



Electrical Resistance Heating (ERH)

Electrical Resistance Heating (ERH), also known as "Electrical Resistive Heating" or "Six Phase Heating", is an *in situ* remedial technology that reduces concentrations of volatile constituents adsorbed to soils in the unsaturated (vadose) zone or to volatile constituents in groundwater, dissolved or in Dense Non Aqueous Phase Liquid (DNAPL) or even Light Non-Aqueous Phase Liquid (LNAPL). In this technology, electrical current is passed through the subsurface soil or groundwater by use of installed electrodes. The natural resistance to electrical current flow provided by the soil creates heat (similar to a toaster oven). This manner of in-situ heating allows the energy to more effectively focused and efficiently delivered to the treatment volume. The subsurface volume is heated to approximately 100 degrees Celsius and, in the process, volatile constituents of the contaminant mass "evaporate" or boil.

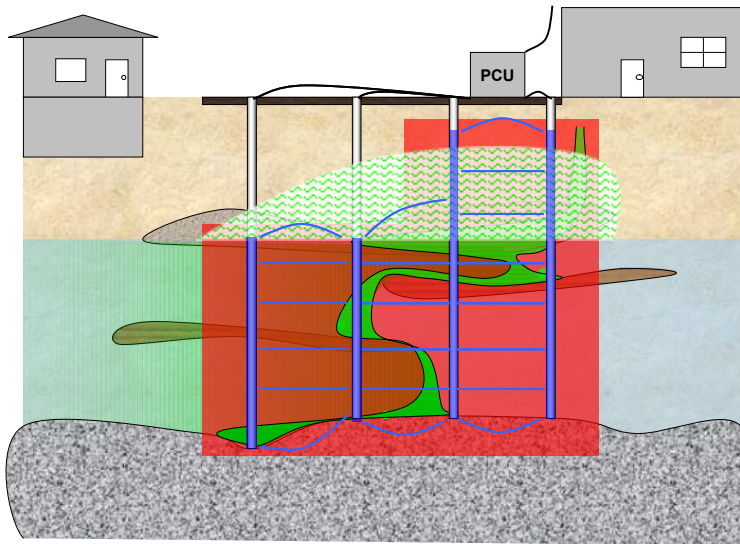
When the subsurface temperature is increased to the boiling point of the pore water or the saturated media in the treatment zone, steam is generated. The steam strips contaminants from the soils and enables them to be extracted from the subsurface. In addition, contaminants are directly volatilized from unsaturated soil.

The vapors and steam are drawn toward extraction wells or vapor capture wells. Extracted vapor is then treated as necessary (commonly with carbon adsorption) before being released to the atmosphere. The increased air flow and heat through the subsurface can also stimulate biodegradation of some of the contaminants, especially those that are less volatile. Also subsurface heat can reduce the viscosity of heavier contaminants such as creosote allowing for easier removal. Wells may be either vertical or horizontal. In areas of high groundwater levels, water table depression pumps may be required. Remediation of sites occurs rapidly on the order of 3 to 9 months of heating and can treat to very low concentrations.

Application

This technology has been proven effective in reducing concentrations of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs). Although a relatively new technology more than 60 sites have completed remediation using this technology and the number is growing rapidly. Electrical Resistance Heating is generally more successful when applied to the lighter

(more volatile) products such as gasoline and chlorinated hydrocarbons such as PCE. However, significant success has been obtained for such constituents as diesel fuel, heating oils, and kerosene, which are less volatile than gasoline. It has been proven that significant biological stimulation occurs with the application of this technology therefore opening up a wide range of applications.



In general Electrical Resistance Heating performance is independent of soil types and can equally be applied to fine grain and course grain materials. ERH can easily be applied in stratified lithologies with little concern for precise assessment of the subsurface. Electrical Resistance Heating (ERH) can be especially effective in soils of low permeability. This is due to the electrical properties of lower permeability soils improving electrical current flow. Electrical Resistance heating has also been proven to be capable of removing significant quantities of contaminant mass. Reductions in contaminant concentrations on the order of 99.99% are not uncommon.

Pilot testing of Electrical Resistance Heating is not always required but can provide important design information. Electrical Resistance Heating may also be appropriate near or beneath a building foundation. The ERH technology appears to have little negative affect on soil structural properties and many applications of this nature have been completed.

Operation Principles

The key physical and chemical properties that govern the fate and transport of contaminants, including viscosity, solubility, vapor pressure, octanol-water partition coefficient, and Henry's Law constant, are temperature dependent. At the higher temperatures employed during *in situ* thermal treatment, or Electrical Resistance Heating these properties change, typically in a way that enhances the treatability of the contaminant. The primary thermal effects applicable to

contaminants present in the free phase, sorbed phase and the dissolved phase are summarized below and

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

Source: Derived from Davis 1997

Typically, the boiling points of aqueous contaminant mixtures are less than the pure-phase boiling points of both the chlorinated solvent and water. For example, an azeotropic mixture of PCE and water will boil at 88°C, more than 30°C less than the 121°C boiling point for pure PCE and significantly less than the boiling point of water.

