



ENHANCED REMOVAL OF SEPARATE PHASE VISCOUS FUEL BY ELECTRICAL RESISTANCE HEATING AND MULTI-PHASE EXTRACTION

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ABSTRACT

A floating hydrocarbon plume at a manufacturing facility in a metropolitan area located in the southeastern part of the U.S. was remediated using Electrical Resistance Heating (ERH) and Multi-Phase Extraction (MPE). The hydrocarbon was a specialty fuel similar to kerosene or diesel fuel. Initially, hydrocarbon covered an area of 4900 ft² (500 m²) and was up to 10 ft (3 m) thick, with most wells containing 1-3 ft (0.5-1 m) of hydrocarbon. Most of the floating hydrocarbon was beneath the manufacturing building. The soil from the floor to a depth of about 50 ft (15 m) is composed of sandy clay saprolite with moderately low permeability and high heterogeneity. The static water table is about 24 ft (7 m) below grade. Remediation began on 27 May 1999. Remediation to less than 1/8-inch (4 mm) hydrocarbon was completed on 10 December 1999. The ERH and MPE system relied on several mechanisms to remove hydrocarbon: 1) heating to reduce hydrocarbon viscosity, 2) hydrocarbon floatation/agitation by rising steam bubbles, 3) thermally enhanced vaporization (fuel boiling), and 4) vacuum-enhanced pumping.

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Background

The site was a former manufacturing facility. A large release of a specialty fuel occurred from a hydrocarbon pipeline where it passed beneath the exterior facility wall. The plume was composed of a specialty fuel with boiling point (228°C) and viscosity (2 mm²/s St) between those of jet fuel and diesel fuel.

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Technology Selection

Conventional product pumping or MPE can be used to remove such fuels; however, these processes are impeded by soil heterogeneity, hydrocarbon interfacial tension, and low fuel vapor pressure. Thus, conventional in-situ techniques would typically require in excess of one year of operation and have a greater chance of later hydrocarbon rebound. ERH is an electrical heating technology that uses in situ resistance heating and steam stripping to accomplish subsurface remediation.

ERH was originally developed by the oil industry to enhance the production of viscous crude oil from pumping wells. ERH uses electrodes that are installed like wells to direct the flow of electrical current through the subsurface soil and rock. The flow of electrical current through the subsurface heats the soil and groundwater directly and uniformly. In the 1990s, ERH was adapted for environmental purposes. The technology has now proven capable of remediating both dense and light non-aqueous phase liquids (DNAPL and LNAPL) from both the vadose and saturated zones, regardless of permeability or heterogeneity.

The ERH Power adjusts conventional 60- from standard utility voltage for subsurface volts). The electrical throughout the by vertical, angled, or using standard drilling



Control Unit (see Figure 1) hertz three-phase electricity power lines to the proper heating (typically 150-450 current is then delivered subsurface treatment volume horizontal electrodes installed techniques.

Figure 1. 500 kW PCU

A standard computer controls the operational status of the ERH PCU and monitors the temperature conditions in the subsurface. Operations personnel can access these computers and control the PCUs either directly or remotely by phone line.

ERH increases subsurface temperatures to the boiling point of water. The technology is equally effective in the vadose and saturated zones. Because the ERH electrodes are electrically out of phase with each other, electrical current flows from each electrode to all of the other out of phase electrodes adjacent to it. In this manner, a volume of subsurface surrounded by ERH electrodes is saturated by the electrical current moving between the electrodes. It is the resistance of the subsurface to this current movement that causes heating.

All soils in the treatment region are heated; however, 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 ion content. As dense compounds sink through the lithology, they tend to become trapped on these same silt and clay lenses (see Figure 2). Over time, trapped solvents undergo biological dehalogenation producing daughter compounds and free chloride ions. Thus, at chlorinated hydrocarbon sites, the most impacted portions of the subsurface are also the low resistance electrical pathways that are preferentially treated by ERH. In a similar fashion, rock fractures and weathered rock are more electrically conductive, and heat faster, than competent rock. Thus, low permeability soils, bedrock fractures, and solvent hot spots heat, and clean up, slightly faster than other soils.

