Electrical Resistance Heating
Technology Screening Report
Solvents Recovery Service of New England

Thermal Remediation Services, Inc. prepared this technology screening report for Tetra Tech NUS, Inc. (TtNUS) under subcontract S04-RAC1-292. The purpose of the report is to assess the viability of electrical resistance heating (ERH) for the treatment of pooled and residual non-aqueous phase liquid (NAPL) in the saturated overburden unit at the Solvents Recovery Service of New England (SRSNE) Superfund Site in Southington, Connecticut.

The pertinent site-specific information provided by TtNUS concerning geology, hydrogeology, the nature and extent of NAPL in the overburden groundwater unit, and fate and transport was reviewed as part of the evaluation process. Additionally, this information was compared with the characteristics of a very similar site where ERH has been successfully used to reach remediation goals comparable to those set for the SRSNE site.

ERH is a very applicable technology for the removal of NAPL from the saturated overburden at the SRSNE site. Remedial goals for the overburden can be achieved within a year using ERH without the risk of NAPL migrating from the overburden into the underlying bedrock. The technology has been proven as a reliable process with respect to the site contaminants and conditions, can be installed and operated at the site without impacts to human health or the environment, and is commercially available. Thermal remediation technologies may be a high cost remediation alternative, but may represent the only *in situ* option that can achieve the site remediation goals in a reasonable time frame.

SRSNE Site Description

The site geology consists of silty, fine to medium-grained sand with minor amounts of gravel (the outwash) that extends to an approximate depth of 16 feet below grade surface (bgs). The outwash is underlain, in most of the treatment area, by a three to six-foot thick till consisting of fine to medium sand with silt, that rests on several feet of weathered bedrock.

The geometric mean hydraulic conductivity of the outwash has been estimated as 2×10^{-3} centimeters per second (cm/sec). The geometric mean hydraulic conductivity of the till has been estimated as 6×10^{-4} cm/sec.

Groundwater is presently located about 6 to 10 feet bgs. The flow direction is generally upward and toward the Quinnipiac River. The existing groundwater containment system operates at an average extraction rate of approximately 12 gpm; if this extraction rate is just sufficient to achieve capture then the average native groundwater flow rate is approximately 0.6 feet per day – too slow to be significant from a thermal remediation perspective.

The principal contaminants of concern in the overburden are primarily chlorinated solvents and aromatic compounds which are co-mingled with fuel hydrocarbons to form a NAPL mixture that is near neutral buoyancy.

The desired treatment region extends from approximately 2 feet bgs to the base of the till layer at approximately 20 feet bgs. The treatment region has an area of about 63,500 square feet and a volume of 42,000 cubic yards.

Thermal Treatment Process Options

As described in the SRSNE Feasibility Study (FS), there are several methods of *in situ* thermal treatment, including steam injection, electrical resistance heating (ERH), and thermal conduction heating. In most cases, only one *in situ* thermal method is used at a given site. The SRSNE desired treatment interval is rather thin (less than 20 feet) and it is more difficult and expensive to construct and implement two different heating techniques in such a thin zone. As a result, the use of a single heating method is preferred for the SRSNE site.

It is desired to treat both the outwash and the till. The treatment region is heterogeneous, with varying hydraulic conductivity. These conditions favor ERH over steam injection as the method of thermal treatment because ERH generates heat and steam throughout the target lithology, without regard to hydraulic conductivity. ERH is the most mature and widespread thermal treatment method for volatile organic compounds (VOCs), especially VOCs found in saturated lithologies.

ERH Description

ERH is an *in situ* remediation technology that uses the heat generated by the resistance of the soil matrix to the flow of electrical current to raise subsurface temperatures. ERH has been demonstrated as an effective technology for the removal of volatile and semi-volatile contaminants from both soil and groundwater and ERH is equally effective in saturated and unsaturated soils. Subsurface heating may be used for a variety of remedial purposes including contaminant volatilization, *in-situ* steam stripping, enhancing soil vapor extraction efficiency, and increasing biological degradation and chemical dechlorination reaction rates.

