Electrical Resistance Heating: Rapid Treatment for Soil and Groundwater Remediation

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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 the technology development, the process, and provides two case studies where ERH was used to remediate complex lithologies.

Overview

ERH quickly and evenly heats the subsurface to the boiling point of water by passing electrical current through contaminated soil and groundwater. This gentle heating evaporates volatile contaminants *in situ* and steam strips them from the subsurface. Vapors and steam are then recovered, cooled, and treated using standard methods. The technology has been demonstrated as an effective method for the removal of volatile and semivolatile chlorinated and petroleum hydrocarbons from both vadose and saturated zones regardless of soil permeability or heterogeneity[2].

The technology is not affected by soil type and can be applied almost anywhere, even under operating facilities and public areas. Few remediation technologies can offer equal levels of chlorinated non-aqueous phase liquids (NAPLs) cleanup in the same time frame and for the same price as ERH. Because ERH has been applied successfully under so many site conditions, it is possible for site owners to obtain price and performance guarantees for most site cleanups.

ERH can be used to steam strip volatile organic compounds (VOCs) from the subsurface, enhance vapor and multi-phase extraction systems, and increase biological degradation and chemical dechlorination reaction rates. During a typical ERH site remediation, all of these processes are utilized to ensure that an effective and lasting remediation is achieved.

Deploying ERH requires a power control unit (PCU) to condition and control the application of power, electrodes to deliver power to the subsurface, recovery wells to collect steam and contaminant vapors, a steam condenser, a vapor treatment system, and control and data acquisition systems. The training and experience of the personnel applying the technology is critical to a successful deployment.

ERH Background

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 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.

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. This application was 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 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).

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, nearly 60 sites throughout North America have been treated with ERH by TRS alone, 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 below maximum contaminant levels (MCLs).
- ERH has been combined with multiphase extraction (MPE) for light nonaqueous phase liquid (LNAPL) treatment.
- Successfully applied at depths up to 130 feet below ground surface.
- Methylene chloride, ethylene dibromide, and 1,1,1-trichloroethane have been remediated by heat-enhanced *in situ* hydrolysis.
- 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.

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 ERH process

Resistance to the flow of electrical current between electrodes warms the treated soil until a portion of the soil moisture is converted into steam. This *in situ* steam generation occurs in all soil types as well as in fractured or porous rock. The electrical energy evaporates the target contaminants and also produces steam as a carrier gas to sweep the vapors to the recovery wells for capture and eventual treatment at the surface.

Electrodes are placed in the subsurface throughout the remediation area using standard drilling or pile driving techniques. The spacing between the electrodes is usually 14 to 22 feet. The depth at which electrodes may be placed at a given site is only dependent upon the depth to which drilling can be accomplished. Electrodes can be constructed with multiple elements in a single borehole. These electrode elements can then be used to vary the flow of electrical current, and thus the level of heating, at different subsurface depths.

Electrodes are really just remediation wells with the added capability to direct electrical current to the proper depth for subsurface heating. Electrodes can 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.

The PCU directs three-phase electricity from municipal power lines to the electrodes. The electricity may be directed to groups of electrodes, or electrode depth intervals, either simultaneously or sequentially depending on the size of the volume being treated, or the desired heating pattern.

Subsurface temperature, voltage, airflow, and pressure data are collected automatically and uploaded to the PCU computer. The PCU computer is used to both monitor and control site activities and may be accessed directly or remotely. Subsurface temperatures are measured using thermocouples set at predetermined subsurface locations.

The overall ERH heating pattern is remarkably even throughout the treatment volume. However, while all soil in the targeted treatment volume is heated simultaneously, electricity prefers to take pathways of lower resistance when moving between electrodes and these pathways are heated slightly faster. Examples of low resistance pathways in the subsurface include silt or clay lenses and areas of higher free ion content.