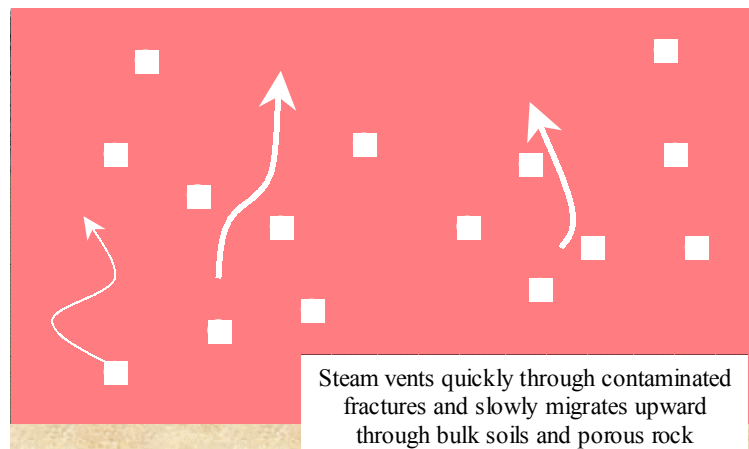
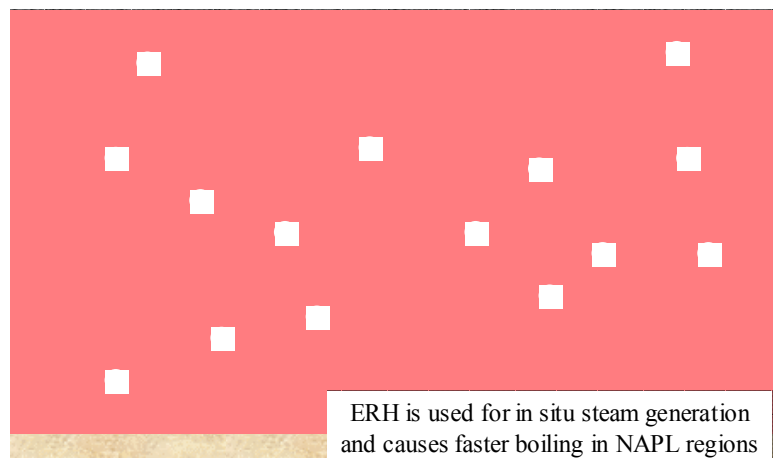
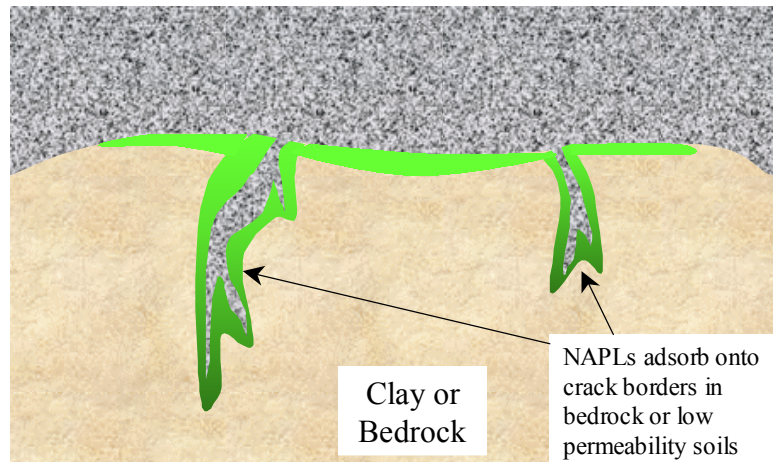


Figure 2.
Insitu
Steam
Generation

By increasing subsurface temperatures to the boiling point of water, ERH speeds the removal of contaminants by two primary mechanisms: increased volatilization and steam stripping. As subsurface temperatures begin to climb, contaminant vapor pressure, and the corresponding rate of contaminant extraction, increases by a factor of about 25. However, it is the ability to produce steam in situ that represents a significant advantage of ERH. 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 the MPE wells (Figure 4, below).

At the surface, a condenser separates the mixture of soil vapors, steam, and contaminant liquids which is extracted from the subsurface into condensate and contaminant laden vapor. If these waste streams require pre-treatment before discharge, standard air abatement and water treatment technologies are used (Figure 3).