To implement the technology, electrodes are placed into the ground so that they are spaced throughout a targeted contaminated region. Electrodes also serve as vapor recovery or multi-phase extraction wells and are most commonly installed by conventional drilling techniques. However, electrodes can also be installed by pile driving and the SRSNE is amenable to that technique based on the previous installation of the sheet piling wall. The use of pile electrodes at the SRSNE site could represent an opportunity for significant cost savings.

The ERH electrodes conduct electrical current into the subsurface and are designed to input electrical energy at the targeted depth interval. The electrodes do not get hotter than the rest of the site; it is the passage of electrical current between the electrodes that uniformly generates the heat in the soil itself.

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 *in situ* steam stripping of VOC contaminants from groundwater and the soil matrix. 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.

Vapor Recovery

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 are recovered by a vapor recovery or multiphase extraction (MPE) system. The predominant contaminants of concern at the SRSNE site are VOCs; however, there are also fuels and other compounds of lower volatility present. For this reason, an MPE system would be used to remove steam, VOC vapors, groundwater and liquid hydrocarbons simultaneously from the wells. As a cost-effective measure, the MPE wells are co-located with the electrodes.

Once steam and volatile contaminants have been collected by the MPE system, the steam is condensed to water and the vapor stream is cooled to near ambient temperatures. The condenser is a good application of Henry's Law: although the steam condenses, less than one percent of the VOCs will condense and become dissolved in the condensate. The extracted air and VOC vapors are treated by conventional vapor abatement technologies such as thermal oxidation.

Water Treatment

A low flow rate of groundwater is extracted from the MPE wells to "skim" low volatility fuel hydrocarbons off the surface of the water table. At the SRSNE site, approximately 10 gallons per minute (gpm) of groundwater would be extracted in liquid form in addition to the removal of about 5 gpm in the form of steam. The combined total of about 15 gpm passes through an oil-water separator and is then directed to the existing water treatment system. Based on theoretical calculations and previous experience, less than one percent of the extracted VOC mass would be sent to the water treatment system.

As the treatment area is cleaned, contaminant concentrations in the recovered soil vapors decrease. When these concentrations decrease to a low level, ERH is stopped. Post-remedial sampling can then be conducted to determine if the cleanup objectives for soil and groundwater have been achieved. For most ERH remediation projects, the duration of heating is less than one year.

ERH accelerates VOC remediation by the following principal mechanisms:

- ERH increases subsurface temperatures beyond the boiling point of most VOCs, causing them to transition to the vapor phase and rise upward to the MPE system in the vadose zone above the heated region.
- ERH boils a portion of the water in all soil types, regardless of permeability. The resulting steam sweeps VOC vapors out of low permeability soil lenses and carries them upward to the MPE system.
- As subsurface temperatures rise, the rates of naturally occurring biological activity and chemical reactions that cause *in situ* dechlorination are dramatically increased.

Dalton's Law of Partial Pressures

The boiling points of the main targeted contaminants at the SRSNE site are near the boiling point of water (100 degree Celsius (°C) at sea level pressure conditions). It should be noted that when a VOC is immersed or dissolved in water, 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 are 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, followed by dissolved VOCs, and finally, uncontaminated groundwater. This order is advantageous for remediation since contaminated water will tend to boil off before uncontaminated water, reducing the time and energy required to complete treatment. All boiling points increase with pressure, so higher temperatures are required to create boiling conditions with increasing depth below the groundwater table. The effects of depth on the boiling points of the targeted contaminants are summarized below in Table 1 for the SRSNE site where the groundwater table is located at approximately eight feet bgs.

TABLE 1.
The Effect of Depth Below Groundwater on Boiling Temperatures

Compound	Boiling Temperature of Compound		
	In Air (°C)	In Water at 8 feet bgs (°C)	In Water at 18 feet bgs (°C)
pure water	100	100	107
pure trichloroethylene (TCE)	87	73	89
pure perchloroethylene (PCE)	121	88	104
pure toluene	110	84	92
MWD-601 NAPL*	96	78	85
RW-5 NAPL*	96	78	85
MW-705DR*	94	77	85

* A mixture of VOCs will boil at an intermediate temperature, in proportion to the fraction of each in the liquid mixture. The calculated VOC mixture boiling temperature shown here is based on NAPL samples reported in Table 5 of the Remedial Investigation.

