New Advancements for *In Situ* Treatment Using Electrical Resistance Heating

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Electrical resistance heating (ERH) is proving to be an effective technology to rapidly heat the subsurface and, in doing so, removing volatile organic compounds. Practitioners of this technology have observed that other processes (biodegradation, abiotic degradation, hydrolysis, and possibly others) occur to break down the chemicals of concern, and remediation is not solely accomplished through vaporization. Few sites treated using ERH have been monitored during and after treatment to identify and evaluate the processes occurring and assess the contribution of these other biological and chemical processes in the remediation effort so that they may be incorporated in the remediation design.

At Fort Lewis, Washington, a landfill has been undergoing ERH treatment in three phases, where chlorinated volatile organic compounds represent the primary chemicals of concern in soil and groundwater. Other chemicals of concern include petroleum products, oils, and lubricants. The Fort Lewis remediation projects provided an opportunity to observe the reactions occurring in the subsurface during ERH and fine-tune the study with each phase of operation. This study is still under way. However, the data gathered to date, which focuses on biodegradation, provides insights into the processes that have been observed. For the Fort Lewis site, biotic and abiotic degradation processes have been observed throughout the range of operating temperatures. At the lower temperature ranges (up to 70°C), biological processes appear to predominate. Above 70°C, abiotic processes become much more active. The goal of this work is to eventually optimize the use of these intrinsic processes in ERH remediation to reduce energy requirements and costs. © 2007 Wiley Periodicals, Inc.

INTRODUCTION

Electrical resistance heating (ERH) has been applied at more that 50 sites across the United States to remediate a variety of volatile organic compounds (VOCs). The ERH technology was discussed in detail in the summer 2005 issue of *Remediation* (Beyke & Fleming, 2005). This article will first provide a brief overview of the technology, followed by an update on the case study discussed in the summer 2005 article. Postclosure data on the first remediation phase will be reviewed with additional results presented, further demonstrating the dechlorination capabilities of the technology. A second case study, the second phase of the remediation project will also be presented, highlighting very high removal efficiency, an aspect not previously associated with this technology.



ELECTRICAL RESISTANCE HEATING

Electrical resistance heating provides quick and even heating by passing electrical current through soil moisture and groundwater. This gentle heating evaporates volatile contaminants *in situ* and steam strips them from the subsurface. ERH has been demonstrated as a rapid and 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 (U.S. Environmental Protection Agency [US EPA], 1999).

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Developed for the U.S. Department of Energy in the early 1990s at the Pacific Northwest National Laboratory, ERH can be applied using three or six phases of alternating current electricity. Three-phase heating is generally more applicable for full-scale treatments and the general term *electrical resistance heating* is now used to describe the remediation technique regardless of the number of electrical phases employed. ERH can be used to aggressively steam-strip VOCs from the subsurface, enhance vapor and multiphase recovery systems, and increase biological degradation and chemical dechlorination reaction rates. About 50 percent of recent ERH remediation projects have included price and performance guarantees.

ERH requires a power control unit (PCU) to condition and control the application of electrical 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. A typical ERH process flow diagram is shown in Exhibit 1.

After ERH remediation is complete, the subsurface will slowly cool. The extended period at elevated temperatures after ERH provides an important polishing step for further reduction in VOC concentrations by heat-enhanced bioremediation, hydrolysis, and dehalogenation by zero-valent iron in the electrodes. This is a result of all chemical reactions being accelerated at elevated temperatures, as described by the Arrhenius Equation:

$$k = A * exp^{(-E_a/R * T)}$$
 (1)

where k is the rate coefficient, A is a constant, E_a is the activation energy, R is the universal gas constant, and T is the temperature (in degrees Kelvin).

CASE STUDIES

The case studies presented in this article represent an enhancement to the ERH technology by utilizing heat-enhanced biodegradation. At the Fort Lewis, Washington, East Gate Disposal Yard (EGDY), nonaqueous-phase liquids (NAPLs) are being successfully treated *in situ* using ERH and multiphase extraction (MPE). The project is being performed under a fixed-price performance-based remediation contract administered by the Seattle District of the U.S. Army Corps of Engineers (US ACE).

The remediation of NAPL Area 1 was discussed in depth in the summer 2005 issue of *Remediation* (Beyke & Fleming, 2005), as previously noted. The project involves 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 encompasses 25,400 ft²; Area 2, 22,400 ft²; and Area 3, 18,200 ft², as shown in Exhibit 2.