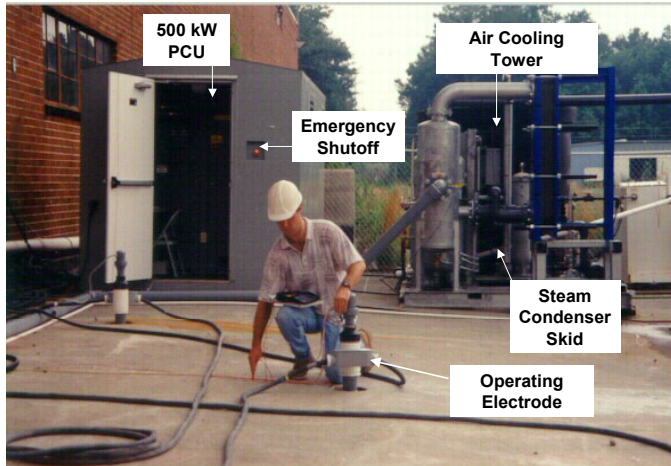


Figure 3. Equipment Staging and Voltage Checks

ERH and MPE System Installation

The impacted region inside the facility had low ceilings, 11 ft (3.3 m) high. The low ceilings required the use of special limited-access drilling equipment that could not turn large diameter augers. For this reason, smaller, but more numerous electrode/wells were installed than is most commonly used for ERH.

The electrode/wells were installed in 8-inch (200 mm) boreholes. A 2-inch (50 mm) steel casing and screen were inserted; this casing served as both as an electrical conductor and as a conduit for hydrocarbon extraction. A backfill of steel shot was used as the well gravel pack and electrode conductive region. The borehole above 22 ft (6.5 m) was backfilled with neat cement grout (Figure 4).

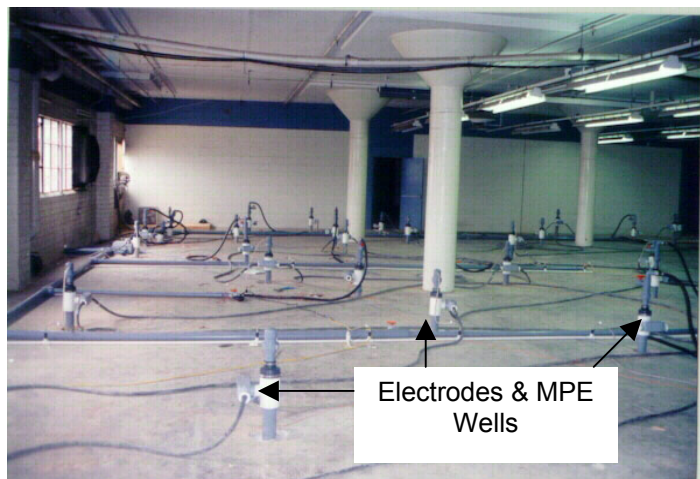


Figure 4. Electrodes & MPE Wells Inside Building

A total of 50 combination extraction/monitoring wells and ERH electrodes were installed. The electrodes directed electrical heating into the region from 20 to 30 ft (6 to 9 m) below grade. The wells extracted hydrocarbon and vapor from 22 to 27 ft (6.5 to 8.5 m) below grade.

A positive displacement vacuum blower was used to apply a vacuum to the subsurface. Vapor and steam flow from the wells passed through a steam condenser to cool the vapor and remove steam. A thermal oxidizer destroyed hydrocarbon vapors before emission to the atmosphere. An oil-water separator was used to remove separate phase hydrocarbon from the condensed steam and extracted groundwater. Most of the liquid hydrocarbon was pumped to the oxidizer for destruction. Extracted water was used to cool existing PVC monitoring wells.

ERH and MPE Operations

Upon start-up of the ERH system, an extensive voltage survey was performed to ensure that no hazardous voltages were present at the surface. We use a standard of less than 15 volts in areas that are accessible to personnel.

Usually, a well/electrode was alternately used for either heating or for extraction; however, well/electrodes occasionally performed both functions simultaneously to optimize hydrocarbon removal. Typically, 11 inches of mercury vacuum (0.35 bars absolute) was applied to the extraction wells, resulting in a vapor extraction rate of about 12 scfm (20 m³/hr) per well and a liquid (groundwater/fuel) extraction rate of about 0.25 gpm (1 l/min) per well.