As chlorinated contaminants sink through the lithology, they tend to become trapped on silt and clay lenses. Over time, trapped solvents undergo natural dehalogenation processes that produce daughter compounds and free chloride ions. Thus, at chlorinated hydrocarbon sites, the most impacted portions of the subsurface are also the lower resistance electrical pathways that are preferentially treated by ERH. Subsequently, low permeability soils and high solvent concentration spots heat, and clean up, slightly faster than other locations during ERH remediation.

By increasing subsurface temperatures to the boiling point, ERH speeds removal of contaminants by two primary mechanisms: increased volatilization and *in situ* steam stripping. As subsurface temperatures begin to climb, contaminant vapor pressure, and the corresponding rate of contaminant extraction, typically increases by a factor of about 30.

However, the ability of ERH to produce steam *in situ* represents its most significant advantage over other subsurface heating techniques. Through preferential heating, ERH creates steam from within silt and clay stringers and lenses. The physical action of steam escaping these tight soil lenses drives contaminants out of those portions of the soil matrix that tend to lock in contamination via low permeability or capillary forces. Released steam then acts as a carrier gas, sweeping contaminants to vapor or multiphase extraction wells constructed in the saturated and vadose zones.

The boiling points of most common VOCs in air are either below or just slightly above the boiling point of water (100℃). However, when a VOC is immersed or dissolved in water, its boiling point is depressed, because a low solubility VOC/water mixture boils when the vapor pressure of the VOC plus the vapor pressure of water is equal to the ambient pressure as described by Dalton's Law of Partial Pressures. An example of this effect is perchloroethylene (PCE), which has a boiling point in air of 121°C. The boiling point of PCE in contact with water or moist soil is 88℃, allowing its effective remediation by ERH.

Once subsurface heating starts, the boiling point of various VOC/water mixtures is reached in the following order: NAPL in contact with water or moist soil, groundwater containing dissolved VOCs, and then pure groundwater. This is advantageous for remediation because contaminated water will boil off before uncontaminated water, reducing the time and energy required to complete treatment.

Although volatilization is usually the primary removal mechanism for VOCs during ERH, VOCs may also be degraded in place by *in situ* processes. These *in situ* processes include increased biodegradation, hydrolysis, and reductive dehalogenation by zero valent iron.

The biodegradation of chlorinated solvents is most commonly an anaerobic process. Heating increases the degradation rate far beyond what is typically observed under ambient conditions. Heating is especially important at sites with high levels of total organic carbon (TOC), which provide a carbon source for an electron donor. Boiling of the site converts a portion of the natural TOC into water soluble forms and therefore makes the TOC more bio-available. In essence, even heterogeneous sites are uniformly bioamended without the injection of amendments.

Cost Considerations

No matter what remediation technologies are employed, remediation cost accounting is site specific and dependent on the shape and volume of the treatment area, the target contaminants and level of contaminant reduction required and the TOC content of the soil. Cost considerations should include both the direct costs to pay for application of the remediation technology and ongoing project costs such as real estate opportunity costs, interaction time with regulatory agencies, sampling and analysis, and reporting.

An EPA-sponsored study was conducted comparing technologies for cost and performance on DNAPL sites across the United States[3]. The results are presented in Figure 1.