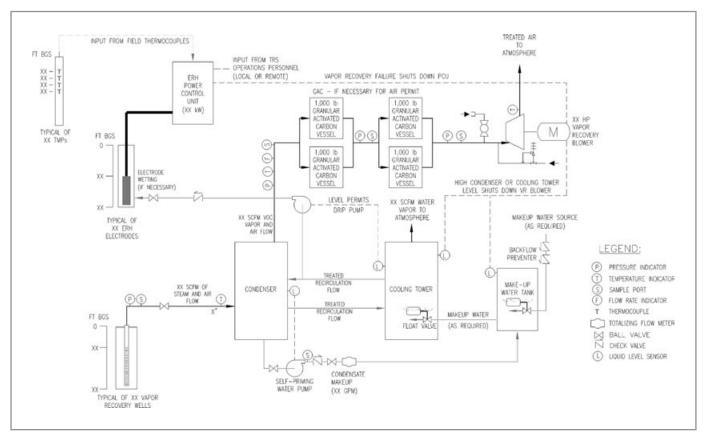


Exhibit 1. Typical process flow diagram

A brief update on NAPL Area 1 is included and describes the continued decline in TCE concentrations in soil inside NAPL Areas 1 and 2 and groundwater in the interior and exterior monitoring wells ten months and two years following remediation operations. This is followed by a section detailing the remediation of NAPL Area 2 and a concurrent laboratory/field test conducted by an independent third-party research subcontractor to quantify TCE dechlorination as a function of temperature.

The operations in Area 2 commenced in February 2005. Chemicals of concern (COCs) are chlorinated solvents, primarily trichloroethylene (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; and
- provide a system for near-real-time data delivery, performance and compliance monitoring, and project communications.

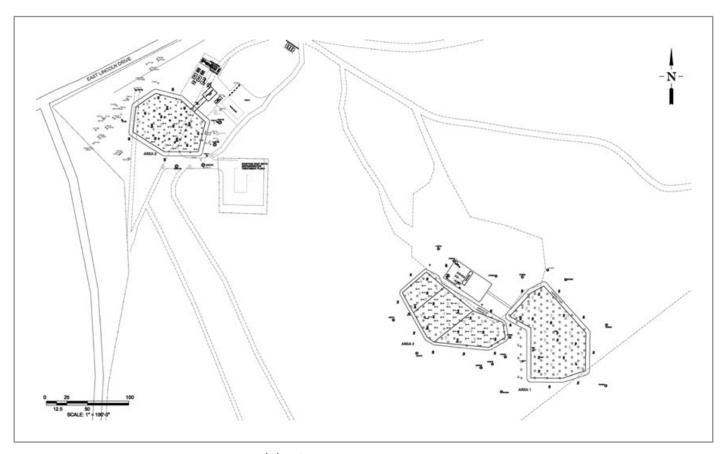


Exhibit 2. Fort Lewis map, NAPL Areas 1, 2, and 3

The size of the treatment areas, the types of COCs, the coarse-grained sediments, an unpredictable and high-velocity groundwater flow, and the in-depth studies of the effects of heat on *in situ* biotic and abiotic degradation represent the most complex ERH project ever implemented.

Case Study 1, Fort Lewis, Washington, NAPL Area 1

The maximum and average TCE concentrations in groundwater before ERH from monitoring wells inside NAPL Area 1 were 4,831 μ g/L and 1,102 μ g/L, respectively. Approximately 13 months after power input to NAPL Area 1 ceased, TCE concentrations inside NAPL Area 1 ranged from nondetect (<0.2 μ g/L) to 85 μ g/L.

Groundwater samples were collected from nine interior and eight exterior monitoring wells in NAPL Area 1 and analyzed for TCE concentrations in June 2005, ten months following ERH. The interior monitoring wells were also sampled in August 2006, two years post-ERH. The exterior monitoring wells were not sampled in the August 2006 groundwater sampling event. Exhibits 3 and 4 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 following ERH. Ten months following ERH in NAPL Area 1, average TCE groundwater concentrations continued to decline significantly from approximately an 89

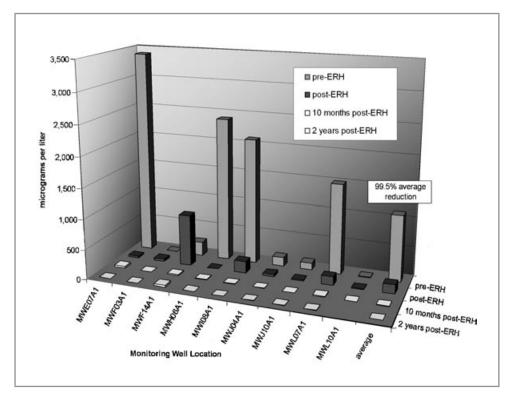


Exhibit 3. TCE reduction—NAPL Area 1 interior monitoring wells

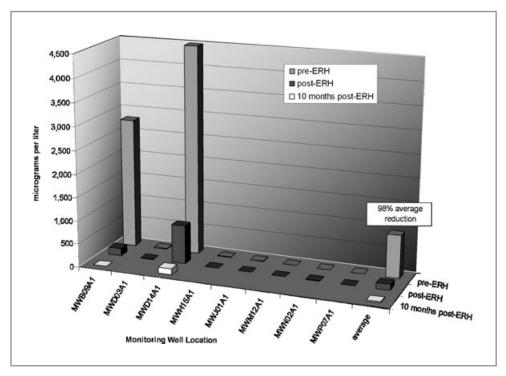


Exhibit 4. TCE reduction—NAPL Area 1 exterior monitoring wells

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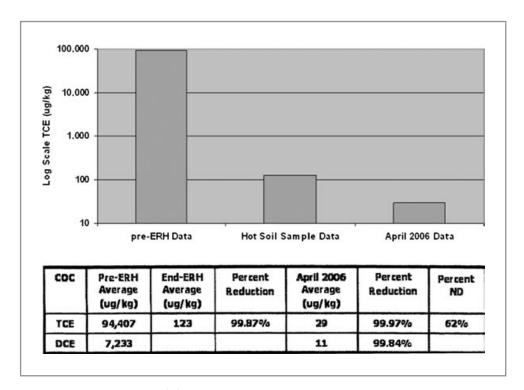


