

In Situ Thermal Remediation of DNAPL and LNAPL Using Electrical Resistance Heating

Gregory Beyke

David Fleming

Electrical resistance heating (ERH) is an in situ thermal treatment for soil and groundwater remediation that can reduce the time to clean up volatile organic compounds (VOCs) from years to months. The technology is now mature enough to provide site owners with both performance and financial certainty in their site-closure process. The ability of the technology to remediate soil and groundwater impacted by chlorinated solvents and petroleum hydrocarbons regardless of lithology proves to be beneficial over conventional in situ technologies that are dependent on advective flow. These conventional technologies include: soil vapor recovery, air sparging, and pump-and-treat, or the delivery of fluids to the subsurface such as chemical oxidization and bioremediation. The technology is very tolerant of subsurface heterogeneities and actually performs as well in low-permeability silts and clay as in higher-permeability sands and gravels. ERH is often implemented around and under buildings and public access areas without upsetting normal business operations. ERH may also be combined with other treatment technologies to optimize and enhance their performance. This article describes how the technology was developed, how it works, and provides two case studies where ERH was used to remediate complex lithologies. © 2005 Wiley Periodicals, Inc.

INTRODUCTION

Electrical resistance heating (ERH) was developed at the Pacific Northwest National Laboratory (PNNL) in the early 1990s with funding provided by the U.S. Department of Energy's (DOE's) Office of Science and Technology. The technology was originally conceived as a dewatering tool for the PNNL's *in situ* vitrification process. It was later discovered that ERH was remarkably well suited for the *in situ* thermal remediation of volatile contaminants and petroleum hydrocarbons. In such applications, the subsurface is heated to the boiling temperature of water and steam is generated *in situ*; however, only a small portion of the groundwater or soil moisture is boiled off during the remediation.

ERH became commercially available for use as a stand-alone technology in 1997. ERH can be applied using three or six phases of electricity; three-phase heating is generally more applicable for full-scale treatment and six-phase heating is generally more applicable to the pilot scale. Because pilot applications were more common in the early years, the term six-phase heating became almost synonymous with ERH. Full-scale heating applications are more common today, and the more general term electrical resistance heating is now used to describe the remediation technique, regardless of whether three or six electrical phases are used.

The technology was first field-tested at the DOE Hanford, Washington, facility in an arid soil setting. In 1993, ERH was used at the Department of Defense (DOD) Savannah River, South Carolina, facility to clean tetrachloroethene (PCE) from a 10-foot-thick clay lens located 30 feet below the surface as part of the Volatile Organic Compounds in Non-Arid Soils Integrated Demonstration. More than 99 percent of the contaminants in the treatment area were removed within 25 days.

In 1996, ERH was deployed as an interim remedial action (IRA) at the United States Air Force Reserve's Niagara Falls Air Reserve Station on location at the Niagara Falls International Airport. As part of a fire training center remediation, ERH was used to remediate a site containing chlorinated and fuel hydrocarbons. In three months, ERH removed four times the mass of trichloroethene (TCE) initially estimated to be present in the treatment area. While this was a vadose-zone remediation, the treatment area was open to the weather, and heavy rainfall occasionally produced near-saturation levels during heating. This was an early indication that ERH could be applied under saturated conditions for the remediation of dense nonaqueous phase liquids (DNAPLs).

In three months, ERH removed four times the mass of trichloroethene (TCE) initially estimated to be present in the treatment area.

Armstrong Laboratory's Environics Directorate had selected ERH as a promising technology for treating DNAPLs in the saturated zone in 1995, and in early 1997, an ERH pilot test was performed at the Dover Air Force Base Groundwater Remediation Field Laboratory (GRFL). During the test, a flowing aquifer within a 30-foot diameter treatment area was heated to boiling within 12–17 days.

In 1998 and early 1999, ERH was deployed in Alaska at Fort Richardson and Fort Wainwright under the direction of the U.S. Army Corps of Engineers (US ACE). At Fort Richardson, the contaminants of concern were PCE, TCE, and 1,1,2,2-tetrachloroethane, and at Fort Wainwright, they were diesel and benzene, toluene, ethylbenzene, and xylene (BTEX) compounds. In 1999, the first TCE DNAPL site closure in the United States was accomplished by utilizing ERH. Since then, more than 30 sites throughout North America have been treated with ERH, and a series of technology advancement milestones have been achieved:

- Areas containing underground utilities have been treated without adverse impacts.
- ERH has been implemented safely under operating facilities and in areas open to the public.
- Chlorinated solvent concentrations in groundwater have been remediated to maximum contaminant levels (MCLs).
- ERH has been combined with multiphase extraction (MPE) for light nonaqueous phase liquid (LNAPL) treatment.
- DNAPL has been successfully remediated at depths up to 100 feet below ground surface.
- Methylene chloride, ethylene dibromide, and 1,1,1-trichloroethane have been remediated by heat-enhanced *in situ* hydrolysis.
- Thermal barriers have been used to mitigate the potential of downward DNAPL migration.
- ERH has been successfully applied in aquifers with high groundwater flow rates (10 feet per day).
- ERH has been applied in areas containing significant amounts of metal debris.

THE ELECTRICAL RESISTANCE HEATING PROCESS

Electrical resistance heating passes an electrical current through the soil and groundwater that requires treatment. Resistance to this flow of electrical current warms the soil and then boils a portion of the soil moisture into steam. This *in situ* steam generation occurs in fractured or porous rock and in all soil types, regardless of permeability.

Electrical energy evaporates the target contaminant and provides steam as a carrier gas to sweep volatile organic compounds (VOCs) to vapor recovery (VR) wells. After the steam is condensed and the extracted air is cooled to ambient conditions, the VOC vapors are treated using conventional methods, including granular activated carbon (GAC) or oxidation.

Electrodes are usually placed in the subsurface throughout the remediation area using standard drilling techniques. Occasionally, electrodes are installed by direct-push methods or piling. The depth at which electrodes may be placed at a given site is dependent upon the depth to which drilling can be accomplished. The electrodes also serve as vapor- and steam-recovery points, or can operate as multiphase extraction wells for the recovery of vapor, steam, water, and NAPL from the subsurface; in fact, it is best to think of an electrode as a well that has the added capability of directing electrical current to the proper depth for subsurface heating.

The horizontal spacing between electrodes is usually between 14 and 24 feet. The optimal electrode spacing is not influenced by soil type, water saturation, or the electrical conductivity of the subsurface. Closer-spaced electrodes lead to higher installation costs but allow faster heat input and less operating time. Conversely, wider-spaced electrodes result in lower installation costs but require a longer and more expensive operating period.

A power control unit (PCU) is used to direct conventional three-phase electricity from municipal power lines to the electrode field using cables. The electrodes conduct alternating current (AC) into the subsurface and are specifically designed to input energy at targeted depth intervals. Electricity may be directed to groups of electrodes, or electrode intervals, either simultaneously or sequentially depending on the size of the volume being treated, or the desired heating pattern. A representation of the subsurface portion of an ERH system showing various electrode/recovery well configurations is presented as Exhibit 1.

The electrodes, which are in electrical contact but out of phase with each other, pass the electrical current through the soils or rock between them. The natural resistance of the subsurface to this flow of electrical current creates uniform heating throughout the treatment area, regardless of whether it is saturated or unsaturated (vadose). Moisture present in the vadose and saturated zones conducts the electricity in the target treatment interval.