Other In Situ Treatment Process Enhancements resulting from ERH Application

Although volatilization is usually the primary removal mechanism for VOCs, a significant fraction of the VOCs will be degraded in place by other *in-situ* processes including biodegradation, hydrolysis, and reductive dehalogenation by zero valent iron.

Biodegradation

The biodegradation of chlorinated VOCs is most commonly observed as an anaerobic process. Thermophilic (heat-loving) bacteria degrade chlorinated VOCs at a much faster rate than is typically observed under ambient temperature conditions. This mechanism is especially important at sites where relatively high levels of total organic carbon (TOC) or non-chlorinated hydrocarbons provide a carbon source for co-metabolism.

When soils with high levels of TOC are heated, some portion of the carbon will convert to acetone. Acetone is a VOC, but it also provides an easily biodegradable co-metabolic food source for reductive dechlorination by soil microbes. When ERH remediation is completed, any acetone generated will provide a polishing effect on residual chlorinated compounds and concentrations less than 500 mg/l will rapidly biodegrade to non-detectable levels as the site cools to ambient conditions (US DHHS, 1994).

Hydrolysis

Hydrolysis is a chemical substitution reaction in which hydrogen ions in water react with organic molecules, replacing chlorine atoms. Oxidizing conditions or available oxygen are not required for hydrolysis. Hydrolysis can be a significant degrader of some VOCs at room temperature; especially for halogenated alkanes. The rate of hydrolysis increases with temperature and clay soil types tend to accelerate hydrolysis. An example hydrolysis pathway is: TCA → 1,1-DCE or ethene (mineralization).

Dehalogenation

The backfill of an electrode includes 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 an iron-filing remediation wall. Reductive dehalogenation is not likely to be a large mechanism for VOC mass removal at the SRSNE site, however, the presence of iron in the electrode boreholes might 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.

The components required to implement ERH are:

- Electrodes with integral MPE wells and steam vents,
- Steam and soil vapor recovery system, including piping, a blower, and a condenser,
- A vapor treatment system including a thermal oxidizer and an acid gas scrubber,
- ERH power control unit to condition power for application to the subsurface,
- Data acquisition systems and a computer control system for continuous remote control of power.

Effectiveness Evaluation of ERH for the SRSNE Site

ERH has been successfully used in flowing aquifers with hydraulic conductivities of about 1 cm/sec and in tight clay vadose zones with hydraulic conductivities of less than 1×10^{-8} cm/sec. ERH has also been successfully deployed at sites with heterogeneous and "stacked" lithologies where the hydraulic conductivities throughout the treatment volume have varied by several orders of magnitude. The SRSNE site has moderate permeabilities and the information available about the lithology or water saturation at the site indicates the area is well within the parameters that ERH has successfully treated.

ERH has been successfully applied at depths approaching 100 feet bgs and at treatment areas and volumes equal to or larger than those proposed for the SRSNE site. The thickness of the treatment volume, approximately 20-feet, is well suited for ERH remediation. There will be no negative impacts to human health or the environment during the construction and implementation phases of the ERH remediation other than those associated with common subsurface drilling, asphalting, and light construction activities. The ERH and effluent processing equipment is operated in a manner that adheres to noise and pollution release standards.

The main contaminants of concern at SRSNE are VOCs that are amenable to thermal remediation as described above. Multi-phase extraction would also be used to remove lower volatility fuel hydrocarbons and polychlorinated biphenyls (PCBs) in liquid form; however, the removal rates of semi-volatile organic compounds (SVOCs) and PCBs would be less than that of the VOCs. ERH would have essentially no effect on metal contamination.

ERH is capable of remediating the overburden soils to the Connecticut Preliminary Remediation Goals (PRGs) for VOCs. However, neither ERH nor any technology can remediate the overburden groundwater to the Connecticut PRGs due to contaminated groundwater that flows up from the bedrock.

Although soil VOC PRGs are directly attainable by ERH, reaching that remediation goal with ERH would probably be a waste of resources due to the issue of contaminant reflux from the underlying bedrock. A more reasonable goal would be to reduce the overburden VOC concentration and mass to the point at which its health risk is negligible in comparison to bedrock contamination and the potential for further NAPL migration to bedrock is insignificant. This presumably reasonable goal can be accomplished by using ERH to reduce the overburden VOC mass by about 90%. Residual heat and its ability to enhance the biodegradation of chlorinated VOCs would further reduce contamination levels in subsequent years. Given the known site conditions, a 90% VOC mass reduction in the overburden is an easily achievable goal for ERH.