Exhibit 5. TCE reduction in soil—NAPL Area 1

percent average reduction post-ERH in August 2004 to greater than 99 percent average reduction in the interior monitoring wells. TCE concentrations in groundwater in the exterior monitoring wells 10 months following ERH showed a similar percent reduction (98 percent) compared to the 2004 post-ERH samples (85 percent). Two years following ERH average TCE groundwater concentrations in the interior monitoring wells continued to decline by an average 99.5 percent compared to the pre-ERH TCE concentrations in groundwater.

Pre-ERH soil samples were collected and analyzed for TCE and dichloroethylene (DCE) concentrations from six boring locations inside NAPL Area 1. The samples were collected from 14 to 24 discrete depth intervals from the soil borings. A total of 99 pre-ERH soil samples were collected. In the pre-ERH soil samples, the average TCE and DCE concentrations were 94,407 μ g/kg and 7,233 μ g/kg, respectively.

Post-ERH soil samples were collected in April 2006, nearly eighteen months after shutdown. A total of 264 post-ERH soil samples were collected from approximately the same boring locations that were sampled during the pre-ERH sampling event. In addition to the original 99 depth discrete samples during the pre-ERH sampling event, an additional 165 depth intervals were sampled during the post-ERH sampling event. The average TCE and DCE concentration in the post-ERH soil samples were 29 $\mu g/kg$ and 11 $\mu g/kg$, respectively. As a result of the remediation and nearly 1.5 years following ERH in NAPL Area 1, TCE and DCE concentrations in soil were reduced by an average 99.97 percent and 99.84 percent, respectively. Exhibit 5 illustrates the reduction in TCE concentrations in soil 18 months after the completion of ERH remediation in NAPL Area 1.

Additionally, 163 of the 264 post-ERH soil samples in NAPL Area 1, or 62 percent, were nondetect (ND) for TCE and DCE in the April 2006 soil sampling event.

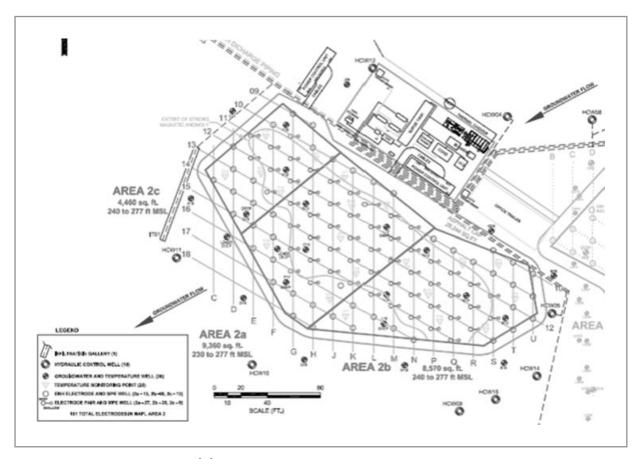


Exhibit 6. NAPL Area 2 map with boring locations

Case Study 2, Fort Lewis, Washington, NAPL Area 2

Site Description

The NAPL Area 2 remediation covered approximately 22,400 ft² with a vertical treatment interval from original grade to 43 feet below grade surface (bgs) in two sections of the site (13,040 ft²) and from original grade to 52 feet bgs in the remaining section (9,360 ft²). The majority of the NAPL Area 2 borings did not exceed a depth of 40 feet bgs, or 239.0 feet above mean sea level (MSL). Borings D15, F17, G13, G15, L12, L16, LC220, and LC221 (Exhibit 6) were drilled to a depth greater than 40 feet bgs to investigate the possible presence of NAPL. Exhibit 6 also shows a 28,244-foot asphalt cap covering the treatment area, which provides a 10-foot perimeter apron to ensure an adequate surface seal for the capture of remediated vapors and steam.