PCUs of varying sizes are used to deliver, control, and monitor the electricity applied to the subsurface during ERH operations. Subsurface temperatures are monitored throughout operations using temperature monitoring points (TMPs) containing thermocouples at five-foot subsurface intervals. Temperature, voltage, vacuum, airflow, and subsurface pressure data are collected on set schedules and uploaded daily to the PCU control computer. The PCU control computer is used to both monitor and control site activities and may be accessed directly or remotely.

Electrodes are usually placed in the subsurface throughout the remediation area using standard drilling techniques.

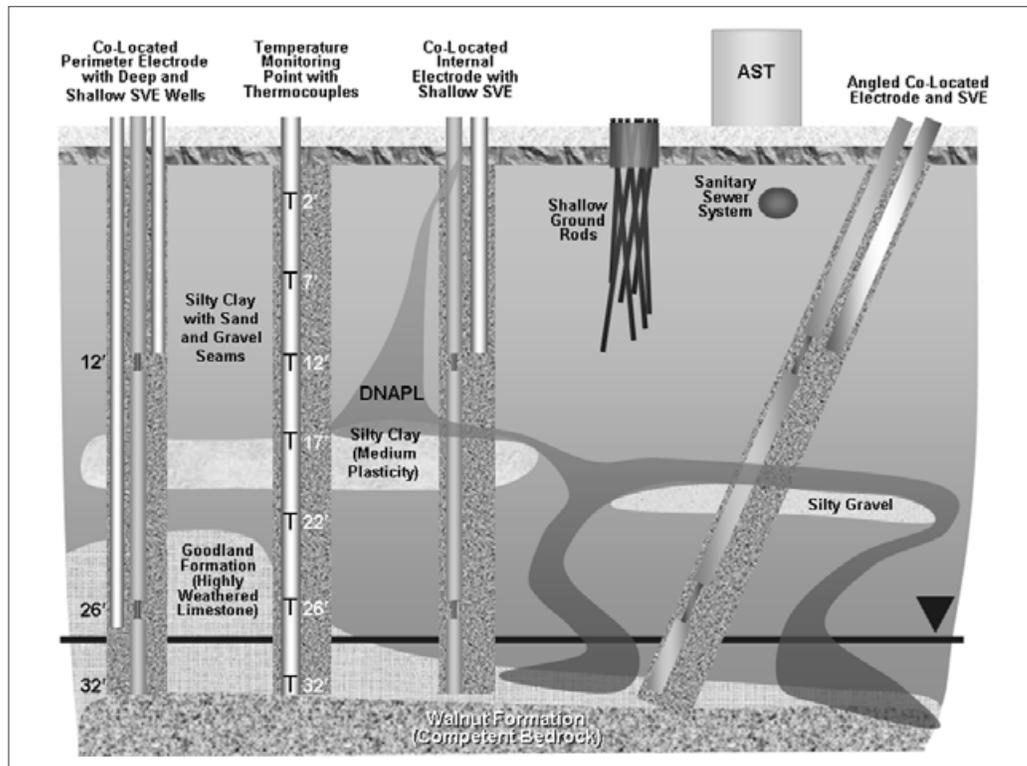


Exhibit 1. ERH subsurface cross-section

Portions of the subsurface with higher electrical conductivity, such as low-permeability silts and clay lenses or stringers, and chlorinated solvent source areas are heated preferentially. Silts and clays are naturally more conductive than sands and gravels. The chloride ions surrounding chlorinated solvents that are undergoing reductive dechlorination also create areas of higher conductivity. These natural factors contributing to areas of higher electrical conductivity are especially important in the remediation of chlorinated solvents, as they are often bound to low-permeability silts and clays.

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 a mechanism for the *in situ* steam stripping of VOCs from both soil and groundwater. *In situ* steaming serves two purposes: (1) the physical action of steam production drives contaminants out of soil that tends to lock in contamination due to low-permeability or capillary forces and (2) the steam acts as a carrier gas that transports contaminants toward the water-table surface and into the VR wells that are integral to the electrodes.

Once at the surface, the steam is condensed to water and vapors are cooled to near-ambient temperatures. As described by Henry's Law, less than 1 percent of the VOCs collected from the subsurface will condense and become dissolved in the condensate. The residual VOCs remain part of the vapor stream and are treated by conventional vapor-abatement technologies such as thermal and catalytic oxidation or granular activated carbon.

Common Compounds	Boiling Temperature of Compound	
	In Air	In Water
Pure water	100°C	100°C
Tetrachloroethene (PCE)	121°C	87°C
Trichloroethylene (TCE)	87°C	73°C
1,1,1-Trichloroethane (TCA)	74°C	65°C
1,1-Dichloroethene (DCE)	32°C	31°C

Exhibit 2. Dalton's Law effects on VOC boiling points

The type of contaminant and the desired cleanup goal affect the energy, time, and cost to remediate a site. However, two subsurface parameters are particularly important: the amount of total organic carbon (TOC) and the presence of heavy hydrocarbons such as diesel, oil, or grease. TOC preferentially adsorbs VOCs in comparison to water; this is why activated carbon is often used for vapor and water treatment. As described by Raoult's Law, the presence of oil, grease, or other low-volatility hydrocarbons can also slow the evaporation rate of VOCs.

Dalton's Law of Partial Pressures

It should be noted that when a VOC is immersed in water or in contact with moist soil, the combined boiling point is depressed as described by Dalton's Law of Partial Pressures. Consequently, the VOC/water mixture will boil when the vapor pressure of the VOC plus the vapor pressure of water is equal to the ambient pressure.

Once subsurface heating starts, the boiling points of various VOC/water mixtures are reached in the following order: separate-phase NAPL in contact with water or soil moisture, followed by dissolved VOCs, and, finally, uncontaminated groundwater. This order is advantageous for ERH remediation, because contaminated water will tend to boil off before uncontaminated water, reducing the time and energy required to complete treatment. The Dalton's Law effect on the boiling points of common chlorinated compounds are summarized below in Exhibit 2, bearing in mind that the flow of air through the vadose zone can cause evaporation to occur at temperatures below these boiling points.

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 necessary to release the contaminants from groundwater and the soil matrix and allows them to migrate up toward the vadose zone, where they can be recovered by a vapor recovery or multiphase extraction system.

Although volatilization is usually the primary VOC removal mechanism during ERH, a significant fraction of the VOCs will be degraded in place by natural *in situ* processes that may include biodegradation, hydrolysis, and reductive dehalogenation by zero-valent iron.

Biodegradation

The biodegradation of chlorinated VOCs is most commonly observed as an anaerobic process, and elevated temperatures increase biotic reaction rates. This *in situ* VOC degradation mechanism is especially important at sites where relatively high levels of TOC or nonchlorinated hydrocarbons provide a carbon source to serve as an electron donor.

When soils with high levels of TOC are heated, some portion of the carbon will convert to acetone and other water-soluble compounds. Acetone is a VOC, but it also provides an easily biodegradable food source for soil microbes that perform reductive dechlorination. When ERH remediation is completed, any acetone generated during the process will help to provide a polishing effect on residual chlorinated compounds. Acetone concentrations in groundwater after ERH are typically less than 500 mg/L, and acetone rapidly biodegrades to nondetectable levels as the site cools to ambient conditions.

Hydrolysis is a water-substitution reaction in which hydrogen ions normally present in water react with organic molecules, replacing chlorine atoms.