This remediation approach will ensure the removal of NAPL from the overburden soils and reduce groundwater contaminant concentrations in the overburden to below concentrations found in the bedrock. The potential for NAPL migration will be eliminated, the size of the highly contaminated groundwater plume will be significantly reduced, and the time frame that groundwater standards are exceeded will be shortened considerably.

Based upon site-specific conditions and previous applications of ERH, TRS does not anticipate downward migration of NAPL from the overburden unit into the bedrock to be a concern during remediation. TRS does not recommend the use of a thermal barrier or "hot floor" at the site and this issue is further discussed in Appendix A of this report. In the short-term, no impact on bedrock contamination, either positive or negative, is expected. Over the long term, concentrations of contaminants in the bedrock are expected to decrease because

NAPL migration from the overburden will cease and natural attenuation processes will then be greater than the rate of source introduction.

Implementability Evaluation of ERH for the SRSNE Site

The SRSNE site is very similar to an operating ERH remediation site at Fort Lewis, near Tacoma, Washington. The Fort Lewis site consists of three remediation areas, each measuring approximately 25,000 square feet with a treatment volume of about 30,000 cubic yards. Like the SRSNE site, geology at the Fort Lewis site consists of an outwash material overlaying a till. At the Fort Lewis site, hydraulic conductivities range from a geometric mean of 3.5×10^{-2} cm/sec in the outwash to a geometric mean of 4.1×10^{-5} cm/sec in the till. The till layer is encountered at approximately 35 feet bgs and the depth to groundwater is about 10 feet bgs. The Fort Lewis site also has a mix of solvents and fuels, forming NAPL of near neutral buoyancy. For both the SRSNE site and the Fort Lewis site, the remediation goal is to reduce the mass of the NAPL to a point that will allow thermally enhanced bioremediation and natural processes to complete restoration. That goal has been achieved at Ft. Lewis Remediation Area 1 and the ERH system is now being deployed at the Remediation Area 2.

The principal difference between the two sites is that the Fort Lewis site has a native groundwater flow velocity of 5 to 10 feet per day, which must be reduced by a hydraulic control system for effective and energy-efficient heating. The Fort Lewis site also appears to have a greater proportion of lower volatility hydrocarbons than found at SRSNE, with a significant mass of bunker fuels and grease. To enhance the recovery of low volatility liquids, the Fort Lewis MPE system operated at a higher rate of groundwater extraction (20-30 gpm) than would be required at SRSNE.

Photos of the Fort Lewis site and Treatment Region 1 follow:

Photograph courtesy of US Army Corps of Engineers (USACE) – Seattle Office

Photograph courtesy of USACE – Seattle Office

The Fort Lewis site has an asphalt cap. The cap was installed for several reasons:

- The cap base rock and asphalt provided thermal insulation with increased the heating and treatment of very shallow soils.

- Vacuum influence exerted by the MPE system controls the VOC vapors. Because heating at the site extends to the native soil surface the cap provides a back-up to help prevent vapor emissions during a power failure.
- The cap prevents the site from becoming muddy - it rains a lot in western Washington.

Although it is probably not necessary, TRS would recommend an additional new layer of asphalt for the SRSNE site as well (unless the existing asphalt is in good condition).

TRS recommends against the use of a thermal barrier or "hot floor" approach for the SRSNE site for the reasons outlined in the attached Appendix A. A thermal barrier was not used at the Fort Lewis site and VOC concentrations in the aquifer immediately underlying the thermal treatment zone decreased as the remediation progressed.

ERH requires the use of a vapor treatment system and TRS would recommend using a high quality thermal oxidizer for the SRSNE site. The thermal oxidizer shown in the Fort Lewis photos above maintained an average 99.79 percent VOC destruction efficiency. The only odor reported by site workers was an occasional light chlorine smell when the wind was right, at a level less than an indoor swimming pool. No odors were ever detected off site. Even the slight chlorine smell in the scrubber stack discharge can be eliminated by adding a reducing agent, such as sodium thiosulfate, to the scrubber.

