Thermal conductive heating (TCH) refers to the application of heat to the subsurface through conductive heat transfer. The source of heat may be from thermal wells or blankets designed to provide sources of heat. TCH as practiced by TerraTherm, Inc. (TerraTherm) is given the commercial name of In Situ Thermal Desorption (ISTD), also referred to as In Situ Thermal Destruction. TCH utilizes both conductive heating and vacuum to remediate soils contaminated with a wide range of organic compounds. Heat and vacuum are applied simultaneously to the soil with an array of vertical or horizontal heaters. For the ISTD technology (which will be the main focus of this EM), each heater contains a heating element (typically electrically powered resistance heaters), with an operating temperature of approximately 1400 to 1500°F (~750 to 800°C). Heat flows through the soil from the heating elements primarily by thermal conduction. Figure 2-14 provides an overall schematic of the ISTD technology, depicting the two most common applications of the technology: 1) vertical “thermal wells” (at right); and 2) horizontal thermal wells (at left), which, when used to treat shallow contamination less than 0.4 m deep, are termed “thermal blankets.”

2.2.1.1.1. As the soil is heated, volatile, semi-volatile and non-volatile organic contaminants in the soil are vaporized /or destroyed by a number of mechanisms, including: 1) evaporation, 2) steam distillation, 3) boiling, 4) oxidation, and 5) pyrolysis (chemical decomposition in the absence of oxygen). The vaporized water and contaminants, as well as some volatilized inorganic compounds, are drawn counter-current to the heat flow into the vacuum extraction wells (termed “heater-vacuum” wells).

2.2.1.1.2. A cross-section of a heater-vacuum well and two heater-only wells, and a plan view representative of a typical thermal conduction well field layout, are depicted in Figure 2-15. Conductive heating wells are most efficiently installed in a triangular pattern, which over a large area makes up a hexagonal “six-spot” of heater-only wells, with a heater-vacuum well in the center of each hexagon resulting in a 2:1 heater to heater-vacuum well ratio. A number of other heater/heater-vacuum wells may be used to provide different ratios.




Reprinted with permission from Stegemeier, G.L. and Vinegar, H.J., 2001, Thermal Conduction Heating for In-Situ Desorption of Soils, in *Hazardous and Radioactive Waste Treatment Technologies Handbook*, Oh, Chang H., Ed. Copyright CRC Press, Boca Raton, FL.

**Figure 2-14. ISTD System Schematic.**

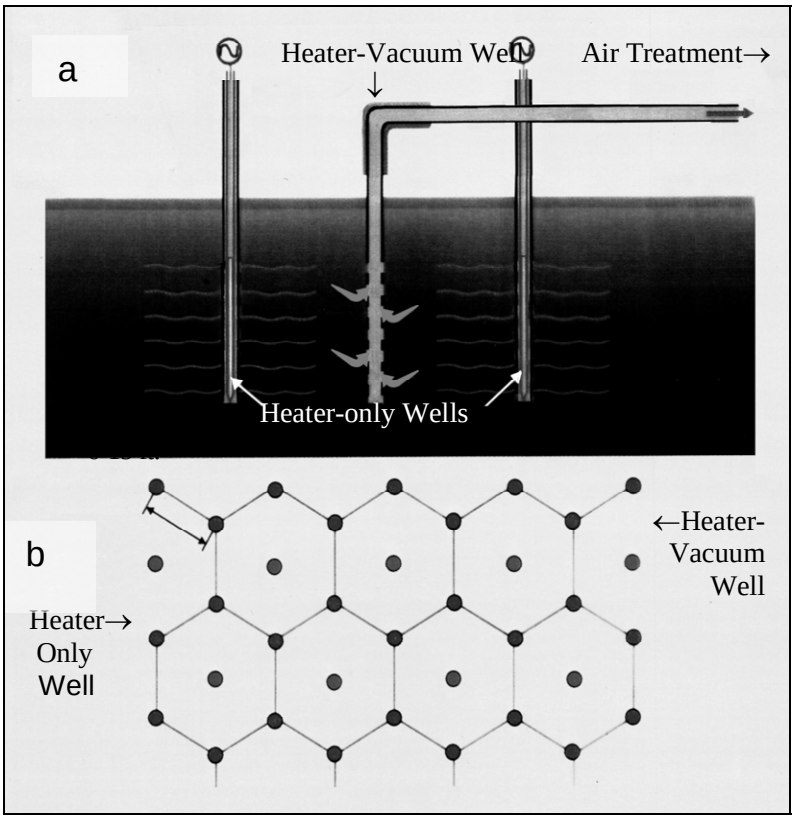



**Figure 2-15. Schematic of Typical ISTD Well Field.**
**(a) Cross-section showing one heater-vacuum well and two heater-only wells within a larger pattern.**
**(b) Plan view showing thermal well field layout. Heater-vacuum wells are located in the center of each hexagon, and well spacing typically ranges from 6 to 15 feet.**

2.2.1.1.3. The conductive heating process is relatively uniform in its vertical and horizontal sweep. This is because: 1) the energy (e.g., in watts) per linear foot input into the soil by thermal conduction heaters is uniform over each heater's length, as well as from heater to heater; and 2) thermal conductivity values vary over a very narrow range (e.g., ± 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 (which varies depending on the contaminant).

2.2.1.2. *In Situ and Aboveground Treatment*. During thermal conductive heating, transport of the vaporized contaminants is improved by an increase in bulk permeability, which results from drying and shrinking of the superheated soil (i.e., above the boiling point of water) that develops within a gradually expanding radius around each thermal well. Closely spaced vapor flow paths may be created even in tight silt and clay layers, allowing capture of the vaporized contaminants and steam by nearby heater-vacuum wells.