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

Electrical Resistance Heating also enhances the removal of contaminants dissolved in source zone groundwater or soil pore water. Physical and chemical properties, such as solubility, Henry's Law constant, octanol-water partition coefficient, and aqueous diffusivity rate, change in ways beneficial to remediation. For solubility, concentrations increase by a factor of two or more as an area is heated. The Henry's Law constant for most contaminants generally increases and the partitioning from the aqueous phase to soil (based on the octanol-water partition coefficient) generally decreases with elevated temperature. For example, the Henry's Law constant for TCE increases by 1 order of magnitude, and its adsorption from the aqueous phase onto soils can be expected to decrease by a factor of approximately 2.2 when the temperature is increased from 20 to 90°C (Heron and others 1996). The aqueous diffusion rate will increase by approximately 30 percent when the temperature is increased from 10 to 90°C (Treybal 1980). This affect results in more rapid remediation for most contaminants.

The elevated temperatures achieved during Electrical Resistance Heating (approx. 100 deg. C) treatment can also enhance abiotic and biotic degradation or destruction of chlorinated solvents. Abiotic degradation pathways, such as hydrolysis, where the hydrogen ions in water replace the chlorine ions in the chlorinated solvent molecule, and hydrous pyrolysis oxidation (HPO), where chlorinated solvents under oxidizing and aqueous conditions may be oxidized (eventually to carbon dioxide), have been shown to increase substantially at elevated temperatures. For example, the hydrolysis rates for chlorinated methanes and ethanes have been shown to result in relatively short half-lives for these contaminants at elevated temperatures (Jeffers and others 1989). In addition, rates of HPO of chlorinated solvents have been shown to increase (up to a maximum rate) with temperature (Baker and Kuhlman 2002).

Biological degradation pathways may also be enhanced at elevated temperatures. One commonly used rule of thumb, (based on the Van't Hoff-Arrhenius relationship) states that, for every 10°C increase in temperature, there is roughly a two-fold increase in biological activity resulting in an increase in degradation rate constants (EPA 1997). Extremely high temperatures (greater than 100 deg C) may sterilize soils of some microbes. However, significant levels of thermophiles (microbes that thrive under high temperature conditions) are present in many soils, and nearly all microbes benefit from elevated temperatures in the more moderately heated soil regions at the fringe of the treatment area. The overall effect of the elevated temperatures achieved during in situ thermal treatment on biological degradation pathways has not been fully determined, and is dependent on site-specific conditions.

System Design

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

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

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

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

ERH is particularly suited to the treatment of lower permeability strata and to DNAPLs that have become consolidated within lower permeability zones with higher organic content.

An ERH system consists of subsurface electrodes to direct current through the subsurface, and a vapor extraction system to capture the volatilized water and contaminants. In some cases, groundwater extraction is also used to lower the water table within the treatment zone during initial stages of treatment (prior to temperatures exceeding the boiling point of subsurface water) or to provide hydraulic control. To improve the uniformity of heating and reduce local current densities at the electrodes, most configurations employ multiple phased arrays of electrodes with a central ground electrode that typically doubles as a vapor extraction well. This method increases the available current pathways as

electrodes are phased so that current can flow from one electrode to any other electrode or to the neutral ground. Larger areas are remediated by installing adjacent arrays so that the heated zones overlap (Beyke 1998).

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

Vapor recovery systems are typically used to remove volatilized water and contaminants from the subsurface. The vapor recovery and aboveground treatment equipment is similar to that used with Soil Vapor Extraction. However, due to the increased temperatures and pressures in the subsurface vapor recovery systems for Electrical Resistance Heating can be typically smaller and require less vacuum than a typical SVE system. Higher temperature conditions should be considered when designing extraction and monitoring wells and associated equipment for the treatment area. Existing equipment may require modifications or replacement to accommodate these elevated temperature conditions.

Furthermore, due to safety concerns with regard to high voltage potentials in surface work areas and/or the potential for buried conductors to carry high voltage potentials out of the immediate remediation area, care must be taken in applying the technology. Typically, all conductive (metallic) equipment, such as well components, process piping, monitoring ports, and electric equipment, are bonded together with a copper conductor, which is connected to an earth ground.

Electrical Resistance Heating uses Power Control Units (PCUs) for electrical power delivery from the municipal power line to the subsurface electrodes installed in the remediation area. These PCUs include isolation transformers that prevent electrical current from traveling outside of the remediation area and offsite to above ground structures. Common electrical grounding techniques developed and used by the electrical utility industry are used on ERH projects to further enhance and ensure safe working conditions during ERH operations. The standard for safe working electrical voltages adopted by the Occupational Safety and Health Administration (OSHA) is less than 50 volts at the surface of a

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

Advantages and Disadvantages

Advantages	Disadvantages
Proven performance; rapid	Can be higher cost
Minimal disturbance to site operations.	Needs significant electrical power
Short treatment times (usually 3 months to 6 months of heating under optimal conditions).	May require costly treatment for atmospheric discharge of extracted vapors.
Cost competitive: \$60-90/ton of contaminated soil.	Air emission permits generally required.
Can be applied at sites with free product, and can be combined with other technologies.	Complete remediation budget often expended in one year
Achieve very high mass removal percentages	