ERH systems have been successfully deployed at sites with much greater logistical challenges that those found at the SRSNE site. ERH remediations have been performed under occupied buildings, in the presence of a wide range of buried utilities, in high-density commercial settings and at remote locations. With successful applications from Florida to Alaska, the technology has also been deployed in a wide range of extreme weather conditions.

ERH is the most mature and widespread of the thermal treatment technologies. The necessary specialty equipment and skilled personnel to install and operate that equipment are available in the commercial marketplace. At the SRSNE site, it will be possible to integrate the existing water treatment plant into the ERH system and reduce capital, operation, and permitting costs. The technology has a high degree of regulatory acceptance at the Federal level, and project permitting has now been achieved in over 12 states.

Cost Evaluation of ERH for the SRSNE Site

The similarities between the Fort Lewis site and the SRSNE site make it possible to compare costs fairly directly. Some of the differences that must be accounted for include:

- The geometry differences between the sites. The area to be treated at the SRSNE site is larger, but the treatment interval at Fort Lewis is deeper.
- The Fort Lewis site required a new hydraulic control system and a new water treatment system. These systems are already in place at SRSNE and the existing water treatment system seems capable of treating 15 gpm of ERH system water with up to 10 pounds per day of dissolved phase VOCs. It is likely that the 15 gpm from

the ERH system would not be entirely additional flow: the existing pumping wells would probably need to pump less due to the aid provided by the ERH MPE system.

- The cost for electricity is higher in Connecticut. A typical electrical usage cost for time-of-use primary voltage metering with a curtailment agreement in Connecticut is \$0.11 per kilowatt-hour (kW-hr). This estimate has been increased by \$0.01 to account for recent increases in crude oil prices.
- Some or all of the electrodes may be installed by pile-driving at a cost savings relative to drilling and drill cutting disposal. At this stage, TRS has not assumed any savings from pile-driven electrodes.

Some of the unit costs used in estimating include:

- Asphalt paving: \$2.50 per square foot (included in Table 2 below, under the “Subsurface Installation” task).
- Drilling subcontractor - no materials: \$75 per foot (included in “Drilling and Soil Sampling” task).
- Soil sample analysis: \$250 per sample (included in “Drilling and Soil Sampling” task). Vapor and water sample analysis: \$250 per sample (included in “Other Operational Costs” task)
- Drill cutting disposal: \$500 per ton. (included in “Drill Cuttings and Waste Disposal” task)
- No new monitoring wells are required.
- Thermal oxidizer with acid gas scrubber: \$370,000 (included in the “Surface Installation and Start-up” task).
- Electrical utility connection: \$15,000 (included in the “Electrical Utility Connection to the PCU” task)
- Electrical usage: \$0.11 per kW-hr (included in the “Electrical Energy Usage” task)
- Propane: \$1.20 per gallon (included in the “Remediation System Operation” task)
- Confirmatory borings: 31 borings with four soil samples each (included in “Drilling and Soil Sampling” task).
- The cost of NAPL/water separation is included (included in the “Surface Installation and Start-up” task). NAPL disposal is not included because information on expected NAPL yield and NAPL disposal costs were not provided.
- The existing water treatment system can treat the dissolved phase VOCs in the ERH discharge with no system modifications. If the proposed VOC loading to the water treatment system is considered excessive then the discharge water can be pre-treated to reduce VOC loading to the water treatment system for little additional cost (<1% of total project costs).
- The cost of the water treatment system operation is not included as it is assumed that its operation would be required regardless of remediation.

- ERH electrodes/MPE wells can be abandoned by pressure grouting at a cost of $150 per well (included in the "Demobilization and Final Report" task). The 4-inch casing MPE wells could be used for biostimulation or bioaugmentation after ERH if desired. However, previous experience and SRSNE site data suggest that neither biostimulation nor bioaugmentation would be required after ERH. The long cooldown period will provide a strong thermal enhancement to bioremediation without further enhancement.

Approximate costs for the SRSNE site are shown in Table 2 below. Also attached are simple graphs depicting the energy distribution and the expected temperatures over time. To be conservative, the costs presented in Table 2 are estimated based on a 95% removal of VOC mass from the overburden soil and groundwater.