2.2.1.2.1. Treatment (destruction or removal) of the contaminants in the conductively heated soil can theoretically attain a destruction/displacement efficiency of 100%. This occurs because the coolest locations within the treatment zone can be heated, if desired, to the boiling points of the compounds of concern (COCs), and maintained at such temperatures (e.g., at >500°C [932°F] for high-boiling compounds), for many days. Convection of air and water vapor drawn into the zone further improves removal by evaporation, steam distillation, and oxidation. Laboratory treatability studies and field project experience have confirmed that a combination of high temperatures and long residence times result in high overall removal efficiency of even high boiling-point contaminants such as polychlorinated biphenyls (PCBs) and polychlorinated dibenzodioxins and furans (PCDD/Fs). The seven field projects that have utilized the ISTD family of technologies have achieved the required concentrations of the COCs, usually below their detection limits, with initial soil concentrations that ranged from 1000 to 20,000 ppm. For remediation of soils contaminated with chlorinated solvents, thermal conductive heating can be used to attain steam distillation temperatures in the cooler interwell locations, while locations in proximity of thermal wells become superheated, enabling in situ destruction of the COCs as they are collected.

2.2.1.2.2. In practice, regardless of the type of COC, most (e.g., >95-99% or more) of the contaminants may be destroyed as they pass through the superheated soil in proximity to the heater-vacuum wells, before they arrive at the extraction wells (Stegemeier and Vinegar 2001). Contaminants that have not been destroyed within the soil may be removed from the produced vapor stream with the aboveground air quality control (AQC) system, as depicted in Figure 2-16. Much simpler AQC equipment, such as carbon beds without thermal oxidizers, may be sufficient in some cases.

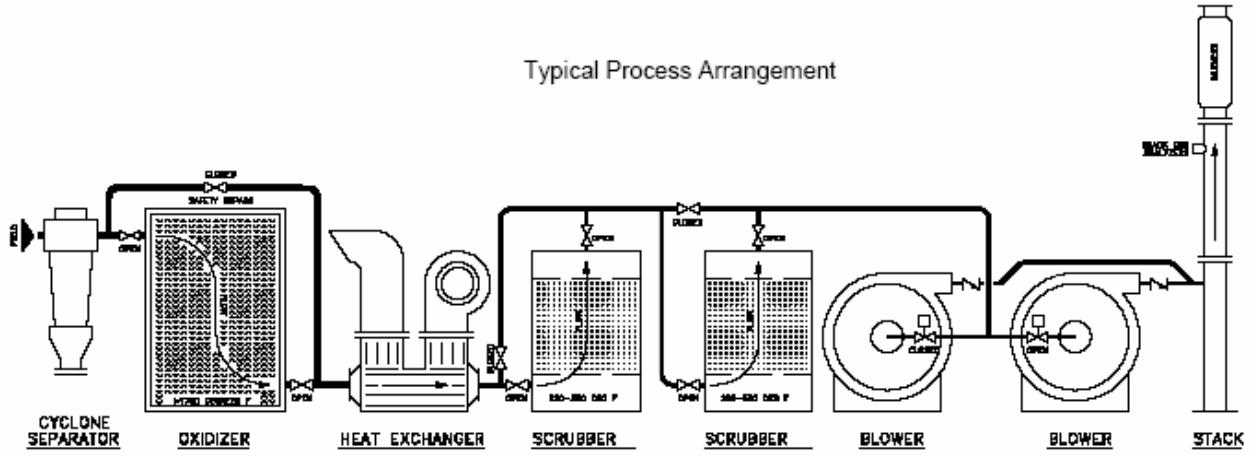



**Figure 2-16. Air Quality Control (AQC) Components Used in Conjunction with Conductive Heating. These often include a cyclone separator, thermal oxidizer, heat exchanger, scrubber beds (e.g., GAC), discharge blowers, and continuous emission monitoring system (CEM).**

2.2.1.3. *Technology Status*. Several ISTD pilot and field research demonstrations, as well as four full-scale remediation projects at contaminated sites, were carried between 1995 and 1999 (See Chapter 7 and Appendix B). The ISTD TCH technology was demonstrated to be effective in removing a variety of contaminants including PCBs, chlorinated solvents (Vinegar et al. 1999), coal tar products, and heavy and light petroleum hydrocarbons. Additional field-scale projects are ongoing. Pilot- and bench-scale studies have also demonstrated the potential of TCH remediation for soil contaminated with polyaromatic hydrocarbons (PAHs), and explosive compound residues, including 2,4,6-trinitrotoluene (TNT), 2,4-dinitrotoluene (2,4-DNT), hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), and nitroglycerin.

2.2.2. *Electrical Resistivity Heating*.

2.2.2.1. *General.* Electrical resistivity heating (ERH) is a remediation technology that involves passing electrical current through saturated or unsaturated soil, resulting in increased subsurface temperatures, usually to the boiling point of water. ERH is generally applied using either six-phase or three-phase electrical heating. ERH has been demonstrated as an effective technology for the removal of volatile and some semivolatile contaminants from soil and groundwater (USEPA 1999).