Remediation Design

The subsurface component of the ERH remediation and monitoring system consisted of an initial 22 groundwater monitoring wells (MWs), 10 hydraulic control wells (HCWs), 20 temperature-monitoring points (TMPs), 1 infiltration trench, and 101 electrode locations. The lateral and vertical ERH treatment application resulted in an estimated

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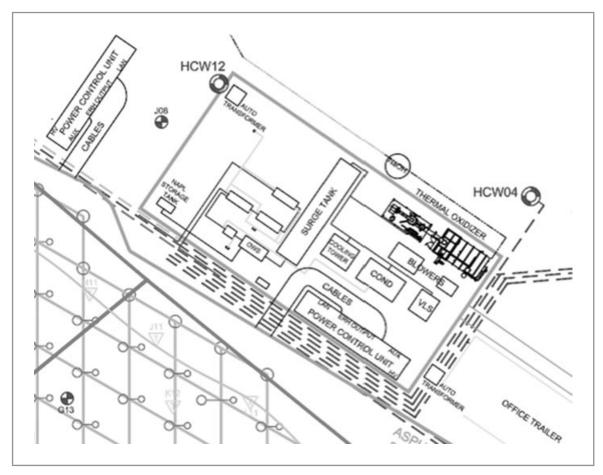


Exhibit 7. Site equipment layout

treatment volume of 36,500 cubic yards. The ERH system was modified during construction to include two additional deep monitoring well locations (designated as LC220 and LC221 in Exhibit 6) to monitor COCs after the observation of NAPL in drill cuttings generated during installation of electrodes in the vicinity. 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.

Prior to system operations, a heat test was performed in NAPL Area 2 from February 7 to 9, 2005. Temperature and groundwater elevations were monitored and the objectives of the heat test were to:

- collect data to determine groundwater flow,
- determine general strategy for ERH and hydraulic control, and
- provide continuous monitoring and evaluation of site data to enable field adjustments during remediation operations.

Operations

System operations began on February 14, 2005, and concluded 172 days later on August 5, 2005. The site layout is shown in Exhibit 7 and includes the following equipment and related components:

- two 2,000 kW Power Control Units (PCUs),
- vapor liquid separator,
- 40 hp and 15 hp vacuum blowers,
- steam condenser and air cooling tower,
- thermal oxidizer and air scrubber,
- oil/water separator,
- surge and air sparge tanks,
- NAPL storage tank,
- office trailer,
- electrodes and co-located multiphase extraction wells,
- temperature monitoring points, and
- electrical cables and conveyance piping.

The vapor-recovery system began operations one week prior to initial power input to the subsurface. This included the MPE components to establish a zone of vapor-recovery influence and enhance the hydraulic control system.

Vapor recovery and MPE were achieved with one 40-horsepower and one 15-horsepower rotary lobe blowers. Vapor flow rate measurements during system operations ranged from 244 to 1,287 cubic feet per minute (cfm), with an arithmetic mean of 490 cfm. Weekly vapor contour figures were based on manual vacuum data collected. These figures were evaluated to ensure that the vapor-recovery system exerted sufficient influence over the NAPL Area 2 treatment volume to recover produced vapors and steam.

Vacuum data were also collected on a weekly basis from 40 piezometer locations across the three NAPL Area 2 subregions. Details regarding the MPE regions are shown in Exhibit 8. The data were documented in raw data tables and used for the calculation and development of the vacuum isocontours shown in Exhibit 9.

The liquid flow rate in the active MPE locations varied throughout the course of operations to assist in the enhancement of hydraulic control. In addition, the overall rate of MPE was monitored and adjusted throughout the remediation. Total MPE liquid flow rates (measured at the vapor/liquid separator and condensers) during system operations ranged from 0 to 50 gpm, with an arithmetic mean of 28 gpm.

The buried metal discovered during certain electrode installations was observed to cause elevated current conditions during operations. As a precautionary matter, these electrodes were removed from the electrical service. Addressing the issue, 56 dual-electrode pairs were installed in the general locations showing the magnetic anomalies identified in Exhibit 10. Each electrode pair consisted of a deep and shallow electrode. The shallow electrodes are 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, 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 than was experienced during the remediation of NAPL Area 1.

The cumulative energy consumption for the project totaled 9,547 megawatt-hours (MW-hrs). This value includes not only energy applied to the subsurface at NAPL Area 2, but also all the vapor treatment equipment, lights, and other electrical equipment on site.

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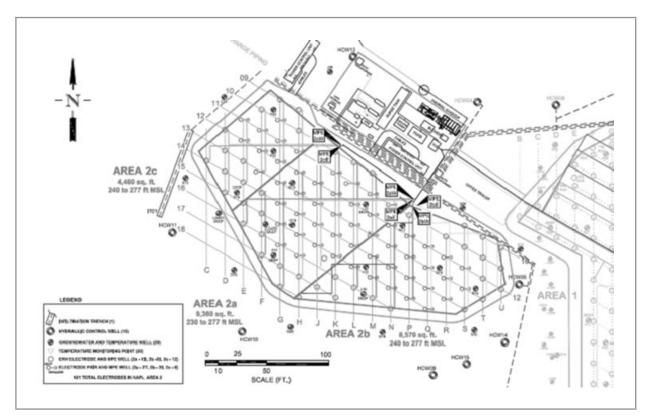


Exhibit 8. MPE regions—NAPL Area 2

A total of 9,181 MW-hrs of electrical energy were applied to the subsurface at NAPL Area 2.