Dr. Brent Sleep of the University of Toronto prepared a simple analysis of ERH temperatures and the potential effect of these temperatures on NAPL distribution, presented in Appendix A of Appendix V of the FS. For the following reasons, the FS Appendix A analysis is not a valid representation of ERH:

- The model assumed that ERH was conducted over a depth interval from 10 to 14 feet bgs (3 to 4.2 m). It is not possible to heat such a thin pancake with ERH. A ten-foot thickness is the practical lower limit.
- The model assumed a depth to water of 3.5 feet bgs (1 m) yet did not extend ERH over the entire saturated zone. Every responsible ERH vendor would recommend that ERH extend to at least the surface of the water table because of the "condensation" issues that Dr. Sleep described in the model summary.
- By assuming an artificially thin heating zone, the heat losses by thermal conduction to the surroundings reduced the model heating to an unrealistically slow rate.

Conclusion

ERH can rapidly and effectively remove the bulk of the NAPL and VOC mass from the overburden soils at the SRSNE site. No short term impact on bedrock contamination would be expected – either positive or negative. Over the long term, bedrock concentrations would be expected to decrease because no additional source contaminants would enter the bedrock from the overburden.

After ERH, the subsurface toxicity would be reduced and site conditions would be more amenable to biological activity. Empirical data suggests that the long, slow cooldown after thermal treatment provides an effective enhancement to anaerobic dechlorination. Due to thermal enhancement and the presence of fuel hydrocarbons that can serve as electron donors, the SRSNE site would probably not require either biostimulation or bioaugmentation following thermal remediation.

A budgetary cost estimate for ERH was provided. Although ERH may be the most effective remediation for the SRSNE overburden, it may not be the lowest cost alternative for site remediation.

Table 2

Site Name:	**SRSNE**	
Electrical Resistance Heating Treatment Area:	63,500 sq. ft.	
Shallow Extent of Electrical Resistance Heating:	2 ft	
Deep Extent of Electrical Resistance Heating:	20 ft	
Typical Depth to Groundwater:	8 ft	
Treatment Volume:	42,300 cu yds	
Soil Organic Carbon Content:	1.00%	This is an assumption due presence of fuels.
Estimated Number of Electrodes:	305	Installed in 12-inch o.d. borings.
Estimated Distance Between Electrodes:	15.5 ft	
Total Depth of Electrodes	21 ft	
Depth to Top of Electrodes	4 ft	
Estimated Number of Vapor Recovery Wells:	305	VR wells are co-located with electrodes.
Number of Temperature Monitoring Points:	31	Each TMP has 5 thermocouples.
Number of New Monitoring Wells:	0	
Piping and Well Installation:	Above grade completion	
Is a New Surface Cap Required?	yes	type: asphalt pavement
Controlling Contaminant:	TCE	
Overall Clean-up Percent:	95%	E.g., reduce 16,500 mg/kg to 825 mg/kg
Assumed VOC Mass:	342,900 lbs	Assumes avg. VOC conc. of 3,000 mg/kg.
Vapor Recovery Air Flow Rate (scfm):	490 scfm	
Minimum Vapor Recovery Blower:	40 horsepower	
Condensate Production Rate:	4.9 gpm	(when the site is at full steam production)
Liquid Groundwater Pumping Rate:	10 gpm	Pumping per actively heated section.
Vapor Treatment Method:	oxidizer	An acid gas stack scrubber is included.
Assumed Activated Carbon Required:	0,000 lbs	
Power Control Unit (PCU) Capacity:	2000 kW	
Average Electrical Heating Power Input:	1271 kW	

In order to increase energy efficiency, the treatment volume is divided into 2 sections for sequential treatment.

Total Heating Treatment Time:	244 - 298 days	Total of all sections.
Design Remediation Energy (kW-hr):	8,272,000	
Assumed Number of Confirmatory Borings:	31	Analysis of 4 soil samples per boring

The above parameters are estimated +/- 20%. Final parameters will be determined during system design.