Remediation began on 27 May 1999. Remediation to less than 1/8 inch (4 mm) hydrocarbon was completed on 10 December 1999. The system utilized several mechanisms to remove hydrocarbon: 1) heating to reduce hydrocarbon NAPL viscosity, 2) steam bubble floatation and hydrocarbon agitation by rising steam bubbles, 3) thermally enhanced vaporization (fuel boiling), and 4) vacuum-enhanced pumping. The relative importance of each is shown in Figure 5:

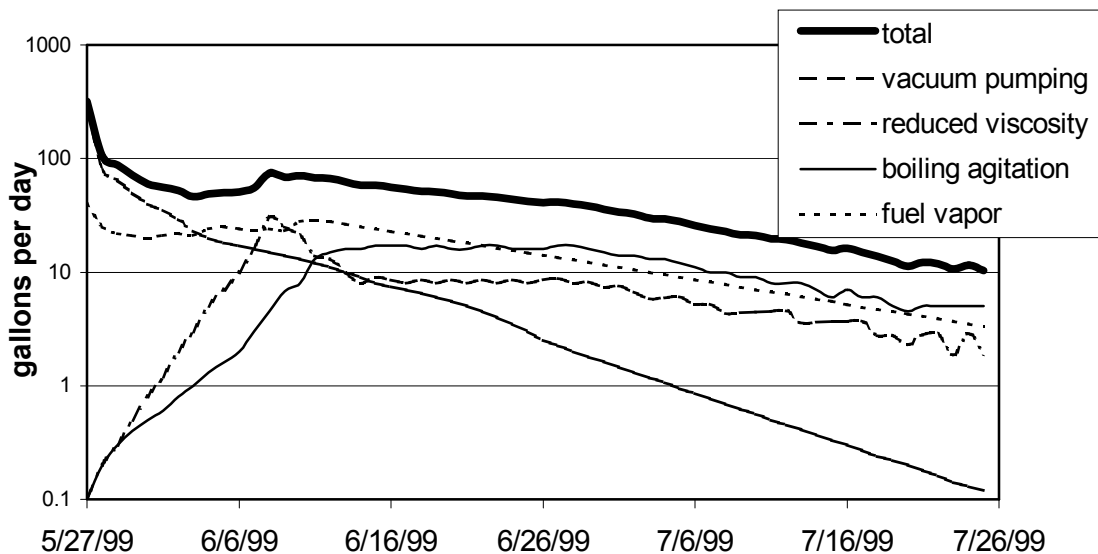


Figure 5. Estimated Hydrocarbon Removal by Mechanism

Prior to beginning remediation, the importance of steam generation as a NAPL removal mechanism was not properly appreciated. It is now theorized that a large fraction of NAPL can be held in the soil formation as dispersed droplets, often below the water table (see Figure 6).