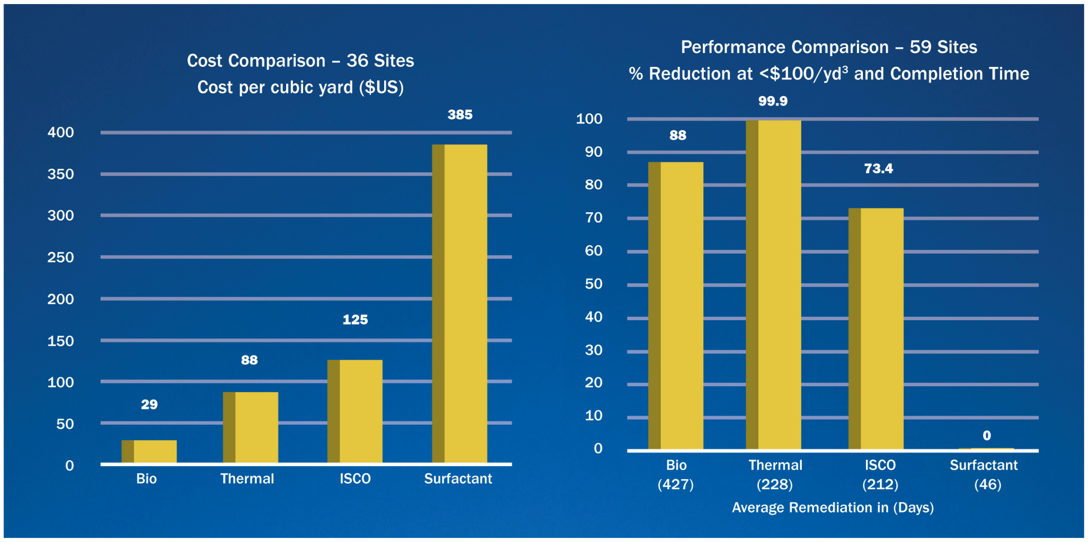


Figure 1. Cost & Performance Metrics

At sites where ERH is applicable, the time spent in remediation is typically reduced from years to months. Larger ERH sites are cleaned within 6 to 12 months and smaller sites can be cleaned in half that time or less. For larger sites, the cost of ERH is about half that of excavation and disposal[4]. A remediation guarantee typically adds 10-15% to the total cost. Remedial goals can be based on soil samples, groundwater samples, or both.

Case Studies

The following are two case studies using ERH. The first case study highlights a small site and the ability to perform a rapid remediation to speed closure for a property in low permeability soil conditions. The second case study highlights a larger site with 3 treatment areas and difficult site parameters.

Case Study #1 - TCE Remediation in Low Permeability Soil

In Olney, Illinois, a former above ground storage tank (AST) that contained TCE was previously removed from the site location, but further investigation results indicated TCE concentrations above acceptable limits were present in the subsurface at varying depths. Based on the tight subsurface conditions and a series of technology comparisons, ERH was determined to provide the most effective, least disruptive treatment to achieve the site goals within a very short time period. The remediation was performed under a guaranteed, performance and time based fast-track remediation of trichloroethene (TCE) in soil. This guaranteed project included liquidated damages and was based on reaching defined cleanup objectives, including Illinois Environmental Protection Agency (ILEPA) Csat limit of 4,400 mg/kg in soil within 20 weeks of notice to proceed.

Site Characteristics & Design Parameters

The target ERH remediation area consisted of two distinct treatment areas as shown in Figure 2 to facilitate cost-effective and rapid remediation. The site lithology consisted of primarily silty clay that increased in density with depth. The groundwater table was approximately 20-feet below grade surface (ft bgs). The lateral extent of Area 1 (Shallow ERH Treatment Area) was approximately 400 ft^2 with an ERH treatment interval from 2 to 10- ft bgs, targeting the vadose zone. Area 2 (Deep ERH Treatment Area) covered approximately 600 ft^2 with an ERH treatment interval from 20 to 35-ft bgs, targeting the saturated zone. The combined treatment volume was delineated as 1,000 ft^2 equating to approximately 500 yd^3. The photograph in Figure 3 shows the small footprint of the project equipment and close proximity to the building, which remained in operation throughout the remediation.