Approximate Costs (+/- 20%)

Thermal Remediation Services Costs		Percent	
Design, Work Plans, Permits:	$115,000	2%	
Subsurface Installation:	$776,000	13%	
Surface Installation and Start-up:	$1,320,000	21%	
Remediation System Operation:	$1,511,000	25%	
Demobilization and Final Report:	$171,000	3%	
Total TRS Costs	**$3,893,000**		
Estimated Costs by Others			
Drilling and Soil Sampling:	$704,000	11%	assumes $75 per foot
Drill Cuttings and Waste Disposal:	$126,000	2%	assumes $500 per ton
Electrical Utility Connection to PCU:	$15,000	0%	
Electrical Energy Usage:	$1,006,000	16%	assumes $0.11 per kW-hr
Carbon Usage, Transportation & Regeneration:	$0	0%	
Water/Condensate Disposal:	$141,000	2%	
Other Operational Costs:	$280,000	5%	includes vapor sampling
Total Remediation Cost:	**$6,165,000**		
Total Cost per Cubic Yard:	$146		

Figure 1 - ERH Energy Distribution in Subsurface

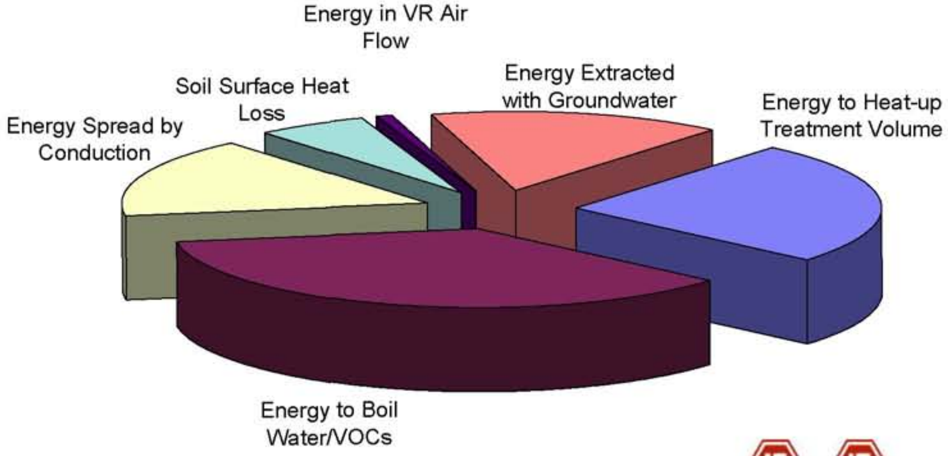
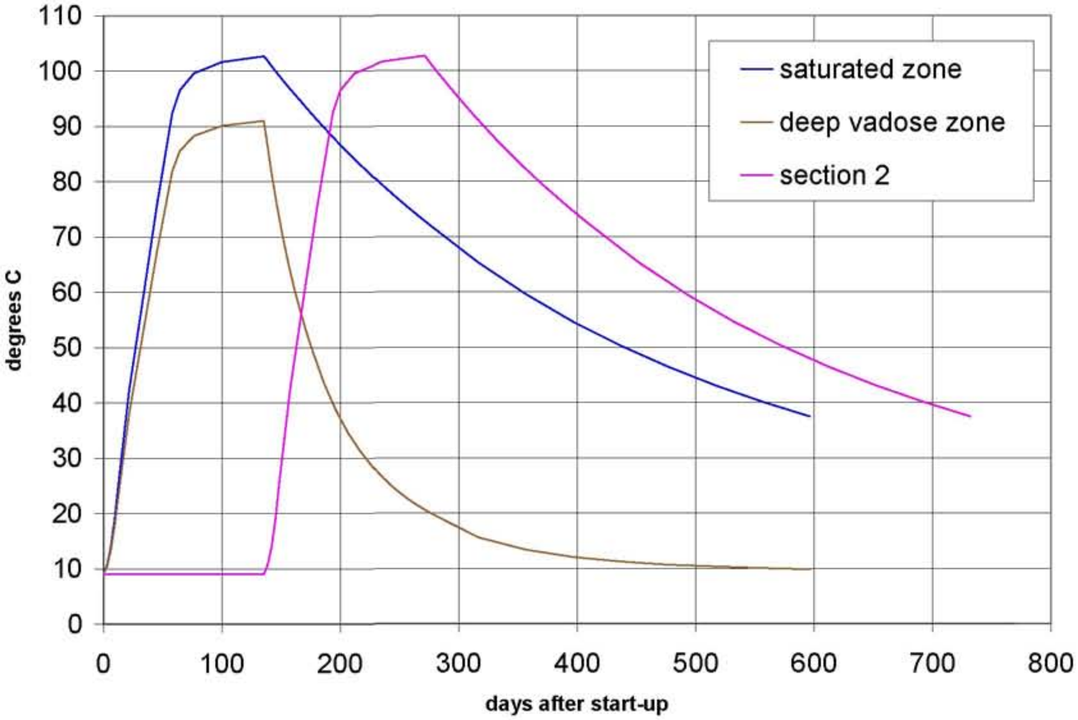