Hydrolysis

Hydrolysis is a water-substitution reaction in which hydrogen ions normally present in water react with organic molecules, replacing chlorine atoms. Oxidizing conditions or available oxygen is not required for hydrolysis. Hydrolysis can be a significant degrader of some VOCs at room temperature, especially halogenated alkanes. The rate of hydrolysis increases with temperature. An example of a hydrolysis pathway is: 1,1,1-TCA → 1,1-DCE → acetic acid (rapidly biodegrades) and 1,2-dichloropropane → 2-chloropropanol → propylene glycol (rapidly biodegrades). In all cases known to the authors, hydrolysis is a favorable reaction and converts VOCs or pesticides to forms that are either less toxic or more volatile, or both.

Dehalogenation

The backfill of ERH electrodes include steel shot, which is a form of zero-valent iron. The reductive dehalogenation process that takes place at the electrode backfill is the same as that produced by iron-filing remediation walls. The presence of iron in the electrode boreholes can provide a significant polishing mechanism for dissolved-phase VOCs after heating has ended.

Hydrolysis and reductive dechlorination are strongly affected by temperature, as described by the Arrhenius Equation. In essence, each 10°C increase in temperature will increase the reaction rates by a factor of about 2.5.

TECHNOLOGY USES

To date, most applications of ERH have focused on contaminant source area treatment and, in particular, the remediation of DNAPLs and LNAPLs. Direct *in situ* volatilization provides a mechanism to rapidly and efficiently extract contaminants with low boiling points, such as PCE, TCE, and cis-1,2-dichloroethene (cis-DCE) from the subsurface. Compared to other technologies, ERH provides higher assurance of source-area contaminant removal at attractive costs per pound removed. However, when contemplating applying ERH on dissolved-phase plumes, the costs per weight of contaminant treated become less attractive. As discussed later, the concept of combining lower-temperature

applications of ERH with bioremediation or chemical oxidization, however, may provide a technique for efficient and cost-effective dissolved-phase plume remediation.

ERH has also been used to enhance fluid-recovery operations by mobilizing heavy hydrocarbons. Heating soil and groundwater makes heavy hydrocarbons less viscous and much easier to pump or vacuum-entrain from the subsurface. In addition to driving heavy hydrocarbons out of tight soil lenses, *in situ* steaming also provides a bubble flotation mechanism to help lift DNAPLs and near-neutral buoyancy NAPLs to the surface, where they can be extracted by MPE.

Soil that contains greater than 3 percent water (measured as weight percent) conducts electricity well and, therefore, ERH has no difficulty heating either vadose or saturated zones. The technology performs well in all lithologies—from tight clays to unconsolidated gravels—and is not affected by heterogeneous mixtures of soil types. ERH can heat fractured bedrock but cannot heat competent nonporous rock except through thermal conduction from nearby heated regions. The ability of ERH to preferentially heat silt and clay, and subsequently form steam within these soil types, releases contaminants from the soil matrix and drives them to VR or MPE wells. Through this mechanism, ERH is able to treat portions of the subsurface where advective flow cannot be established. This allows ERH to greatly enhance remediation technologies that are dependent upon advective flow such as soil vapor extraction (SVE) and MPE.

Soil vapor extraction and MPE are proven advective flow technologies developed specifically for VOC remediation. SVE is most applicable in vadose-zone sites with permeable to highly permeable soil, while MPE can address LNAPL and smear-zone impact in moderately to highly permeable lithologies. The effectiveness of both technologies is severely limited by the presence of low-permeability silt and clay lenses or stringers. Combined with ERH, these technologies can be used to treat almost any lithology, regardless of soil permeability and heterogeneities, or level of water saturation.

Chemical Oxidation

In situ oxidation technologies such as hydrogen peroxide and potassium permanganate have been commercially available for several years. The rate at which a target contaminant will degrade is dictated by the chemical properties of the contaminant and its susceptibility to oxidative reactions. The extent and effectiveness of remediation achieved by *in situ* oxidation is most often a function of soil matrix conditions.

Given the relatively indiscriminate and rapid rate that chemical oxidants react with reduced substances, the method of delivery and distribution throughout a subsurface region is of paramount importance. Oxidant delivery systems often employ vertical or horizontal injection wells and sparge points requiring forced injection to move the oxidant into the more permeable portions of the subsurface. ERH can enhance chemical oxidation technologies by releasing contaminants into those portions of the subsurface that are able to receive injected oxidants and by increasing the rates of the subsequent oxidation reactions.

Bioremediation

Bioremediation uses microorganisms to degrade organic contaminants in soil, sludge, and solids either *in situ* or after they have been excavated. Microorganisms break down

The rate at which a target contaminant will degrade is dictated by the chemical properties of the contaminant and its susceptibility to oxidative reactions.

contaminants by using them as a food source or cometabolizing them with a food source. Aerobic processes require an oxygen source, and the end products typically are carbon dioxide and water. Anaerobic processes are conducted in the absence of oxygen, and the end products can include methane, hydrogen gas, sulfide, elemental sulfur, and nitrogen gas. Sometimes, microorganisms that have been adapted to degrade specific contaminants or chemical supplements are added to the subsurface to enhance the process, provide food sources and cometabolites, or to change subsurface redox conditions.

As with chemical oxidation, ERH can enhance bioremediation by increasing the rate of microbial degradation. Increased natural attenuation has been observed following ERH applications as sites slowly cool over time. It may take as long as one year for subsurface temperatures to return to ambient conditions following ERH remediation, and during that time, a significant amount of bioremediation polishing will be accomplished.

The ERH process has been successfully demonstrated at over 40 sites for both government and private-sector clients.

ECONOMICS

Remediation cost accounting, no matter what technologies are employed, is site-specific and typically dependent on one or more of the following: the size and volume of the treatment area, the target contaminants and level of contaminant reduction required, site geology, depth to groundwater, groundwater velocity, and total organic carbon content in soil.

Cost considerations should include both the direct costs to pay for the remediation application and ongoing project costs such as interaction time with regulatory agencies, analytical sampling and analysis, and planning and reporting. The longer it takes to remediate a site, the greater the ongoing costs, such as site security, legal fees, interim remediation actions, monitoring, and the potential for lost revenues if the business is shut down or hampered during the process, and to the extent the property can not receive closure status for a pending real estate transaction.

At sites where ERH is applicable, the time spent in remediation is typically reduced from years to months. For a typical commercial site requiring a 99 percent reduction of TCE in soil and groundwater, the estimated price for ERH remediation is currently about \$200,000, plus \$40–70 per cubic yard.

CASE STUDIES

The ERH process has been successfully demonstrated at over 40 sites for both government and private-sector clients. The following case studies have been selected to highlight the diverse types of site conditions the technology can respond to.

Paducah Gaseous Diffusion Plant Pilot Study

Historical spills of solvents at the U.S. DOE Paducah Gaseous Diffusion Plant in Kentucky have resulted in TCE impact to the two regional aquifers beneath Building C-400. The unsaturated and saturated zones of the Upper Continental Recharge System (UCRS) extend from grade to approximately 55 feet below grade surface (bgs), and the saturated Regional Gravel Aquifer (RGA) extends from the bottom of the UCRS to the top of the McNairy formation, at about 90 feet bgs. TCE is found throughout the upper formations and exists at NAPL concentrations on top of the clay-rich McNairy formation.