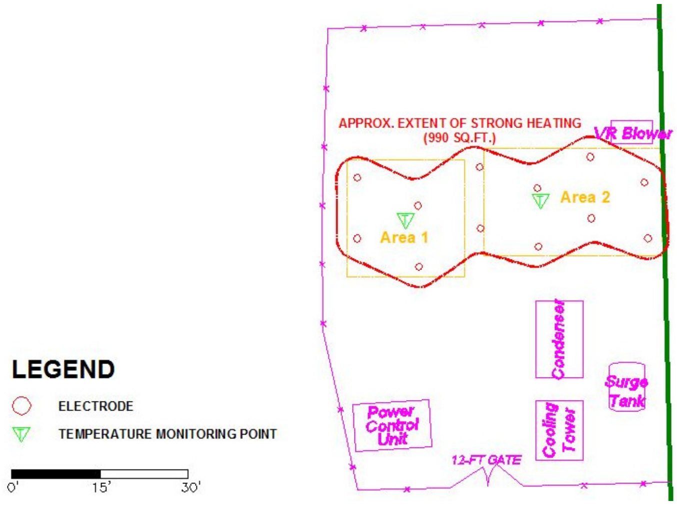


Figure 2. Site Plan

Figure 3. Site Photo with Equipment Compound

A flexible electrode design allowed onsite personnel to make an in-the-field decision to install additional electrodes and co-located vapor recovery (VR) wells in the area between the Area 1 and Area 2 to ensure than any TCE contamination present between the two areas was remediated.

System Construction and Operations

The flexible electrode design (Figure 4) provided distinct remediation intervals for the two areas while operating concurrently from the same Power Control Unit (PCU).

The design provided for four shallow electrodes in Area 1 with separate vapor recovery wells and six deep electrodes with co-located vapor recovery wells for Area 2. Full length electrodes with co-located VR wells were installed between Areas 1 and 2 to ensure any TCE between the areas was remediated. Operations were completed in 56 days from September to November 2004.

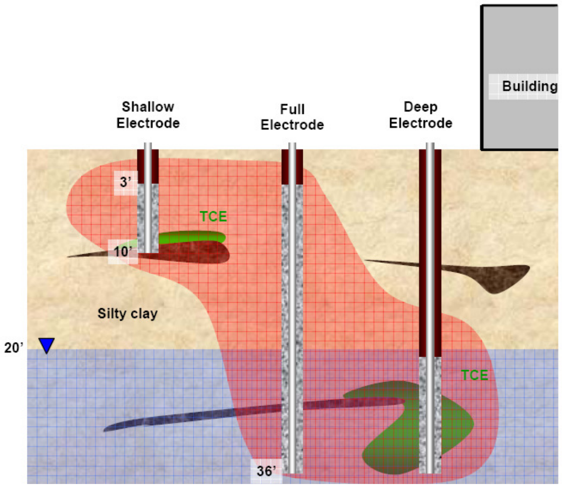


Figure 4. Electrode design for interval treatment

Project Results

Implementing the unique ERH design, TRS was able to achieve a 99.9999% reduction in TCE concentrations. Figure 5 shows the average TCE concentration in soil before and after ERH remediation. The final concentrations of TCE in soil were nearly 100,000 times lower than the ILEPA Csat limit of 4,400 mg/kg. TRS was able to successfully remediate the site in 12 weeks, meeting both the performance goal and the client's compressed time schedule requirements without incurring liquidated damages. Total project cost was US$243,340.