A hydraulic control system was implemented a week prior to operations start-up in NAPL Area 2 utilizing HCW04, 08, 12, 13, and 14 for extraction of clean groundwater upgradient and HCW09, 10, 11, and 15 for injection. The objective of the hydraulic control system was to lower the piezometric head inside the treatment area (as measured in the internal wells) relative to the surrounding groundwater (as measured in the perimeter wells) and flatten the hydraulic gradient within the treatment area. This was accomplished by reducing the head on the upgradient side of the treatment area to level the gradient within the treatment area. Acting on this flattened gradient, the MPE wells further enhanced hydraulic control by lowering the water table within the treatment area.

The hydraulic control scenario was reviewed on a daily basis and adjusted as necessary to maintain a flat gradient across the treatment area. Modifications included altering extraction rates at individual HCWs, changing the function of the wells between extraction and injection, and installing an infiltration trench to maintain the balance while transferring excess groundwater pumped from the hydraulic wells to the on-site stripping tower.

The infiltration trench designated IT01 (Exhibit 11), west of the treatment Area 2c, was installed to assist with site hydraulic control. The trench measured 75 feet long, 5 feet deep, and 3 feet wide. A trench cross-section detail is shown in Exhibit 11.

Groundwater removed by the HCWs and MPE wells was treated to achieve federal maximum contaminant levels (MCLs) in the LWMS and discharged either to

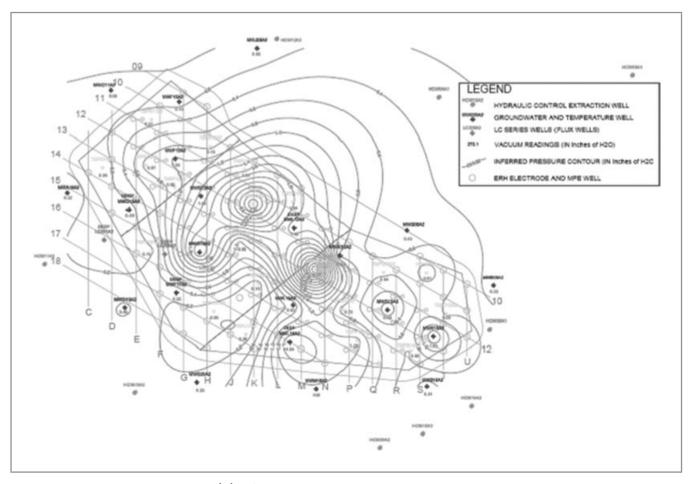


Exhibit 9. NAPL Area 2 vacuum isocontours

downgradient nonpumping hydraulic control wells (injection wells), a downgradient infiltration trench, and/or the far-field infiltration trench system northwest of NAPL Area 2. Additional groundwater pumped from hydraulic wells (beyond the treatment capacity of the LWMS) was transferred to the on-site stripping tower located near NAPL Area 3. Discharging treated water to the downgradient HCWs served to raise the head downgradient of the site, thereby working with the upgradient pumping hydraulic control wells to flatten the gradient within the treatment area.

Because the MPE wells created a number of small cones of depressions internal to the treatment area boundary, the hydraulic gradient measured in internal monitoring wells exhibited an inward gradient from the site boundaries toward the nearest active MPE well(s). The location and radius of influence of the MPE wells was also dependent on the permeability of the stratigraphy in the vicinity of each well. The perimeter monitoring wells were less affected by the hydraulic control system and were used to determine the overall local direction of groundwater movement. The days of operation, maximum sustained yield (based on field performance of the wells), and total volumes extracted from each well during NAPL Area 2 operations exceed the totals removed from NAPL Area 1 (33,873,915 gallons vs. 24,221,147 gallons), reflecting the additional hydraulic control efforts applied.

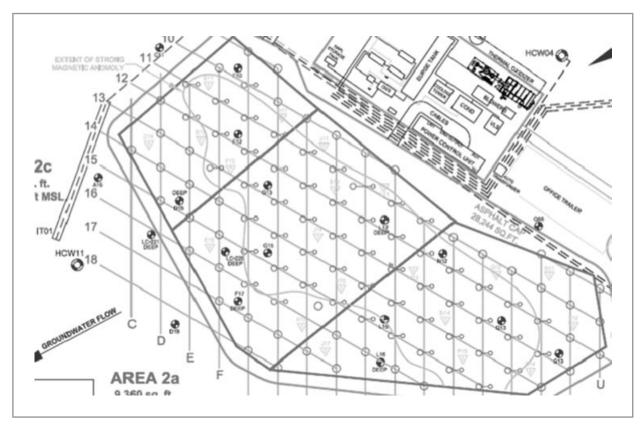


Exhibit 10. Area of magnetic anomalies—NAPL Area 2

Mass Removal

During treatment of NAPL Area 2, data were collected to monitor for *in situ* dechlorination of TCE by periodically measuring groundwater concentrations of TCE, dechlorination products, and geochemical indicators of dechlorination reactions. The data suggest that TCE dechlorination occurred during the heating period as indicated by a significant increase of chloride concentrations and by detection of dechlorination intermediates and indicators of biological activity. These indicators were also independently lab/field tested, and a summary of results is discussed in a subsequent section.