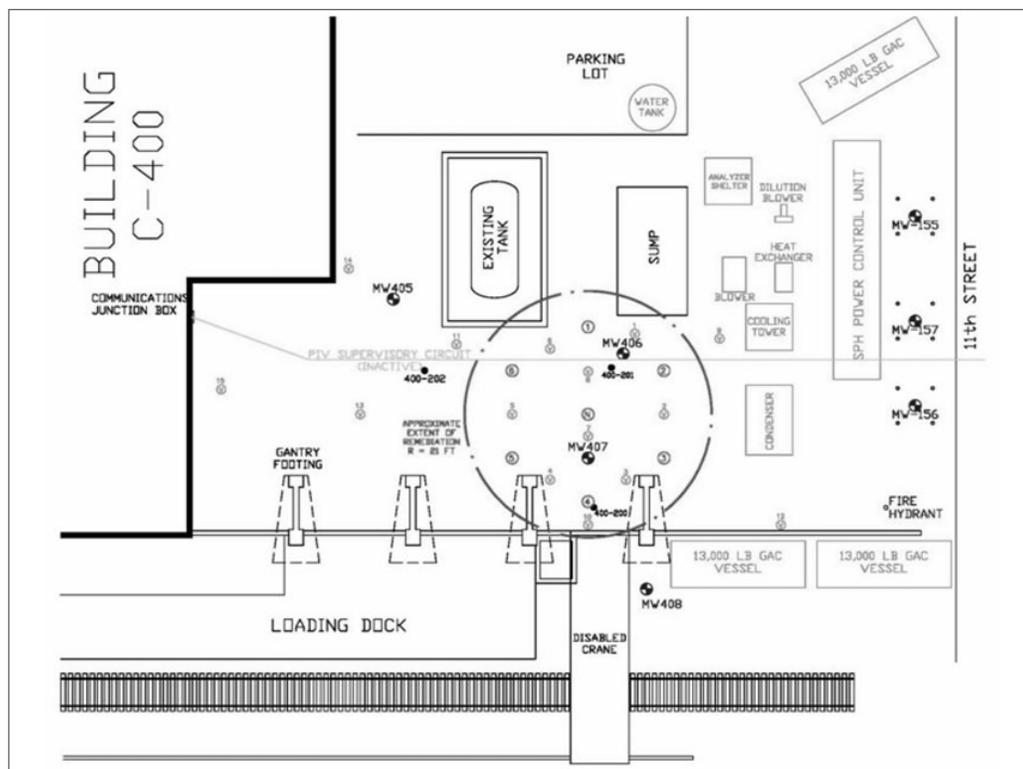


Exhibit 3. Electrode configuration

The objective of the pilot test was to demonstrate the feasibility of ERH to simultaneously reduce TCE concentrations in the tighter and partially unsaturated UCRS and the more permeable saturated RGA, and remove NAPL from the top of the McNairy formation. To accomplish these goals, heating was extended to approximately 100 feet bgs, making the pilot test the deepest application of the ERH technology to date.

The pilot test included the installation and operation of seven ERH electrodes in an area immediately adjacent to Building C-400. As shown in Exhibit 3, the electrode configuration included six power electrodes and a center-neutral electrode. Electrodes were constructed to a final depth of approximately 97 feet bgs, and each electrode consisted of six depth-discrete electrically conductive intervals covering the UCRS, the RGA, and the upper layer of the McNairy Formation (Exhibit 4).

The electrode design underscores the pilot-study nature of the project. The goals of the pilot study were to quantify the energy applied to separate geological layers, while developing design and costing data for a full-scale ERH application that would use a much simpler electrode configuration.

Electrical connection between the conductive intervals in several of the electrodes reduced the quality of data collected on energy input to each geologic interval. However, the overall performance of the electrodes was excellent, as the entire subsurface treatment interval was heated to the boiling point of TCE in water. Heating was started in February 2003 and continued until fall 2003. Subsurface temperatures with depth over the duration of the project are shown in Exhibit 5.

Captured TCE vapors were treated using 13,000-pound vapor-phase granular activated carbon vessels, and treated air was released to the atmosphere. Recovered steam

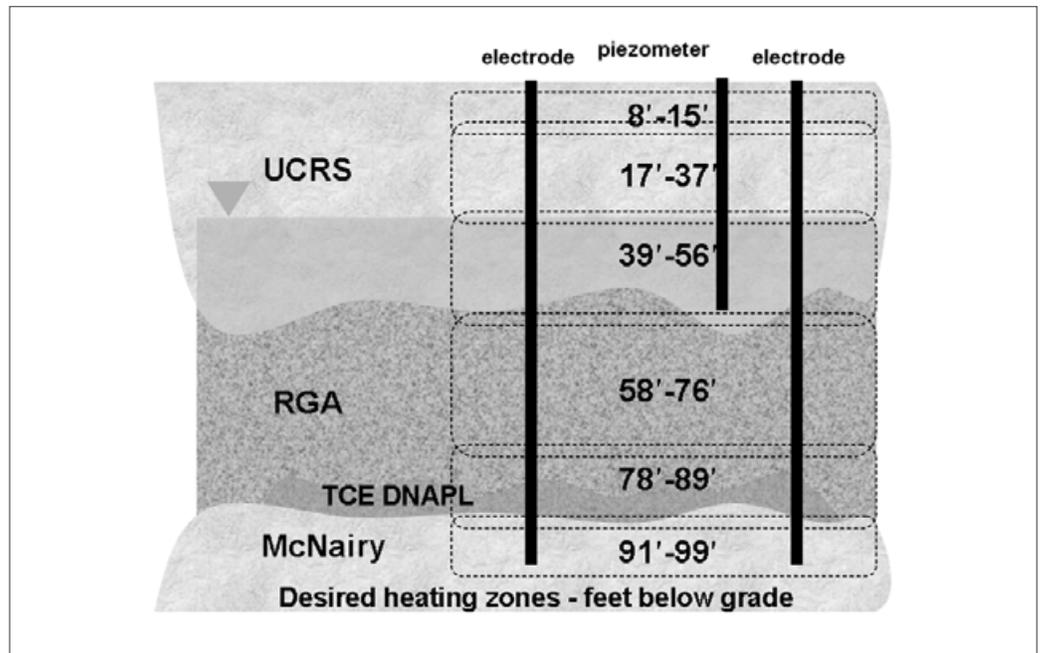


Exhibit 4. Electrode depth intervals, Building C-400

was condensed and the condensate treated with liquid-phase GAC before being recycled within the aboveground system as makeup water for the ERH processes.

The contaminant reduction goals of the project were to remove 75 percent of the TCE mass in soil and reduce groundwater concentrations to less than 1 percent TCE solubility (11 mg/L). Once design temperatures were achieved in the subsurface, approximately 350–400 pounds of TCE were recovered each day of operations, and more than 30,000 pounds of TCE were removed from the subsurface over the course of the 175-day pilot study. Confirmatory sampling showed that concentrations of TCE inside the treatment area were reduced by an average of 98 percent in soil and 99 percent in groundwater. At the conclusion of heating, groundwater samples from all 11 monitoring wells contained TCE at concentrations below 11 mg/L.

Exhibit 6 shows TCE concentrations in soil before and after the pilot test, while Exhibits 7 and 8 present TCE concentrations in groundwater before, during, and after heating. Test heating was scheduled to last 130 days, but the system was recovering such large quantities of TCE mass that the customer requested an additional 45 days of operations to recover additional TCE mass that was diffusing into the pilot-test region from surrounding untreated zones. Based on the success of the pilot project, the U.S. DOE is planning to expand ERH to full scale in three areas at the Paducah Gaseous Diffusion Plant.