2.2.2.1.1. The soil is heated by the passage of current between the electrodes, not by the electrodes themselves. Electrical current passes preferentially through the most conductive soil or groundwater zones initially (e.g., areas having high concentrations of chlorides resulting from the reductive dehalogenation chlorinated organic compounds). Because the electrical current naturally seeks pathways to conduct through the subsurface, the more electrically conductive zones heat first. As water in the more conductive zones heats up and is boiled away, the less electrically conductive zones subsequently heat up. Further, thermal conduction also plays a role in the heating of the subsurface, such that at the completion of treatment (and barring the presence of thermal sinks), a relatively uniform heating of the desired remediation region results. ERH accelerates VOC remediation by the following principal mechanisms:

a. ERH increases subsurface temperatures beyond the boiling point of most VOCs, causing them to transition to the vapor phase to be removed through conventional vapor recovery (VR) wells.

b. ERH boils a portion of the pore water in all soil types, regardless of permeability. If geological conditions are favorable, the resulting steam promotes removal of VOC vapors from low-permeability soil for collection by the vapor recovery systems.

c. As subsurface temperatures rise, the rates of intrinsic biological activity and chemical reactions are dramatically increased. These processes are discussed in greater detail in Paragraph 2.1.

2.2.2.1.2. From a perspective of basic electrical principles, there is no great distinction between the two methods (i.e., six or three phase) and it is becoming common practice to use six-phase heating for a pilot test and then complete the remediation using three-phase heating. For this reason, this EM will treat the two technologies similarly under the term of electrical

resistivity heating (ERH). Six-phase heating involves splitting standard line current from three phases to six phases.

2.2.2.1.3. A depiction of six-phase alternating current (AC) 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 60º 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 (e.g., between electrodes 1 and 2, or between 1 and 6) is less than the voltage difference between electrodes that are two apart (e.g., 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.

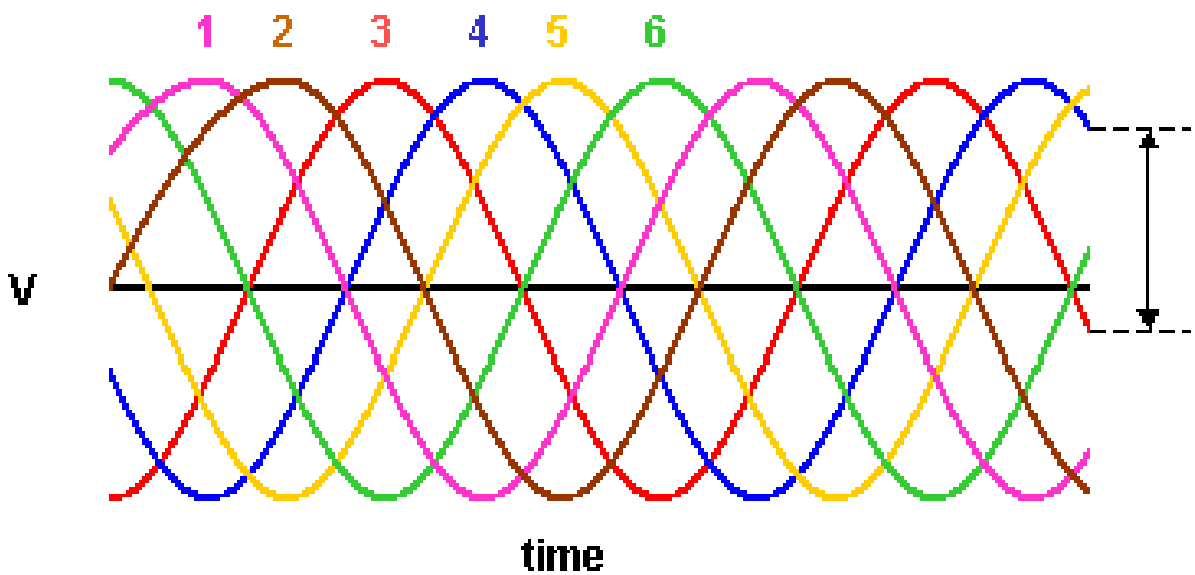



**Figure 2-17. Sine Curves of Voltage vs. Time, Depicting Six-Phase Alternating Current.**

2.2.2.1.4. When applied to a circular treatment region, the geometry of the six-phase electrode layout, and the out of phase charging, results 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 six-phase AC. 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 60 feet (18.3 m).

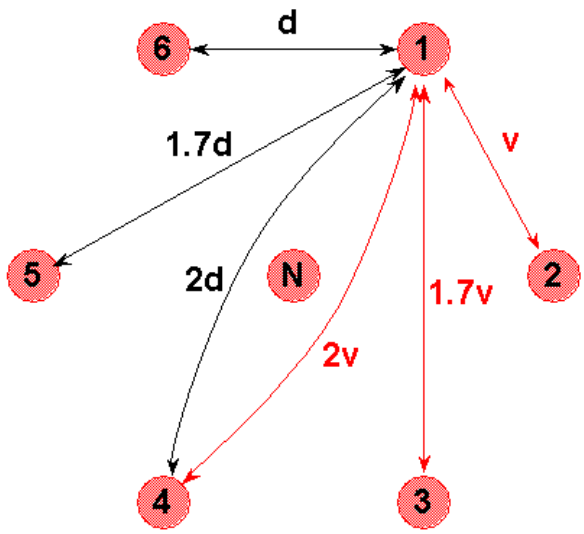



**Figure 2-18. The voltage potential between any two electrodes in a single six-phase heating array is in direct proportion to the distance between them. Current flows uniformly within the array.**

2.2.2.1.5. 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):