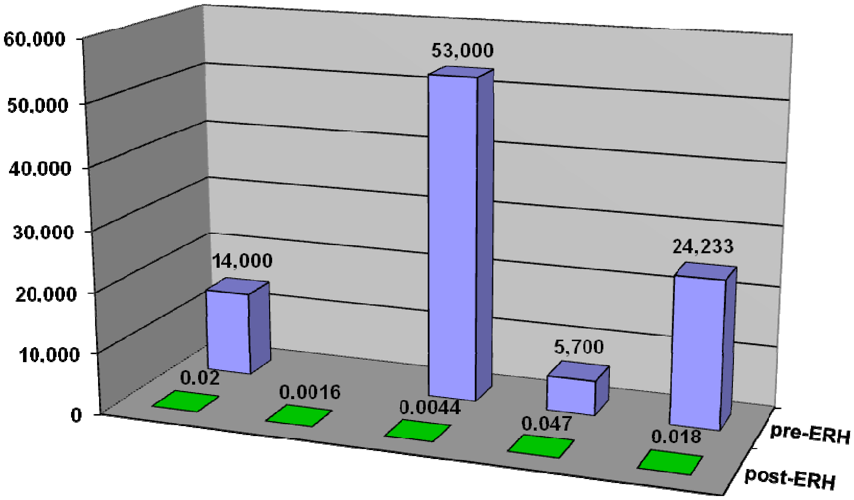


Figure 5. TCE soil results

Case Study #2 – Fort Lewis, Washington East Gate Disposal Yard

At the Fort Lewis, Washington, East Gate Disposal Yard, NAPLs were successfully treated *in situ* using ERH and MPE. The project was performed under a fixed-price, performance-based remediation contract administered by the Seattle District of the USACE. The size of the areas being heated, the types of contaminants being treated, and the 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 required the design and implementation of full-scale ERH/MPE systems to remediate three designated contaminant source areas (NAPL Areas 1, 2, and 3) as shown in Figure 6. Area 1 measures 25,400 square feet, Area 2 measures 22,400 square feet, and Area 3 measures 18,200 square feet.

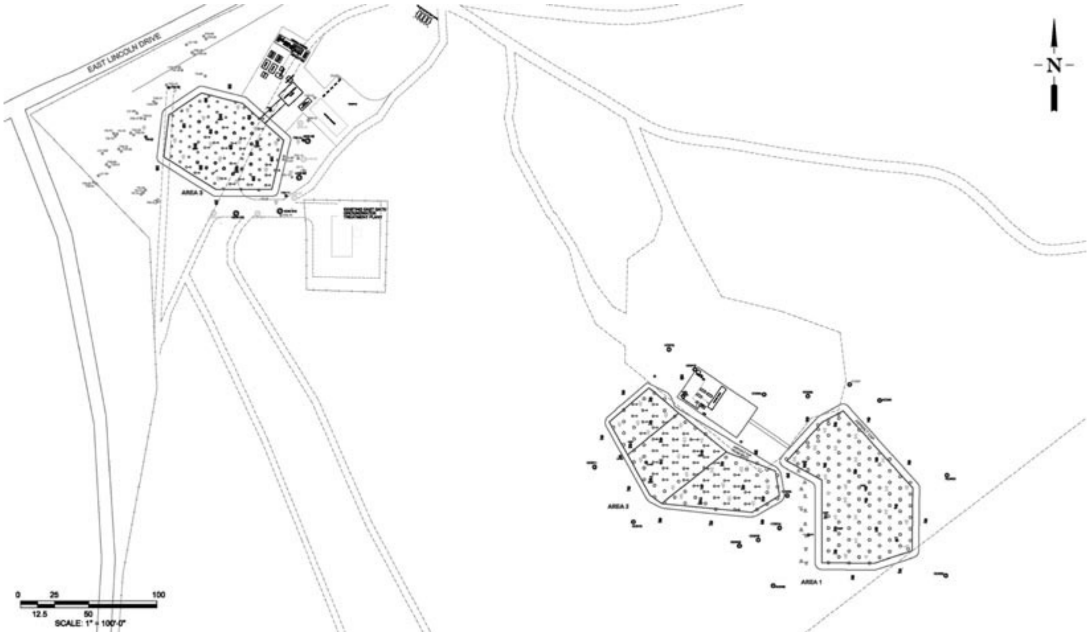


Figure 6. Site Layout Fort Lewis NAPL Areas 1, 2, and 3

Contaminants of concern (COC) were chlorinated solvents, primarily TCE, and petroleum products, oil, and lubricants (POLs). In addition to removal of COC mass, the performance-based contract included 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 90ºC in the vadose zone and 100ºC 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 portion of the lithology, hydraulic control wells were used in addition to MPE to maintain a depressed groundwater table within the treatment area. The use of hydraulic control wells required the addition of a 190 gpm liquid waste management system (LWMS) to treat recovered NAPL and groundwater.

Vapors were treated using a 1,000 scfm thermal oxidizer equipped with an acid gas scrubber.

A TRIAD approach was 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 was developed to facilitate this management approach. The TRIAD approach allowed project decisions to be made on a near-real-time basis and was used successfully to handle a series of challenges related to unexpected site conditions.