Fort Lewis, Washington

At the Fort Lewis, Washington, East Gate Disposal Yard, NAPLs are being successfully treated *in situ* using ERH and MPE. The project is being performed under a fixed-price, performance-based remediation contract administered by the Seattle District of the US ACE. The size of the areas being heated, the types of contaminants being treated, and the

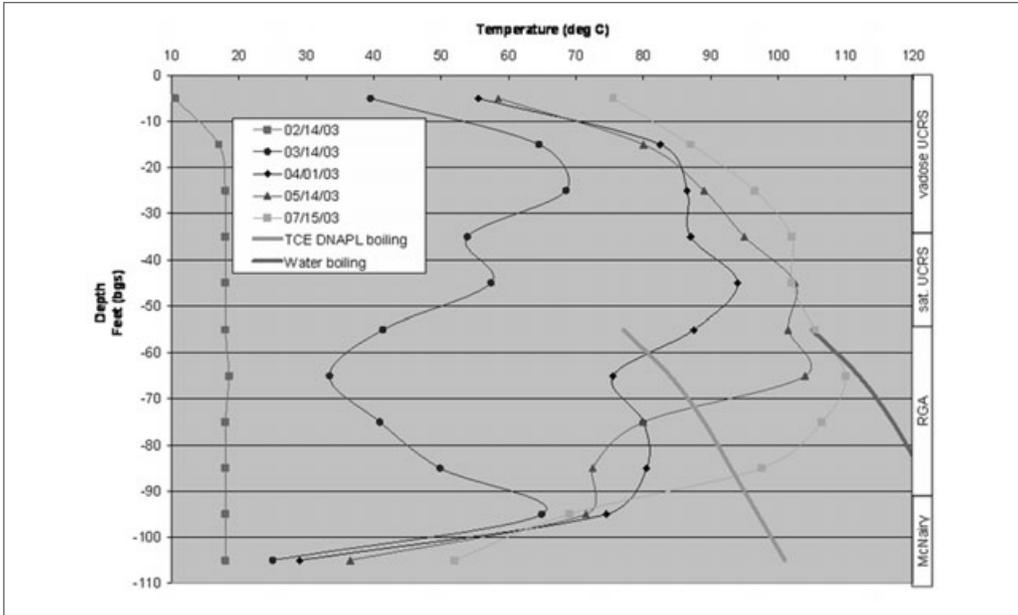


Exhibit 5. Treatment zone temperature vs. depth

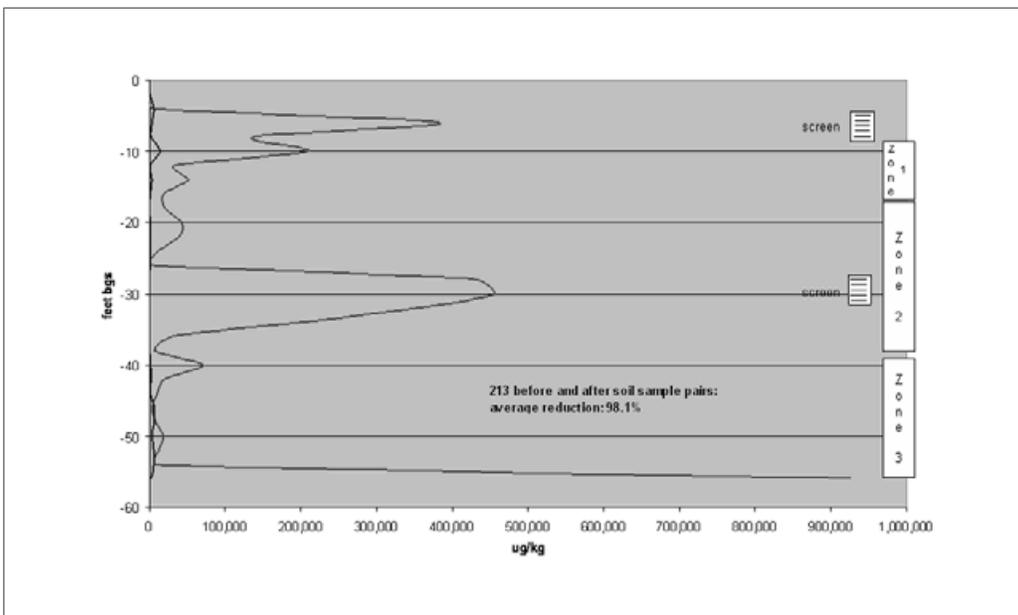


Exhibit 6. Paducah soil results: TCE concentrations inside treatment area

high-energy depositional environment at the site make this the one of the largest ERH projects performed to date—and certainly the most complex.

The project requires the design and implementation of full-scale ERH/MPE systems to remediate three designated contaminant source areas (NAPL Areas 1, 2, and 3). Area 1 measures 25,400, Area 2 measures 22,400, and Area 3 measures 18,200 square feet. Remediation has been completed in Area 1, and ERH operations in Area 2 commenced in January 2005.

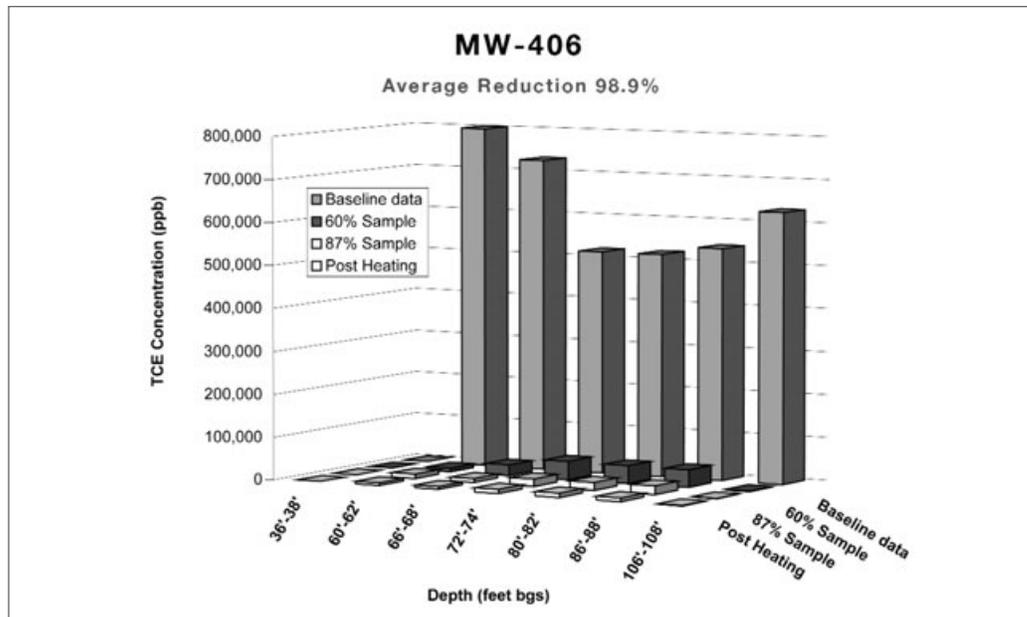


Exhibit 7. Paducah TCE groundwater results inside treatment area: MW-406

Contaminants of concern (COC) are chlorinated solvents, primarily TCE, and petroleum products, oil, and lubricants (POLs). In addition to removal of COC mass, the performance-based contract includes the following specific quality assurance and performance criteria:

- Minimize the time to implement the remedy while maximizing mass removal.
- Establish and verify that the subsurface reaches target temperatures of 90°C in the vadose zone and 100°C in the saturated zone.
- Maintain these target subsurface temperatures for a minimum of 60 days.
- Establish, maintain, and verify control of contaminant migration in groundwater, soil vapors, and air emissions.
- Provide a system for near-real-time data delivery, performance and compliance monitoring, and project communications.