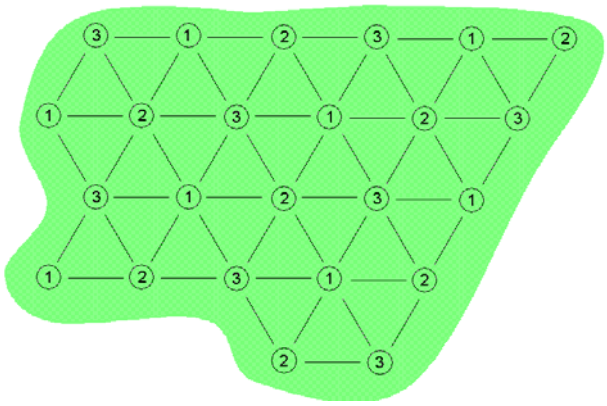


**Figure 2-19. Three-Phase Heating Pattern.**

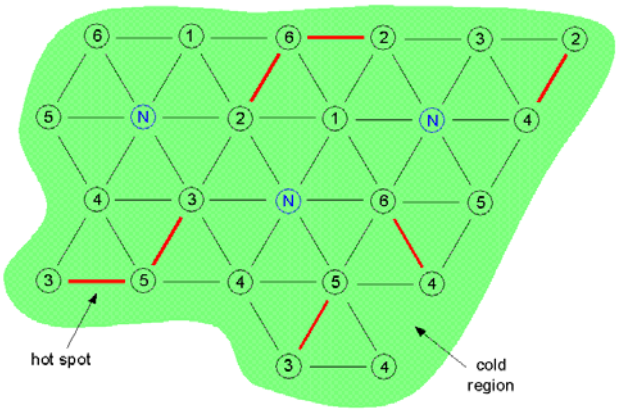



**Figure 2-20. Six-Phase Heating Pattern.**

2.2.2.1.6. When using three-phase heating (Figure 2-19), the current flow and heating pattern (shown as thin black lines) is 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.

2.2.2.1.7. 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. If an electrode is adjacent to an electrode that is one different in phase number, normal electrical current and heating will occur. Normal electrical conduction and heating will occur when an adjacent electrode: 1) differs by one phase number from the electrode, or 2) the adjacent electrode is neutral (labeled "N" above). If adjacent electrodes differ by more than one phase number, excess current will flow and a hot spot will develop as shown between the electrodes labeled as phases "3" and "5" above. Similarly, if adjacent electrodes are the same phase, no current flow or heating will occur as shown in the "cold region" above. Vendors of poly-phase ERH have developed electrical controls to switch configurations or sequences of applying voltages to compensate for hot spots and cold regions in the six phase geometry.

2.2.2.2. *General Description of Treatment Process and Layout*. The components required to implement ERH include:

a. Electrodes.

b. Vapor recovery wells (which are often co-located in the same boreholes as the electrodes).

c. A steam and vapor collection system, including piping, blower, and condenser.

d. A vapor treatment system.

e. An ERH power control unit to condition power for application to the subsurface.

f. Data acquisition systems.

g. A computer control system with modem for continuous remote monitoring and control of power.

A typical ERH schematic is shown in Figure 2-21.

2.2.2.2.1. 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. 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 pipe are installed in the subsurface in a way similar to the methods for installing groundwater monitoring wells. In the 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 those portions of the subsurface where electrical resistivity heating 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 6-3.1.

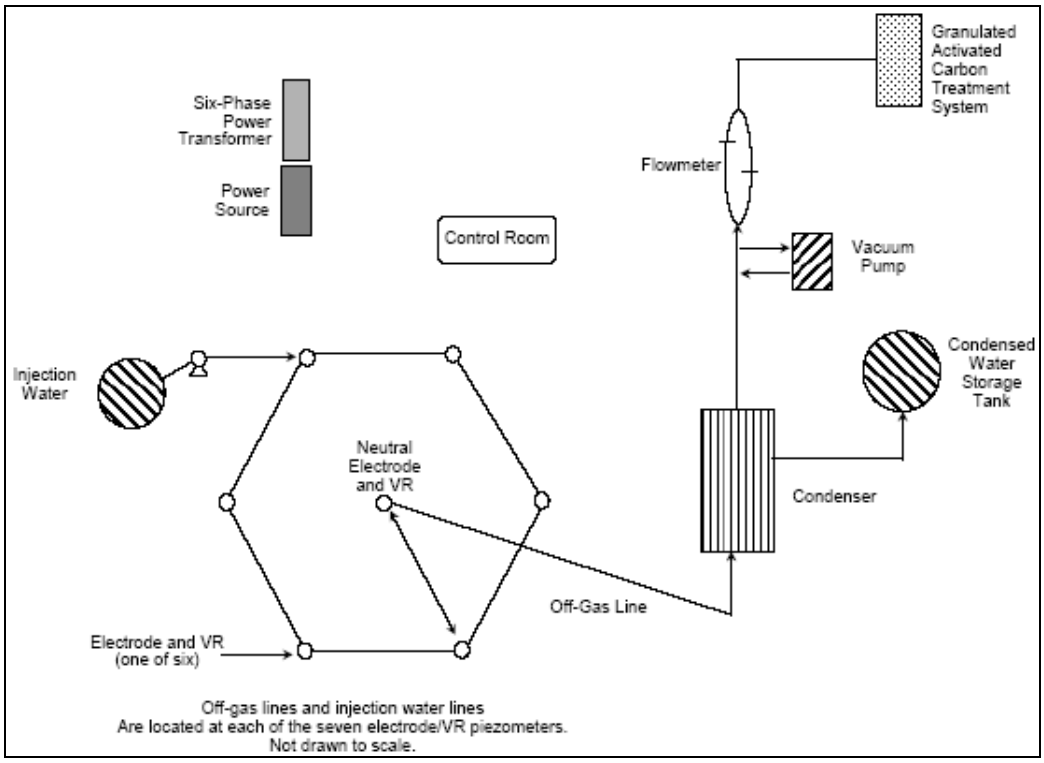



**Figure 2-21. General Schematic of a Six-Phase ERH Treatment System.**

2.2.2.2.2. The electrodes provide the opportunity to heat discrete subsurface depth intervals. In applications having layered sequences, it may be desired 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 the discrete zone is 8 feet because of electrical fanning and thermal conduction.