NAPL Area 1

The ERH system design for NAPL Area 1 included 106 co-located electrode-MPE locations across the 25,400-square-foot treatment area. Electrodes extended from 2 to 38 feet bgs, producing a treatment volume of approximately 33,900 cubic yards.

Installation of combination 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. 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. Figure 7 shows grease deposited at the bottom of the vapor liquid separator prior to the equipment reaching target temperature. Once the entire system was warm, the grease remained a liquid and flowed freely before capture in the oil water separator.

Figure 7. Knock-out pot with grease

Subsurface heating started in February 2003 and ended in August 2004. The maximum and average TCE concentrations in groundwater before ERH from monitoring wells inside NAPL Area 1 were 4,831 µg/L and 1,102 µg/L, respectively. Approximately 13 months after power input to NAPL Area 1 ceased, TCE concentrations inside NAPL Area 1 ranged from nondetect (<0.2 µg/L) to 85 µg/L. Figures 8 and 9 illustrate the continued decline in TCE concentrations in groundwater in NAPL Area 1 in the interior and exterior monitoring wells by comparing groundwater results before, immediately after, 10 months after, and two years after ERH.

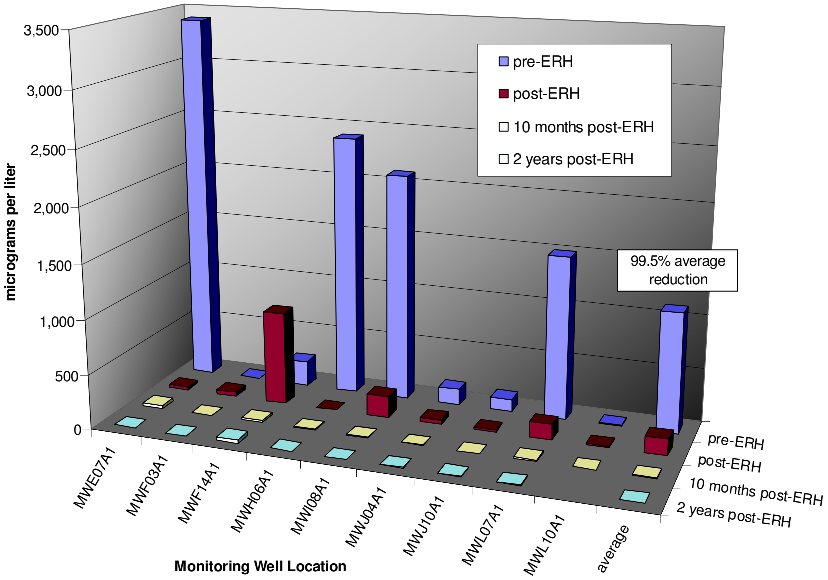


Figure 8. NAPL Area 1 – Interior Monitoring Wells

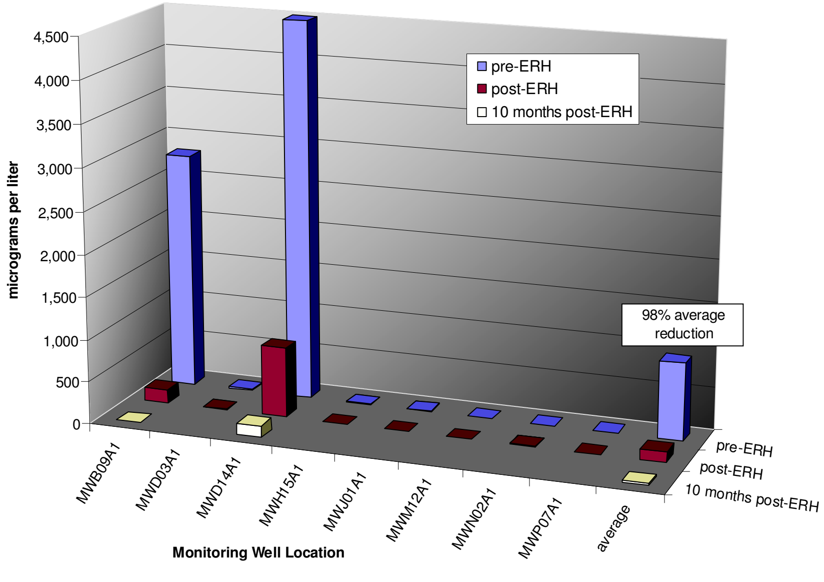


Figure 9. NAPL Area 1 –Exterior Monitoring Wells

NAPL Area 2

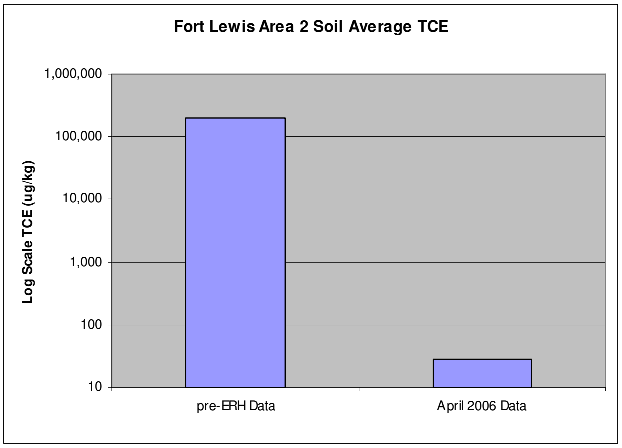
The NAPL Area 2 remediation covered approximately 22,400 ft^2 with a vertical treatment interval from grade to 43 feet below grade surface (bgs) in two sections of the site (13,040 ft^2) and from grade to 52 feet bgs in the remaining section (9,360 ft^2). Figure 10 below shows Area 2 in the foreground with Area 1 in the background.

The subsurface component of the ERH remediation and monitoring system consisted of 101 electrode locations. The lateral and vertical ERH treatment application resulted in an estimated treatment volume of 36,500 cubic yards.