To meet all contract criteria in the high-permeability lithology, hydraulic control wells are being used in addition to MPE to maintain a depressed groundwater table within the treatment area. The use of hydraulic controls wells required the addition of a 190 gpm liquid waste management system (LWMS) to treat recovered NAPL and groundwater. Vapors are being treated using a 1,000 cfm thermal oxidizer equipped with an acid gas scrubber.

A Triad approach is being applied to project management that combines systematic planning, dynamic design and workplans, and rapid data turnaround times. A sophisticated Web-based data storage and communication system has been developed to facilitate this management approach. The Triad approach allows project decisions to be made on a near-real-time basis and it has been used successfully to handle a series of challenges related to unexpected site conditions.

The ERH system design for NAPL Area 1 included 106 colocated electrode-MPE locations across the 25,400-square-foot treatment area. Electrodes extended from 2 to

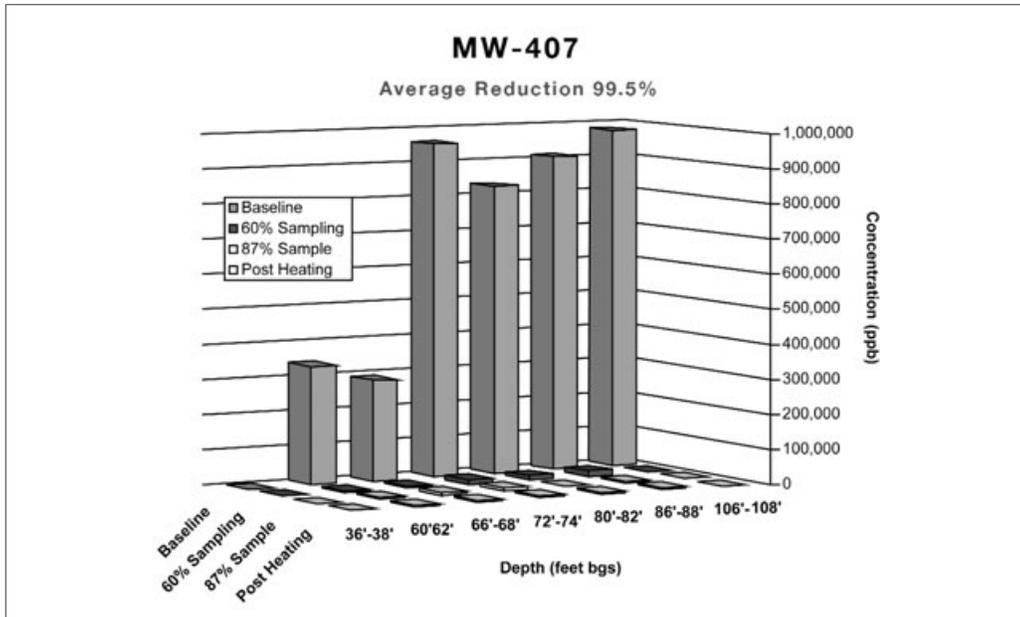


Exhibit 8. Paducah TCE groundwater results inside treatment area: MW-407

38 feet bgs, producing a treatment volume of approximately 33,900 cubic yards. The Area 1 ERH system also utilized 40 TMPs containing over 320 thermocouples, 6 hydraulic control wells, and 20 groundwater monitoring wells, 10 located inside the heated area and 10 located outside (Exhibit 9).

Installation of electrode-MPE wells had to allow for continued delineation of the source areas and the flexibility to set final electrode depths in the field based on actual site lithology and indications of NAPL presence. To maintain an aggressive production schedule, the majority of site borings were placed using air-rotary drilling, while rotosonic drilling was used at selected electrode locations and all groundwater monitoring wells. The continuous soil samples obtained during rotosonic drilling were used to further delineate the contaminant plume during the well-installation process. The installation process allowed an unexpected DNAPL impact zone to be discovered and the ERH treatment and monitoring systems to be expanded without schedule delay.

A few months into the NAPL Area 1 remediation, the subsurface heating profile disclosed that local groundwater velocity was much greater than site modeling had projected. The original ERH design had been based on a groundwater flow of 1 foot per day (ft/day). However, a channel of groundwater flowing at 10 ft/day was discovered running through the center of the treatment area. Additionally, the direction of groundwater flow had changed 180° as seasons changed. Meeting the subsurface temperature specifications with the changed hydrogeologic conditions required additional wells for hydraulic control and PCU capacity to input more electrical power to the subsurface.

During operations in NAPL Area 1, significant quantities of NAPL were recovered at the surface, including grease that is a solid at room temperature. Exhibit 10 shows grease deposited at the bottom of the vapor liquid separator prior to the equipment reaching target temperature. Once the equipment was warm, the grease remained a liq-



Exhibit 9. Area 1 ERH layout

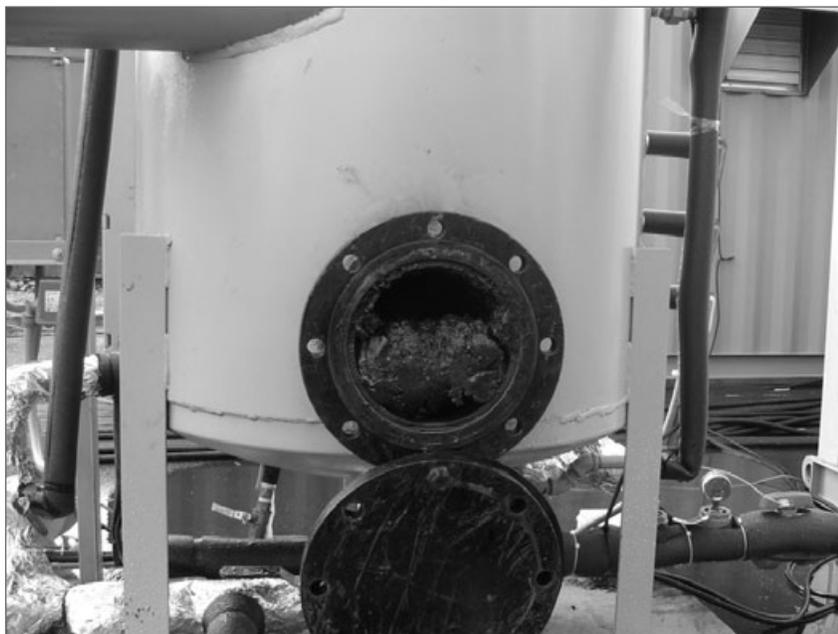


Exhibit 10. Grease accumulation in vapor liquid separator

uid and flowed freely through the vapor liquid separator and oil water separator. Subsurface heating started in February 2004 and ended in August 2005.