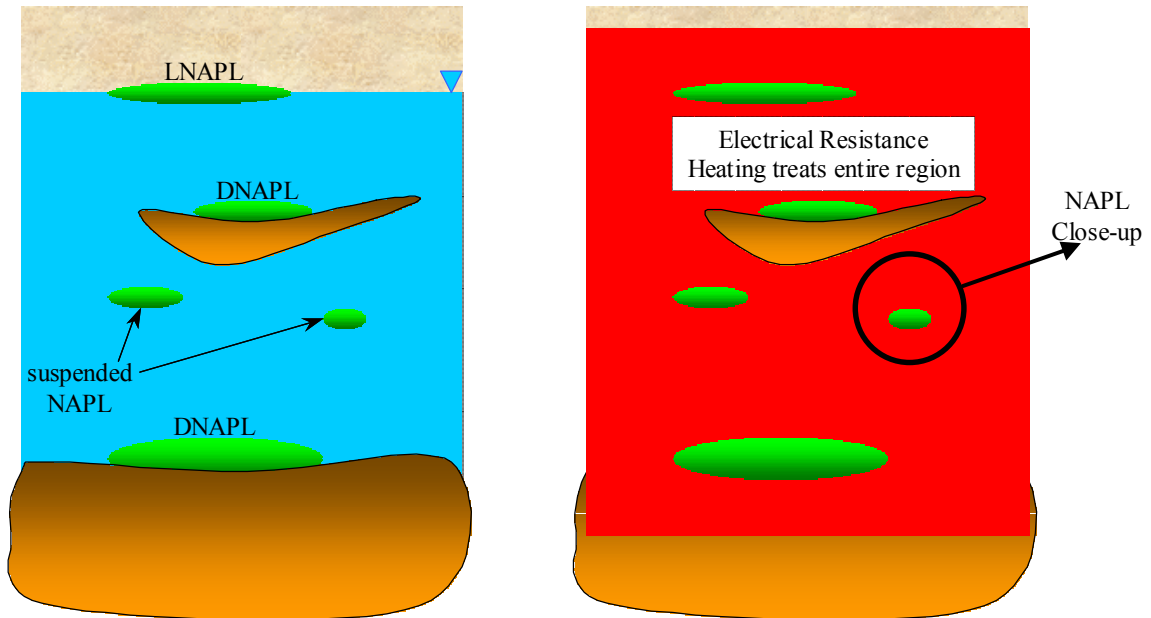


Figure 6. Typical NAPL Distribution in the Subsurface

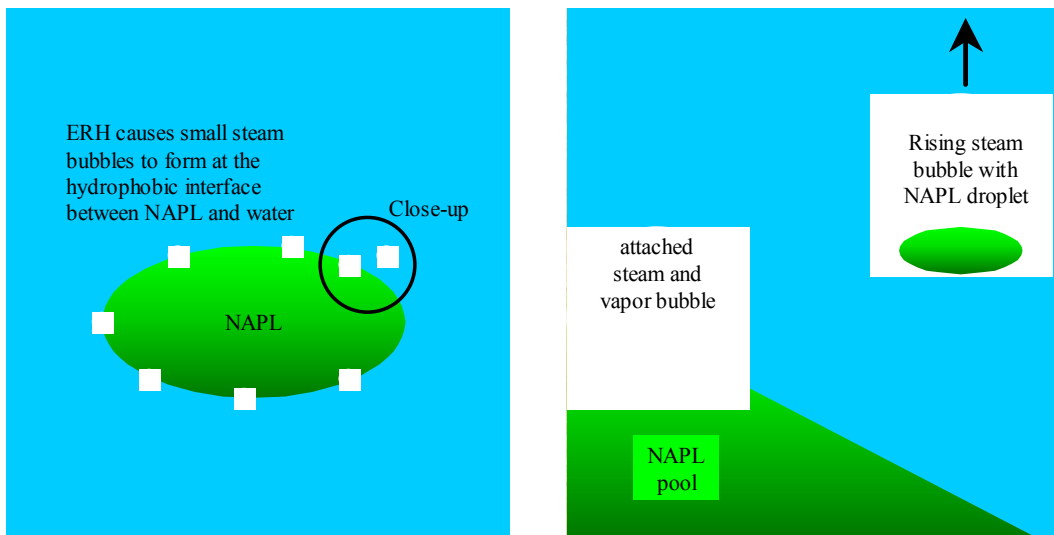


Figure 7. Steam Bubbles Increase the Effective NAPL Buoyancy

These droplets are not strongly influenced by conventional pumping or multi-phase removal techniques. However, during ERH, small steam bubbles are formed throughout the

remediation volume. Some of these bubbles collect at the water/NAPL interface due to surface tension, increasing the effective NAPL buoyancy. This increased buoyancy, in conjunction with the agitation provided by the rising steam bubbles, greatly increases the upward migration rate of the small NAPL droplets that were trapped below the water table (see close-up Figure 7).

At the water surface, the hydrocarbons coalesce into a separate layer that can be removed by pumping. Once at the water surface, the agitation provided by the rising steam bubbles once again reduces the hydrocarbon effective viscosity and increases the rate of hydrocarbon flow toward the extraction wells.

Conclusion

A separate phase viscous hydrocarbon plume was reduced from a thickness of 10 ft (3 m) to less than 1/8 inch (4 mm) in six and a half months of ERH operations coupled with MPE. ERH enhanced product removal by the expected mechanisms: enhanced vapor recovery and reduced product viscosity. However, with steam generated in situ, the product removal was also enhanced by an unexpected mechanism, steam bubble floatation and agitation.

Occasionally, the temperature variations in the NAPL physical characteristics (viscosity, density, interfacial tension) indicate that little remedial benefit should be expected in heating the NAPL above 80°C. However, the strong NAPL recovery enhancement offered by steam bubble floatation and agitation generally makes NAPL recovery more cost effective if the NAPL remediation volume is heated to the boiling point of water - even if the NAPL physical characteristics indicate that more limited heating would be sufficient.