The estimated mass at the site was established in a report prepared in October 2002. Mass estimates were based on the result of early site investigations and did not account for site changes over time or the effect of earlier remediation or intrinsic processes on adjacent areas. Consequently, it is difficult to accurately quantify the NAPL mass removed from Area 2 during the remediation as a percent reduction from the early estimates. Therefore, the total mass-removal quantities presented are based on analytical data and calculations used to derive a mass-removal volume. The following paragraphs provide an overview of the collection points and calculations.

During remediation operations, soil gas, NAPL, water, and steam were extracted from an array of MPE wells and vent points. Upon extraction from the subsurface, the contaminants were separated into a condensate (water) stream and a soil gas (air) stream.

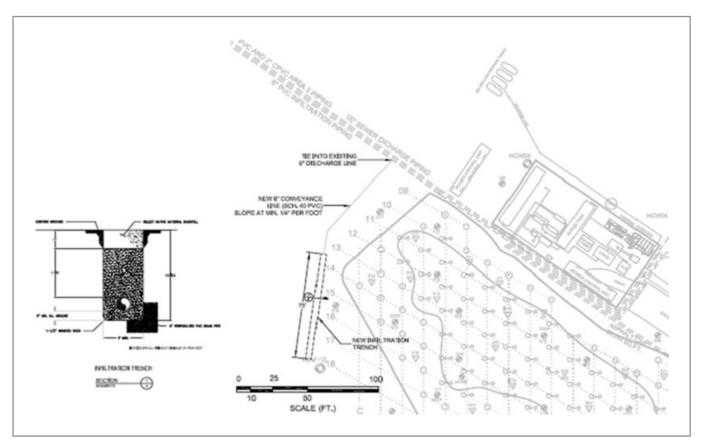


Exhibit 11. Infiltration trench detail layout

Based on the cumulative ERH and vapor recovery, more than 99 percent of the VOCs are recovered in the vapor phase, with only a minor VOC mass being recovered in the liquid phase.

The mass removed in each media type was tracked during operations based on daily and weekly sampling events and presented in Exhibit 12. The cumulative contaminant mass (as tracked by concentrations of chlorinated volatile organic compounds) removed in water totaled 13.826 kg. As shown, the amount of contaminant mass removed in water was negligible in comparison with the mass removed as vapor. The negligible amount in water can be attributed to the elevated temperatures and high soil gas flow rates, which encourage partitioning of contaminants out of the dissolved phase and into the vapor phase (Henry's Law).

The cumulative contaminant mass removed in the soil gas stream totaled 1,340 kg. The contaminants removed from the subsurface during the remediation process were contained and measured in the effluent soil gas stream. Soil gas samples were collected using Summa canisters and they were filled at a single location (OXIN), which was located immediately downstream of the condenser/heater exchange unit (Exhibit 13). Samples were collected on a time-integrated basis, using an eight-hour flow control device. Three samples were generally collected per week during operations. Parameters used to calculate soil gas mass flow rate include: absolute pressure, velocity, head, temperature, relative humidity, barometric pressure, molecular weight of the soil gas, and

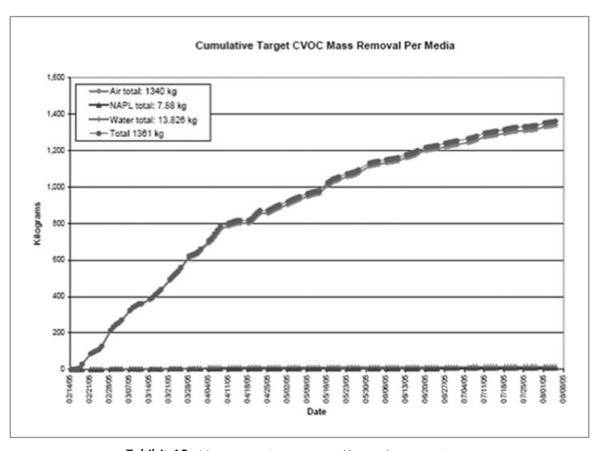


Exhibit 12. Mass contaminant removed by media comparison

cross-sectional area of the pipe. Atmospheric pressure was assumed fixed at 30 inches mercury (Hg) and not measured. Relative humidity and gas molecular weight were also not measured (values considered constants). Soil gas mass flow rate parameters were measured daily each week (excluding holidays) during operations.

The total mass removed from Area 2 during remediation operations was 1,089 kg (approximately four 55-gallon drums) of TCE, 245 kg (approximately one 55-gallon drum) of *cis*-1,2-DCE, and 11,337 kg (approximately 60 55-gallon drums) of TPH. Additional data collected after the operations indicates that additional removal of TCE mass by other *in situ* reactions could range from 20 to 60 percent over the values presented above. The study continues in postclosure operations to refine the mass-removal amounts. In addition to the contaminants, subsurface temperatures and microbial populations are being measured to provide additional information regarding ongoing dechlorination reactions, downgradient temperature movement, and microbial identification.