Contaminant recovery over the course of the Area 1 remediation is shown in Exhibit 11. An estimated 100,000 lbs of NAPL was recovered ten months after the project started. The project goal was to recover as much mass as possible while holding the treatment area at the target temperature of 90°C in the vadose zone and 100°C in the saturated zone for the set period of 60 days. Had temperatures been held for a longer

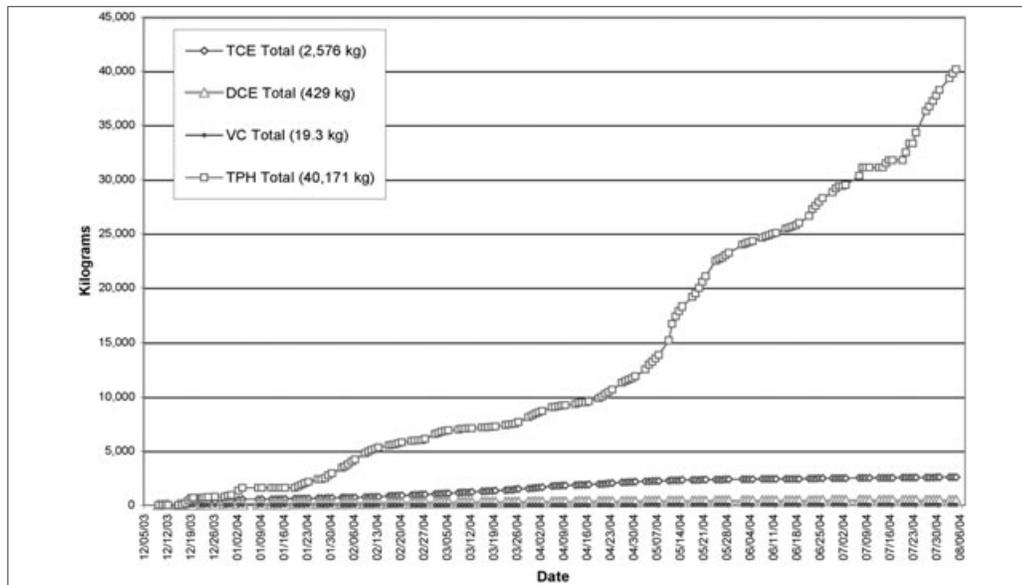


Exhibit 11. Cumulative mass removal of specific COC VOCs in air

time period, final contaminant reduction percentages would have increased. Results for Area 1 showed an average 87 percent reduction in TCE concentrations in groundwater in both the interior monitoring wells (Exhibit 12) and no increases in TCE concentrations in the exterior monitoring wells (Exhibit 13).

Additional Project Results

During the early applications of ERH, it was commonly thought that the total indigenous bacteria population within an ERH treatment area suffered overwhelming losses as a result of increased subsurface temperature. However, as ERH was applied at an increasing number of sites, anecdotal evidence began to emerge suggesting that *in situ* reactions, including biological reactions, could be a significant factor in the VOC reduction.

A limited data set from an early ERH pilot test on petroleum hydrocarbons showed that plate counts of indigenous petrophilic (hydrocarbon-degrading) bacteria taken before and after ERH remediation contained more bacteria after heating than before. Samples taken from a depth of 8 to 10 feet bgs contained 100 times the number of bacteria three months after heating, while samples from 12 to 14 feet bgs contained 46 times the starting number (Exhibit 14).

In order to further understand the effects of heat on indigenous bacteria, including the TCE-degrading bacteria *dehalococcoides*, groundwater samples were collected from NAPL Area 1 in May 2004 at varying locations, depths, and temperatures. The samples were collected from five wells across a range of temperatures and filtered for DNA analysis. Analyses included DNA extraction and quantification, quantitative polymerase chain reaction (PCR) for *dehalococcoides* spp., and terminal restriction fragment length polymorphisms (T-RFLP). Exhibit 15 shows the results of the DNA analysis of the *dehalococcoides* preferential to a temperature range of 30–60°C. Additional microbe identification, sampling, and testing are being conducted during the remediation of NAPL Area 2 to develop a better understanding of the effects of ERH as an enhancement to bioremediation.

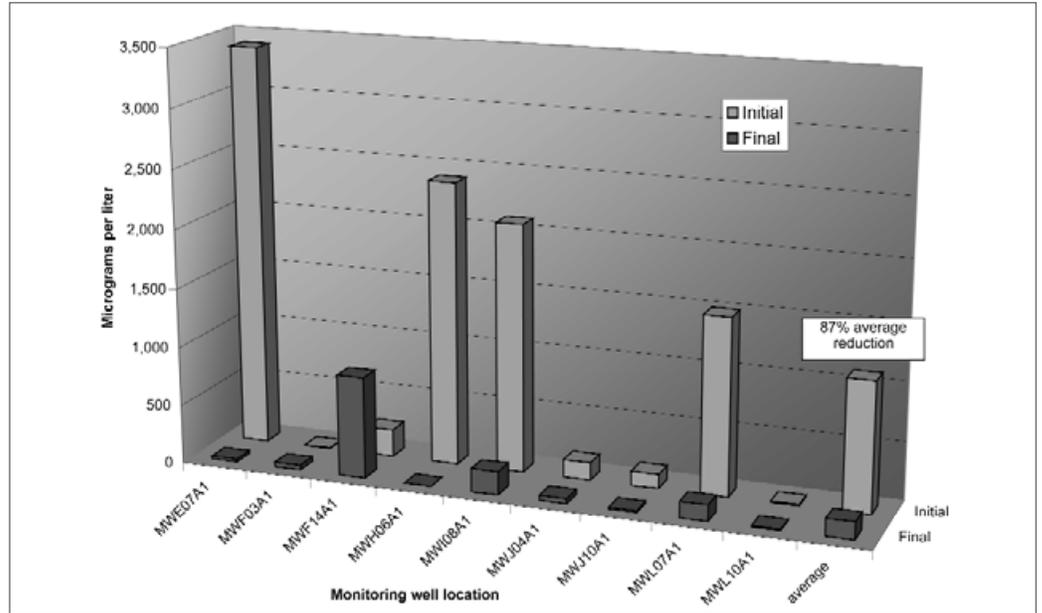


Exhibit 12. Fort Lewis groundwater interior well (treatment area) TCE concentrations for NAPL Area 1

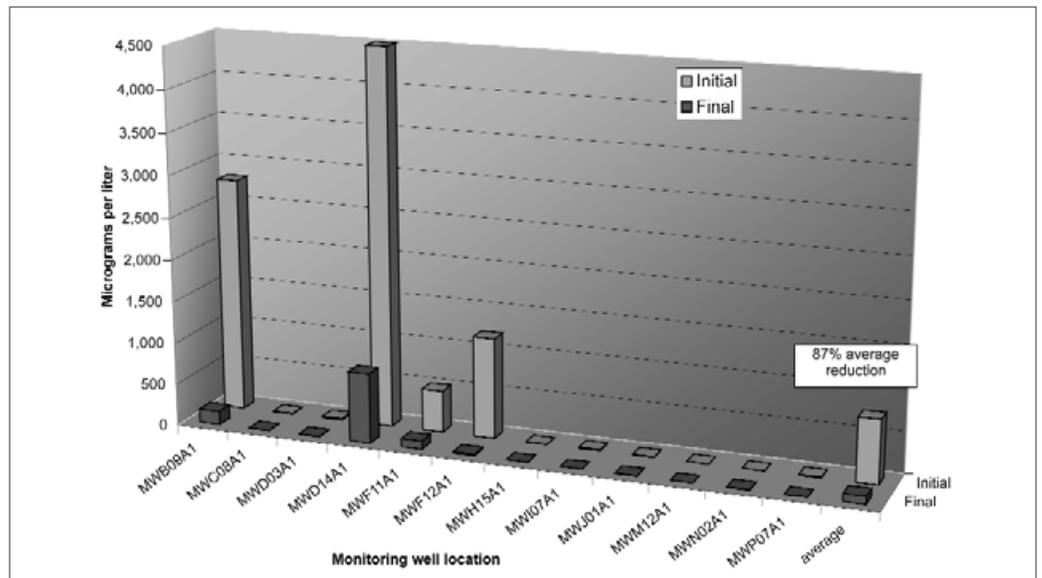


Exhibit 13. Fort Lewis groundwater exterior well (treatment area) TCE concentrations for NAPL Area 1