2.2.2.2.3. Vapor recovery (VR) is accomplished using conventional vapor extraction techniques utilizing shallow wells installed either vertically or horizontally. The wells may extend into the water table, depending upon site conditions. Once steam and volatile contaminants have been collected by the VR system, the steam is condensed and the vapor is cooled to ambient temperatures. Conventional vapor treatment techniques are used to adsorb or destroy the vapors. However, owing to temperatures resulting from application of ERH, the materials for the construction of the wells and headers must be able to withstand temperatures in the order of 100ºC. VR wells and materials are discussed in Paragraphs 6-3.1 and 6-3.3.

2.2.2.2.4. An ERH power control unit (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. 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. Because 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. Resistance by the subsurface environment to this flow of electrical current uniformly heats the soil and groundwater between the electrodes. Because electrically conductive intervals can be installed to 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.

2.2.2.2.5. The ERH process is typically automated, with an onsite computer equipped with a modem and appropriate software for remote access and monitoring. Multiple applications can be monitored and controlled remote 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.

2.2.2.2.6. 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 nonconductive. 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.

2.2.2.2.7. 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.

2.2.2.2.8. The rate of steam formation during ERH is very slow, typically requiring approximately two weeks to reach the boiling point of water. Once boiling does begin, it is a very gentle process, comparable to the rate of bubble formation in a glass of carbonated beverage.

2.2.2.2.9. The process of in situ steam generation converts groundwater to steam and then vapor recovery 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.

2.2.2.2.10. 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% from peak concentrations, electrical resistivity heating typically is 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 upon the results of interim sampling, heating can be continued or post-remedial sampling can be conducted to document that the remedial action objectives for soil and groundwater have been met.

2.2.2.3. *In Situ and Aboveground Treatment*. During heating, pore water increases in volume 1700-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 that 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 contaminant 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.

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

2.2.2.3.2. Above ground treatment typically involves treating vapors, condensate, and entrained water. Vapor treatment involves reducing the moisture content, typically through conventional “knock-out” pot arrangements, followed by appropriate treatment (e.g., granular activated carbon, combustion, thermal oxidation, etc.) prior to atmospheric discharge. Treatment of condensate and entrained water involves condensation and cooling through a cooling tower. The cooling tower in analogous an air stripper, with the vapor fed to the vapor stream treatment equipment. Typically, the condensate and entrained water makes multiple passes through the cooling tower, significantly reducing concentrations of volatile constituents. The treated water is then disposed as appropriate for the site (e.g., offsite treatment and disposal, discharge to the local POTW, NPDES-permitted discharge, etc.).

2.2.2.4. *Technology Status.* ERH is currently widely applied at a variety of 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.

2.2.3. *Steam Enhanced Extraction.*

2.2.3.1. *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: 1) steam soak, and 2) steam drive. The steam soak approach involved injecting steam into a production well, and holding the steam in the well and formation for a period of time, 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 pressure gradient from the formation to the well.

2.2.3.1.1. 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. Because 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 injection to increase oil production through modifying subsurface pressures, decreasing viscosity, and mobilizing oil from locations that may not have been accessible through gravity drainage.

2.2.3.1.2. For environmental applications, the analogous oil production technique is the 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. As such, there are differences in injection pressures and scale of the application, as well as application goals. The use of steam in the oil industry was typically for 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. 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. Because environmental remediation applications are typically shallow and under unconfined conditions, injected pressures and hence steam temperatures are typically lower than those used in the petroleum industry.

2.2.3.1.3. Figure 2-22 presents simplified steam injection in a pool of volatile organic compounds in the subsurface. The figure illustrates steam injection above the water table for simplicity, but steam enhanced extraction (SEE) has also been successfully injected below the water table (Udell and Stewart 1989, Newmark and Aines 1995, Smith et al. 1998, SteamTech Environmental Services 1999, Southern California Edison 2000, Heron et al. 2002). The initial injection of steam heats the well bore and the formation immediately surrounding the injection zone of the well. The steam condenses, transferring the latent heat of condensation from the steam to the well bore and the groundwater and the matrix of the formation. 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 will begin to enter the formation, pushing ahead of it the cold formation water and hot (condensate) water.