NAPL Area 2 Groundwater and Soil Results

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. TCE concentrations within the NAPL Area 2 treatment volume

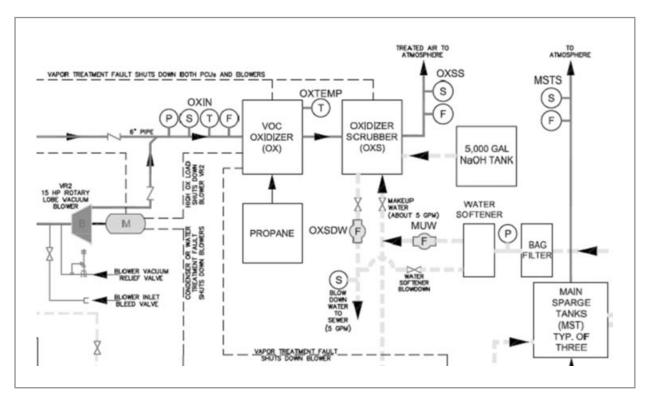


Exhibit 13. OXIN location for soil gas sampling

immediately prior to thermal treatment ranged from 246 to 1,728 $\mu g/L$. During ERH, the concentrations of TCE during the approximate time of peak TCE/DCE concentration in groundwater ranged from 317 to 7,707 $\mu g/L$ within the zone of thermal treatment. Approximately one month after power input to NAPL Area 2 ceased, TCE/DCE concentration within the zone of NAPL treatment ranged from 6 to 188 $\mu g/L$.

Beginning TCE concentrations in soil inside NAPL Area 2 were typically higher than TCE concentrations in NAPL Area 1, while *cis*-1,2-DCE concentrations in soil were lower in NAPL Area 2 than in Area 1.

Pre-ERH soil samples were collected and analyzed for TCE and DCE concentrations from six boring locations inside NAPL Area 2. The samples were collected from 4 to 25 discrete depth intervals from the soil borings. A total of 98 pre-ERH soil samples were collected. In the pre-ERH soil samples, the average TCE and DCE concentrations were 202,338 $\mu g/kg$ and 5,130 $\mu g/kg$, respectively.

Post-ERH soil samples were collected in April 2006, nearly eight months following shutdown. A total of 276 post ERH soil samples were collected from approximately the same boring locations that were sampled during the pre-ERH event. In addition to the original 98 depth discrete samples during the pre-ERH soil sampling event, an additional 178 depth intervals were sampled during the post-ERH sample event. The average TCE and DCE concentrations in the post-ERH soil samples were 28 $\mu g/kg$ and 58 $\mu g/kg$, respectively. This represents a reduction of 99.99 percent and 98.88 percent for TCE and DCE respectively, approximately eight months after treatment. Exhibit 14 illustrates the reduction in TCE concentrations in soil eight months following the completion of ERH in NAPL Area 2.

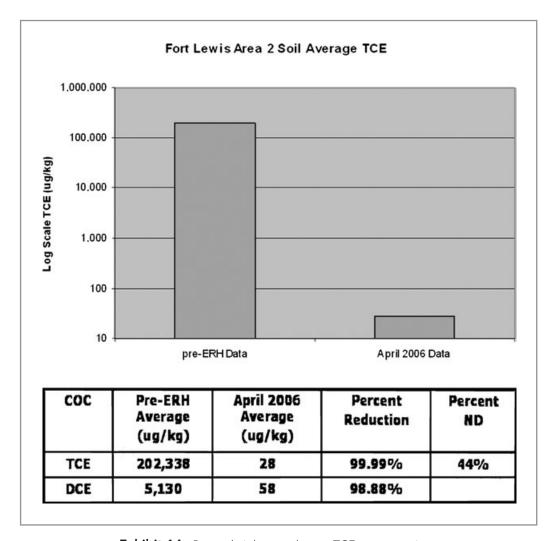


Exhibit 14. Pre and eight-month post-TCE concentrations

Additionally, 117 of the 276 post-ERH soil samples in NAPL Area 2, or 42 percent, showed nondetect concentrations of TCE and DCE in the April 2006 soil sampling event.

In Situ Dechlorination Laboratory and Field Test at Fort Lewis

The Pacific Northwest National Laboratory conducted additional experiments with cooperation from Thermal Remediation Systems and the U.S. Army Corps of Engineers using sediment samples and during ERH treatment at the Fort Lewis East Gate Disposal Yard. The goal of the concurrent study was to examine the TCE dechlorination as a function of temperature (ambient vs. approximately 70°C) as the aquifer was heated to temperatures approaching the boiling point of water during ERH.