Buried metal was discovered during certain electrode installations and was observed to cause elevated electrical current conditions during operations. Addressing the issue, dual-electrode pairs were installed in the locations showing the magnetic anomalies. Each electrode pair consisted of a deep and shallow electrode. The shallow electrodes were generally located in the vadose zone, with the corresponding deep electrodes spanning the remaining associated saturated treatment zone. This configuration allowed removal of the electrodes experiencing electrical overcurrent conditions as a result of the buried metal objects, while continuing to supply current to the deeper electrode within the pair for uninterrupted heating capabilities. This also ensured a much more even application of heat to NAPL Area 2. The electrode design included an MPE component for removal of NAPL, dissolved-phase hydrocarbons, groundwater in the uppermost portion of the water table, and vapor recovery.

System operations began on February 14, 2005, and concluded 172 days later on August 5, 2005. Beginning TCE concentrations in groundwater within the NAPL Area 2 treatment volume were typically orders of magnitude lower than TCE concentrations in NAPL Area 1, while *cis*-1,2-DCE concentrations were significantly higher than TCE in NAPL Area 2 than in NAPL Area 1.

The average TCE and DCE concentrations in the post-ERH soil samples were 28 µg/kg and 58 µg/kg, respectively. This represents a reduction of 99.99 percent and 98.88 percent for TCE and DCE respectively, approximately eight months after treatment (Figure 11). Additionally, 117 of the 276 post-ERH soil samples in NAPL Area 2 (42 percent) showed nondetectable concentrations of TCE and DCE in the April 2006 soil sampling event.



COC	Pre-ERH Average (ug/kg)	April 2006 Average (ug/kg)	Percent Reduction	Percent ND
TCE	**202,338**	**28**	**99.99%**	**44%**
DCE	**5,130**	**58**	**98.88%**	

Figure 11. Pre- and Post- ERH TCE/DCE results

NAPL Area 3

The ERH system design for NAPL Area 3 was designed to treat three separate areas (3a, 3b, and 3c) and included 97 co-located electrode-MPE locations across the 18,200 sq^2 treatment area. Electrodes extended from 14 to 37 feet bgs, producing a treatment volume of approximately 20,900 yd^3. Lessons learned in NAPL Areas 1 and 2 were applied during the design of NAPL Area 3 leading to installation of a variety of electrode configurations.