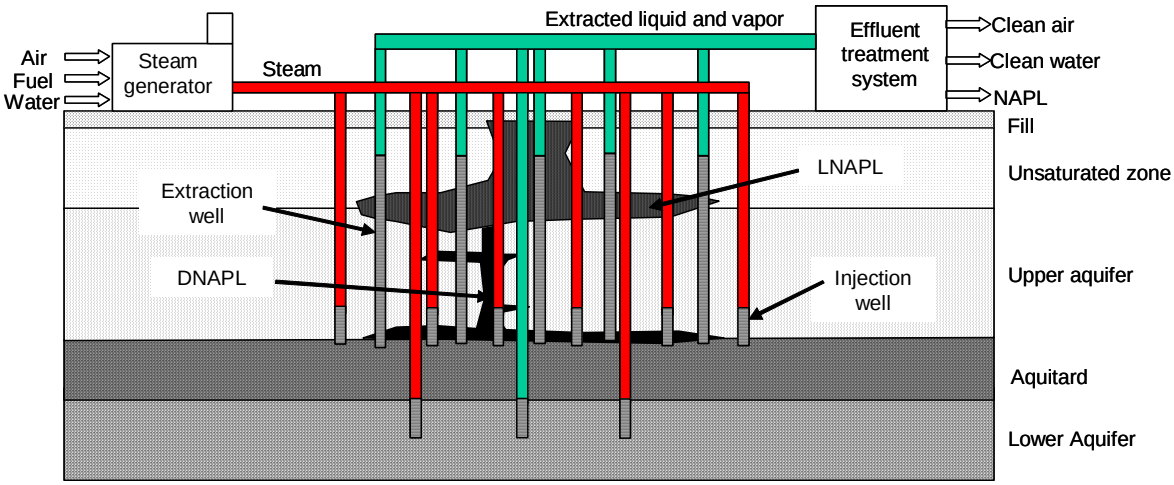



**Figure 2-22. Example Sketch of a Steam Injection Remediation System for a Site With Both DNAPL and LNAPL, and Multiple Zones of Contamination.**

2.2.3.1.4. From Figure 2-23, the first fluid to come in contact with the compounds of concern is the cold-water bank, which flushes mobile compounds in groundwater. The hot water that follows reduces the viscosity of the NAPL, displacing the compounds of concern 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, and or steam distillation of volatile and semi-volatile compounds (Stewart and Udell 1988).

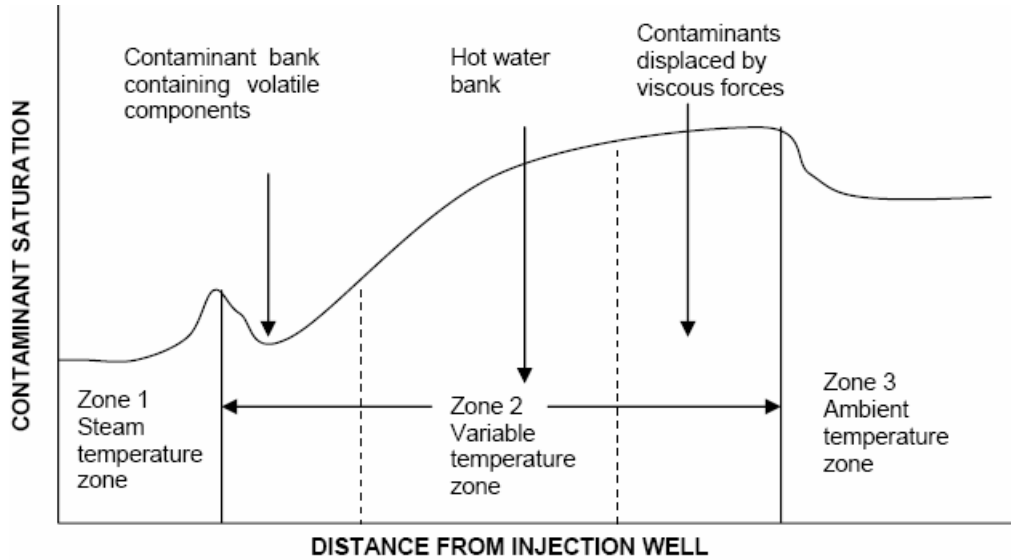



**Figure 2-23. The Three Temperature Zones that Form During a Steam Flood. (From Wu 1977, copyright Society of Petroleum Engineers, used with permission.)**

2.2.3.1.5. 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. A NAPL bank forms when 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 condense in advance of the steam front. Studies at University of Stuttgart (Schmidt et al. 1998) and University of California at Berkeley have indicated that the formation of NAPL banks can be eliminated by co-injection of air. Other practitioners use pre-heating 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.

2.2.3.1.6. 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). This is described in Paragraph 2.2.3.2.1.

2.2.3.1.7. 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 hydrocarbon having boiling points up to 175ºC (approximately 350ºF), and can remove 96.8 to 99.9% of #2 fuel oil and jet fuel, given sufficient number of pore volumes of injected steam (Hadim et al. 1993). Applications of greater volumes (i.e., greater than one pore volume) of steam can result in further reduction in concentration in groundwater and the aquifer matrix. One dimensional laboratory experiments have shown that compounds, or mixtures of compounds with boiling points of up to 300ºC, were removed by continuing steam injection past its breakthrough point (i.e., one pore volume) (Udell and McCarter 1997). Continuing steam injection to 100 pore volumes reduced concentrations of compounds with boiling points of 450ºC by at least one order of magnitude. Injecting 100 pore volumes may not be economically feasible at many sites, but what this does illustrate is that, with greater effort, further concentration reductions may be realized.

2.2.3.2. *In Situ and Aboveground Treatment.* When the pollutants represent a mixture of volatile and semi-volatile compounds, such as is the case for minerals spirits, gasoline or other fuels, the compounds with lower boiling points will vaporize first, followed by the lower boiling point compounds. As a result, there will be 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 (ICE) are to be used to destroy gasoline vapors, a higher- octane mixture will be 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 the ICE.

2.2.3.2.1. In environmental applications, the pressure of the injected steam may increase pore pressure, which 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 flow of oil.