Sediment and groundwater samples were collected prior to ERH treatment and used in the laboratory microcosm studies. Details of the laboratory studies are presented by Truex (2003) and Truex et al. (2007). The laboratory results are summarized below:

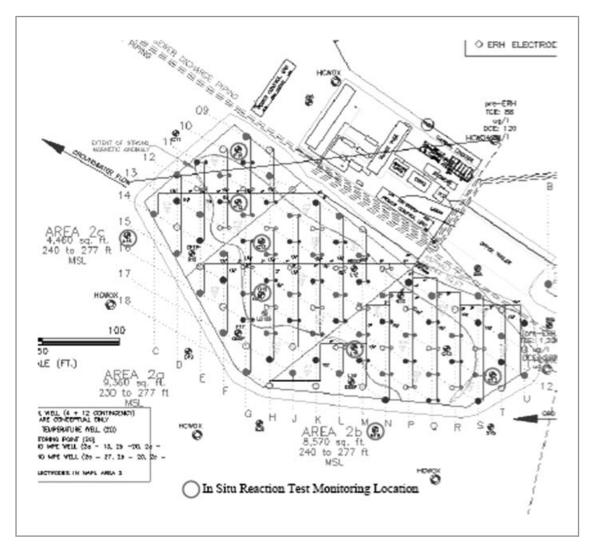


Exhibit 15. Laboratory and field-test zone with monitoring locations

- TCE dechlorination was observed in all active treatments.
- The dechlorination products and rate of transformation changed as a function of temperature.
- Abiotic degradation was shown in the 70°C treatments.
- A reductive dechlorination pathway for TCE was shown in the 10°C treatments.

The heated zone and six monitoring locations for the study are shown in Exhibit 15. The field test for *in situ* reactions was conducted by measuring the groundwater concentrations of reactants, products, and geochemical indicators for potential TCE dechlorination reactions. Details of field study results are provided by Truex et al. (2007). Indicators of *in situ* dechlorination and biological reactions were observed at elevated temperatures during the field test, which were analogous to the laboratory test results and are summarized below:

 Chloride concentrations increased over time and are a potential indicator of dechlorination during the field test.

- Acetylene, an indicator of abiotic TCE dechlorination by reduced iron processes, and ethane, a product of both biotic and abiotic dechlorination, was observed at elevated temperatures.
- Methane, an indicator of anaerobic biological activity, was observed at elevated temperatures.

In summary, the laboratory microcosms with Fort Lewis sediments showed TCE dechlorination at 70°C with measured products of acetylene, ethene, and ethane, indicating an abiotic component of the degradation.

In summary, the laboratory microcosms with Fort Lewis sediments showed TCE dechlorination at 70°C with measured products of acetylene, ethene, and ethane, indicating an abiotic component of the degradation. In contrast, TCE was dechlorinated to cis-1,2-DCE in experiments at 10°C, likely by biological reductive dechlorination. The observed products at 70°C suggest dechlorination catalyzed by reduced sediment iron. Indications of in situ dechlorination were also observed in periodic groundwater samples collected during field-scale ERH from an average ambient temperature of about 19°C to near boiling. Dechlorination indicators included an increase in chloride concentration at the onset of heating and observation of acetylene, ethene, and methane at elevated temperatures. The data collected in this study suggest that dechlorination can occur during ERH. The overall cost-effectiveness may be enhanced by this in situ dechlorination and, potentially, can be further enhanced by specifically designing and operating ERH to maximize in situ dechlorination.

SUMMARY

In summary, the success of the ERH remediation in NAPL Areas 1 and 2 include:

- greater than an average 99 percent reduction in TCE concentrations in groundwater 10 months following ERH in NAPL Area 1;
- average TCE reductions in soil of 99.97 percent and 99.99 percent in NAPL Areas 1 and 2, respectively;
- 62 percent and 42 percent of soil samples were ND for TCE and DCE in NAPL Areas 1 and 2, respectively;
- groundwater data indicate surgical treatment in both areas;
- data suggest potentially significant in situ destruction of contaminants in both areas;
 and
- no foreseeable rebound in NAPL Areas 1 or 2 based on bio-geochemical data.

CONCLUSIONS

Lessons learned during previous operations performed in NAPL Area 1 were applied in the Area 2 remediation to achieve the desired subsurface heating objectives and, overall, allowed for a total shorter operations period.

The site-specific anomalies in the NAPL Area 2 included: the unexpected flow of cool water through high hydraulic conductivity zones, which lengthened the duration of treatment; a nonroutine minor equipment failure associated with electrical power application contributing to an extended operational period; and the suspected buried metal debris.

The ERH system design flexibility allowed modifications to enhance its effectiveness during the NAPL Area 2 remediation as a result of both Area 1 lessons learned and the anomalies encountered during ERH in Area 2.

Based upon review of all data collected concerning NAPL Area 2, it was determined that treatment in several portions had reached a point of diminishing return, and power was discontinued without the risk of recontamination. The subsequent discontinuation of power at the specified locations allowed the ability to focus power at specific locations to enhance the COC mass removal in remaining locations.

Aspects of both NAPL Area 1 and Area 2 remediation will be implemented for phase three (NAPL Area 3) remediation. These include: hydraulic control (to offset hydrogeology influences); electrode construction (flexibility to remove sections offline as remediation goals are achieved and utilizing dual-electrode pairs to remove vadose zone overcurrent conditions while keeping power online); and reconfiguring soil vapor piping to allow for more accurate air flow measurements, resulting in more accurate mass-removal estimates.

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