COMBINING TECHNOLOGIES AND NEW DEVELOPMENTS

Throughout this discussion, ERH has been presented primarily as a contaminant source-area remediation technology. Promising results have been observed in the field at several project sites that support the potential for cost-effective deployment of ERH to remediate dissolved-phase contaminants by heat-enhanced bioremediation. Field investigations are beginning to show that heating to temperatures between 30° and 40°C can signifi-

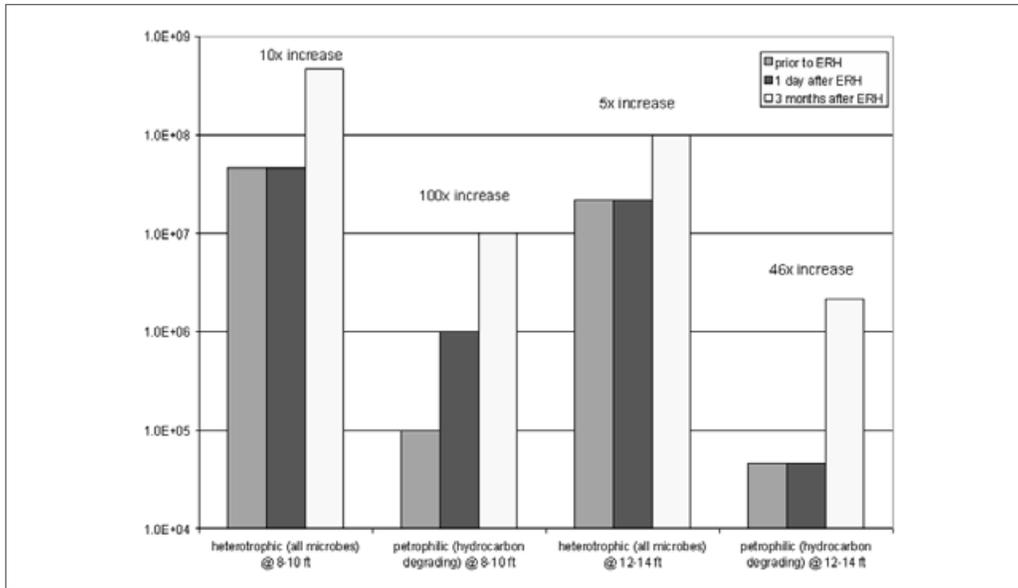


Exhibit 14. Microbe counts average of three wells

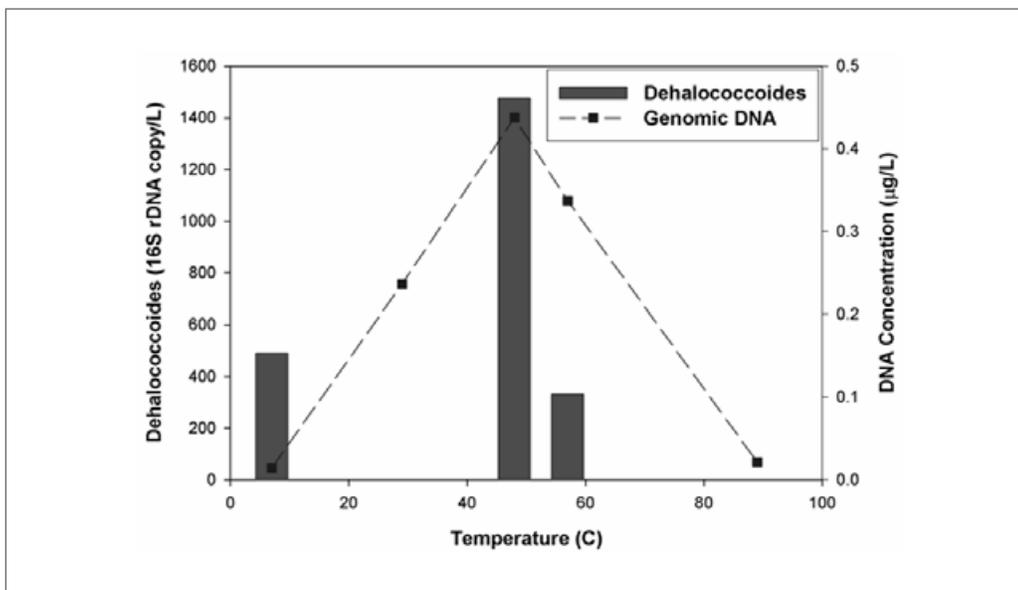


Exhibit 15. Effect of temperature on total DNA and *dehalococoides*

cantly enhance biodegradation rates. Combining these two technologies offers a possible solution to total plume remediation.

Significant cost savings can be achieved using low-heat ERH to enhance bioremediation for polishing the source area or treating the downgradient dissolved-phase contaminant plume. The design of a low-heat ERH system would utilize fewer electrodes that could be installed by direct-push technology (Geoprobe™). Because all treatment would be *in situ* and site temperatures would be below boiling, there would not be vapors or steam to collect and treat. Smaller PCUs could be utilized, and much less electrical energy would be required.

SUMMARY

ERH is now recognized as a proven and cost-effective remediation tool capable of successful cleanup at sites where other technologies have had limited success. ERH is commonly selected as the preferred cleanup alternative for highly impacted sites, including those with DNAPL and LNAPL sources, heterogeneous lithologies, and sites with low-permeability silt and clays. The technology can be used under operating buildings and roads with limited impact to business operations or the public.

ACKNOWLEDGMENT

The authors would like to thank North Wind, Inc. of Idaho Falls, Idaho for their assistance with the preparation of figures for this article.

Gregory Beyke, P.E., is a founder and vice president of engineering for Thermal Remediation Services, Inc. He received a BS in aerospace engineering from the U.S. Naval Academy in Annapolis, Maryland, and an MS in aerospace engineering from the University of Maryland. He is a registered professional engineer in Georgia, Kentucky, and Washington. Mr. Beyke is a recognized expert in the development, design, and deployment of innovative *in situ* remediation technologies, including electrical resistance heating, and has pioneered many of the commercial improvements to ERH.

David Fleming is a founder and vice president of marketing and sales for Thermal Remediation Services, Inc. He received a BS in environmental health in 1985 from Huxley College of Environmental Studies at Western Washington University. During his 20 years in the environmental industry he has worked for federal, state, and local regulatory agencies and led the marketing, sales, and business development for start-up and established consulting engineering firms. Mr. Fleming has been responsible for the marketing and sales development in the commercialization of electrical resistance heating since 1997.