2.2.3.2.2. For sites contaminated by volatiles, the goal of cyclic steam injection is to create temperature and pressure changes that promote volatilization of volatile organic compounds, 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.

2.2.3.2.3. For sites contaminated with semi-volatile or non-volatile chemicals, such as creosote, pressure cycling is used both to enhance vaporization of the lighter fractions of contaminants, and to induce mixing of injected steam and air with the contaminated groundwater. This may stimulate both dissolution of NAPL phases into the groundwater, and degradation reactions that take place under aerobic condition at elevated temperatures (HPO or biological degradation). Also, at creosote sites, the pressure cycling may enhance liquid phase NAPL displacement and removal as a NAPL by mechanisms similar to those used in enhanced oil recovery. Steam breakthrough at all extraction wells is not necessary to operate in a cyclical mode. This technique has been applied at a variety of locations at a remediation site under differing conditions (Smith et al. 2000). For example, at one location, a void resulting from a previously undetected abandoned catch basin did not provide for steam break through at a nearby recovery well. As the injected steam exited from the soils into the void, the resulting pressure drop is believed to have resulted in cooling of the steam. The steam generators that were being used could not provide sufficient steam to pressurize the void, such that steam breakthrough was not observed at the recovery well. However, operation in a cyclic mode greatly improved the removal of volatile organic compounds and improved the heating of the area. At another location at the same site, cyclic operations resulted in the observation of a “solvent bank” being produced from a recovery well, where steam breakthrough had not been previously observed (Smith 2003). Other steam injection projects that have used pressure cycling to enhance mass removal include:

a. Solvent Services, San Jose, CA (Udell and Stewart 1989).

b. Livermore Gas Pad (LLNL 1994).

c. Visalia Pole Yard, Visalia, CA (Davis 1998).

d. Alameda Point, Alameda, CA (Udell et al. 2001).

e. Portsmouth Gaseous Diffusion Plant, Piketon, OH (SteamTech Environmental

f. Services 1999, Heron et al. 2002).

g. Savannah River Site, Aiken, SC (Integrated Water Resources 2003).

h. Edwards Air Force Base Site 61, Edwards, CA (Earth Tech, Inc. and SteamTech Environmental Services, Inc. 2003).

i. Loring Quarry Site, Limestone, ME (Davis 2003).

j. Pinellas STAR Center, Pinellas, FL (Heron et al. 2005).

2.2.3.2.4. 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 vapor recovery 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.

2.2.3.2.5. In summary, there are four main removal mechanisms employed in steam injection for which recovery of pollutants can be made:

a. 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).

b. Vaporization and extraction as a vapor phase (boiling of the NAPL or volatilization of dissolved and adsorbed contaminants).

c. Solubilization and condensation of contaminants with subsequent removal in the dissolved state by the groundwater extraction system.

d. In-situ destruction attributable to either chemical or biological reactions.

2.2.3.2.6. 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 coinject air or oxygen, and adjusting the groundwater and vapor extraction rates.

2.2.3.3. *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 will be less effective for the heavier components of the oil, owing to their lower volatility and mobility as a fluid. Therefore, while the mobile fractions of the oils can be removed, and the groundwater

quality greatly improved, the soil concentrations of TPH may still be above background concentrations following treatment (e.g., Alameda Point, CA).

c. For wood-treating chemicals such as creosote and 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 pentachlorophenol [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, 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 have only been tested at these two locations in the United States, and conclusions regarding remedial end-points are still not available.

e. Concerns about formation of a NAPL bank, and possible downward migration of contaminants, have so far been eliminated either by co-injection of air with the steam, or by pre-heating part of the treatment zone prior to steam injection. Soils have been pre-heated using ERH techniques. This will increase project costs to some degree, and the economic impacts 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 straight-forward 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 are being investigated for steam injection as a remedial technique. These include the use of air and oxygen to enhanced in-situ destruction reactions (biological or chemical, such as hydrous pyrolysis oxidation), use of single-well treatment schemes for small sites (Beale AFB) (Yoon et al. 2005) and innovative pressure cycling modes for difficult fractured rock sites.

2.3. Unavoidable and Potential Effects. The use of ISTR may result in detrimental impacts to both the treated area and the surrounding vicinity. These impacts may be considered significant and need to be evaluated on a site-specific basis. At many sites, the potential effects of ISTR are of little to no significance compared to the ongoing negative impact of site contamination. In some cases, these potential effects may require engineering controls, mitigation, or modification of the ISTR approach. In other cases, the economics or logistics of implementing the ISTR technology may be so profoundly affected by these impacts that ISTR may be inappropriate.

2.3.1. *Ecological Impacts*. The use of heat to remediate the undisturbed soil will affect the biological community within the treated volume and impacts may extend outward from this zone due to the conduction of heat to surrounding soils. Both microorganisms and larger organisms may be directly affected in the treatment zone.

2.3.1.1. *Microbiological Impacts.* Microbial communities will be heavily skewed toward mesophiles and thermophiles during and following ISTR. The predominant species under ambient conditions will be significantly diminished in the treated volume. This effect, though diminished in intensity, will extend outward from the treated volume as temperatures rise in the surrounding soils. Soil drying that takes place during conductive and electrical resistivity heating reduces the active populations of all microorganisms where the drying occurs, but may enhance the activity outside of these areas. High temperatures associated with thermal conductive heating may locally sterilize the soil or at least force the organisms into an inactive state.