Based on experiences in NAPL Areas 1 and 2, the system design was modified to enhance effectiveness, streamlining operations for NAPL Area 3. Subsurface heating started in October 2006 and ended in January 2007. The total mass removed from Area 3 during operations of the ERH remediation system was 1,674 kilograms (kg) (approximately 5.5 55-gallon drums) of chlorinated volatile organic compounds (CVOCs) and total petroleum hydrocarbons (TPH). This includes approximately 1,145 kg of CVOCs and 529 kg of TPH.

The average baseline TCE concentration in groundwater before ERH from monitoring wells inside NAPL Area 3 was 1,920.9 µg/L. The average peak concentration was 11,633.4 µg/L. Prior to cessation of ERH operations, groundwater sampling recorded TCE concentration of 69.2 µg/L, indicating a 96.4% average removal and the elimination of NAPL within the Area 3 treatment volume. Final samples collected indicated a removal efficiency of approximately 99.9%.

Ft. Lewis – Case Study Summary

For the 3 sites, TRS remediation costs were approximately $12M over a timeframe of approximately 3 years. The use of the TRIAD approach proved to facilitate the decision-making process throughout the project. This allowed enhanced field modifications to address unexpected site conditions, which ultimately saved over $1M on the total project.

	NAPL Area 1	**NAPL Area 2**	**NAPL Area 3**
Duration of ERH Operations	231 days	172 days	107 days
Treatment Area (ft^2)	25,400	22,390	18,200
Treatment Volume (yd^3)	31,040	36,500	20,900
TCE Mass Removed	2,576 kilograms	1,089 kilograms	847 kilograms
cis-1,2 DCE Mass Removed	405 kilograms	245 kilograms	285 kilograms
TPH Mass Removed	40,171 kilograms	11,337 kilograms	529 kilograms
Groundwater Volume Removed	24,221,147 gallons	33,873,915 gallons	25,920,937 gallons
Groundwater Removal Rate	104,863 gallons per day (73 gpm)	200,437 gallons per day (139 gpm)	243,161 gallons per day (169 gpm)
ERH Energy Applied	7,898 megawatt-hours	9,181 megawatt-hours	5,856 megawatt-hours
Cost (inc. electricity)	$5,326,404 ($178/yd^3)	$3,726,717 ($108/yd^3)	$2,938,522 ($144/yd^3)

Summary

ERH is now recognized as a proven and cost effective remediation tool capable of successfully cleaning sites where other technologies have had limited success. ERH is commonly selected as the preferred clean-up alternative for highly impacted sites, including those with NAPL sources, heterogeneous lithologies, and low permeability silt, clay, or rock. The technology is often applied under operating buildings and roads with limited impact to business operations or the public. About half of the current ERH remediation projects are being performed under contracts that include guaranteed results.

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- Davi Damasi is the Director of Remediation for Doxor, Brazil

[2] US EPA Technology Innovation Office, Cost and Performance Report – *Six-Phase Heating™ (SPH) at a Former Manufacturing Facility Skokie, Illinois,* October 1999 http://www.thermalrs.com/TRS_docs/EPA%20Skokie%20Cost%20Perform%20Rpt.pdf

[3] Analysis of DNAPL Source Depletion Costs at 36 Field Sites and Performance of DNAPL Source Depletion Technologies at 59 Chlorinated Solvent-Impacted Sites, James M. McDade, Travis M. McGuire, and Charles J. Newell, Groundwater Service, Inc.

[4] US EPA, EPA 542-R-04-010, *In Situ Thermal Treatment of Chlorinated Solvents Fundamentals and Field Applications*, March 2004 http://www.thermalrs.com/TRS_docs/epa542r04010.pdf