2.3.1.2. *Impacts on Higher Organisms***.** Lesser multi-celled organisms, such as worms and insects, will be killed or driven from the treated volumes and from the surrounding soils that experience temperature increases to levels outside those tolerated by the species. Burrowing mammals will be forced from the treated zone, and the noise and activity will further drive them from the surrounding vicinity. Animals that prey on the lower species may see an impact on their hunting success. In cases where the impacted species are threatened or endangered, a biological survey and relocation of at least some of the species may be necessary. However, it was also observed that, during the steam injection and later ERH applications in Skokie Illinois (an urban mix of industrial commercial and residential land uses), small mammals and birds were drawn to the treatment area by the warmth, especially during winter.

2.3.1.3. *Vegetation and Habitat Impacts*. The heat and construction will destroy vegetation within and near the treatment area and the site restoration activities may need to include revegetation for aesthetic or ecological reasons. Site activities may need to avoid certain areas to protect unique habitat or engineering controls may be needed to prevent heat-related impacts from propagating into certain areas. However, it has also been observed that vegetation flourishes at the fringe of ISTR applications and in the treatment area after completion. Weed control in the fringe of the treatment area may be an issue during longer-term applications of ISTR.

2.3.1.4. *Aquatic Habitat.* ISTR applications adjacent to surface water bodies are difficult owing to the heat losses that would occur. The implementation of ISTR adjacent to or under aquatic habitat may be particularly disruptive to the ecological community. Many benthic and free-swimming species are sensitive to water temperatures. The conductive loss of heat to the water or the discharge of hot groundwater to surface water bodies may result in elimination or diminishment of certain species, while the heating of the water may enhance the growth of others. Engineering controls to minimize heat loss may be necessary, ranging from alternate injection and extraction point layout (that emphasize extraction near the water bodies to be protected), to barriers for both water and heat flow (low permeability and thermal conductivity clay barriers) to extreme measures such as soil refrigeration near the water bodies.

2.3.2. *Physical Impacts*. The use of heat will also significantly affect the physical characteristics of the soil, groundwater, and buried objects. Potential impacts and remedies are discussed below.

2.3.2.1. *Soil Impacts.* The drying that may occur with electrical resistivity heating* and thermal conductive heating may affect the engineering properties of the soils. In cases where the soils are expansive, the drying has the potential to cause shrinkage and desiccation, which may affect nearby or overlying structures. Dewatering associated with thermal remediation may result in consolidation of the soils, which also may result in some subsidence, potentially damaging foundations. 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.

2.3.2.1.1. Moisture content was measured in soils prior to and after ERH treatment at a site containing clay soils in the metropolitan Chicago area, where ERH was used to remove trichloroethene DNAPL from a dense glacial clay till. The minimum measured moisture content was reduced from a range of 10 - 11% to 8 - 9%, but the maximum measured moisture content was actually higher in the set of post-treatment samples compared to the pre-treatment set of samples. The post-treatment samples with the lowest moisture contents were measured in the 1.5 – 2.7 m (5 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 de-watered as part of the remediation.

2.3.2.1.2. 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. Soils in the vadose zone do 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 be in a zone experiencing de-watering in the vicinity of the water table. The project manager would need to evaluate potential shrinkage at the depth of the water table and capillary fringe and impacts to foundations also found in the vicinity of the water table.

2.3.2.2. *Groundwater and NAPL Impacts.* Groundwater withdrawal from the site as part of ISTR may reduce water resources available to nearby groundwater users. Reinjection of treated water may be necessary to sustain adequate supply. Groundwater in contact with the treated zone (both during and following treatment) will transport heat away from the site. These higher temperatures may persist for some distance down-gradient of the site and affect water resources used by others. The higher groundwater temperatures can also alter geochemical conditions.

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* During the application of ERH methods, the reduction in moisture content appears to be restricted to depths at or around the water table.

The solubility of many materials is modified by temperature, which may increase the dissolved solids, including silica, or may cause others to precipitate near the treated zone. These impacts are generally unavoidable unless steps are taken to prevent groundwater contact with hot and warm soils, or unless groundwater does not naturally contact warmed soil. NAPL often undergoes significant physical change at elevated temperatures, many of which enhance mobility. .If migration is not controlled adequately by the design of the recovery system, the NAPL may migrate away from the treated zone. The increased mobility of NAPL outside the treatment zone (due to heat loss to surrounding soils) may result in unwanted NAPL migrating to adjacent or deeper soils or to surface water bodies. The recovery system design can be modified in most cases to assure such migration is controlled.

2.3.2.3. *Impacts on Buried Objects and Utilities.* Heating soils that contain buried utilities risks damage to them both from heat and electrical currents and fields. Plastic piping, electrical lines, and communication cables may be particularly susceptible to damage. Furthermore, the utilities may be a pathway for steam, vapors, or hot air to migrate to buildings or other facilities and, as such, may be a safety consideration. All ISTR remediation sites must be carefully surveyed for buried utilities prior to treatment. Utilities may need to be rerouted prior to treatment. Subsurface utilities may also allow water to accumulate within sewers or utility backfill after precipitation events, providing localized cooling of soils, which may result in condensation of VOCs, in turn providing localized zones for VOC accumulation during treatment. For example, an application of ERH in the Chicago area involved treating soils in a sub-grade loading dock. The sub-grade loading dock represented the lowest point onsite, hence the location to which water drained. Storm sewers were redirected away from the treatment area prior to the start of treatment. However, the building roof drains and downspouts did not sufficiently direct water away from the building foundation during precipitation. As a result, even though drainage within the loading dock was redirected, water infiltrated the area after each precipitation event. This had the effect of cooling the near surface soils, condensing the vapors, and creating local zones of accumulation for the condensed VOCs.