Figure 2 - Expected Subsurface Temperatures



Appendix A
Thermal Barriers and the Risk of Vertical NAPL Mobilization

Greg Beyke was a member of the project team that designed and implemented the first thermal barrier or "hot floor" used in an *in situ* remediation at the ICN Pharmaceuticals Site in Portland, Oregon. While a thermal barrier is not appropriate for most electrical resistance heating (ERH) remediations, the Portland site had characteristics that led to its recommended use there.

Three factors can lead to the recommendation of a thermal barrier:

1. Does the NAPL have physical parameters (density, viscosity, etc.) that make it likely to move downward;
2. Is the DNAPL in a precarious geologic setting, and
3. If a small amount of DNAPL were to migrate downward, what would be the significance or environmental impact?

All of these factors have a range of classification (e.g., minimal, moderate, or severe). Hypothetically, a decision might be made to implement a thermal barrier if only one of the three factors is assessed as minimal because the other two parameters are rated as severe. There is not a general rule of thumb to make a decision to implement a thermal barrier, but the aforementioned factors should be considered integral to the decision-making process.

A brief discussion of the Portland site will illustrate how these factors are evaluated.

Portland DNAPL Characteristics

The principal volatile organic compound (VOC) present at the Portland site was trichloroethylene (TCE) which has low viscosity and high density (specific gravity: 1.46). These parameters make pure chlorinated solvent dense non-aqueous phase liquid (DNAPL) much more likely to migrate downward than other environmental contaminants. The DNAPL characteristics were considered to be a severe factor at the Portland site.

Portland Geologic Setting

The second factor can be described as a precarious geologic setting. Examples of a precarious setting would be DNAPL that is perched on a thin or discontinuous aquitard that overlies a highly permeable aquifer. The Portland site had DNAPL in an extremely precarious setting: DNAPL was located in fine-grained sand that became progressively coarser with depth as it transitioned into a prolific gravel aquifer. The geologic setting at Portland was so precarious that it was not possible to explain why the DNAPL was being held up at all.

Portland Environmental Setting

The final factor decision-making process is the environmental impact resulting from potential downward migration of DNAPL. The prolific aquifer underlying the Portland site, the Troutdale Gravel Aquifer, is a backup water supply for the City of Portland. Prior to the remediation, the aquifer retained a relatively high level of groundwater quality; only a minimal portion of the aquifer beneath the site was contaminated by VOCs at levels just above those permitted for drinking water. Because potential downward DNAPL migration would have seriously degraded the aquifer, the environmental impact factor was assessed as severe for the Portland site.

The Portland site was deemed an excellent candidate for the use of a thermal barrier because of the characteristics of the DNAPL; the extremely precarious geological setting; and the possibility of severe environmental impact, The thermal barrier technique was applied during the ERH remediation of the site and the barrier prevented any degradation of the underlying aquifer.

Other Thermal Barrier Considerations

The decision to use thermal barrier must also take into consideration the negative consequences of its implementation. Implementation of a thermal barrier is accomplished by drilling through the DNAPL region to heat below the DNAPL zone. The drilling process has the potential to provide migration pathways for downward DNAPL movement as the thermal barrier wells or electrodes are installed.

A second consequence results from heating of the thermal barrier. It is not possible to stop the upward spread of heat as the thermal barrier is formed. Consequently, rising heat slowly warms the DNAPL region and provides a prolonged period in which the DNAPL is in the "warm, but not yet boiling" regime – the regime in which the risk of DNAPL movement is elevated.

A third consequence of a thermal barrier is increased remediation time, energy usage and cost. For most thermal remediation sites, the use of a thermal barrier ultimately results in a waste of project resources.

Is a Thermal Barrier Appropriate for the SRSNE Site?

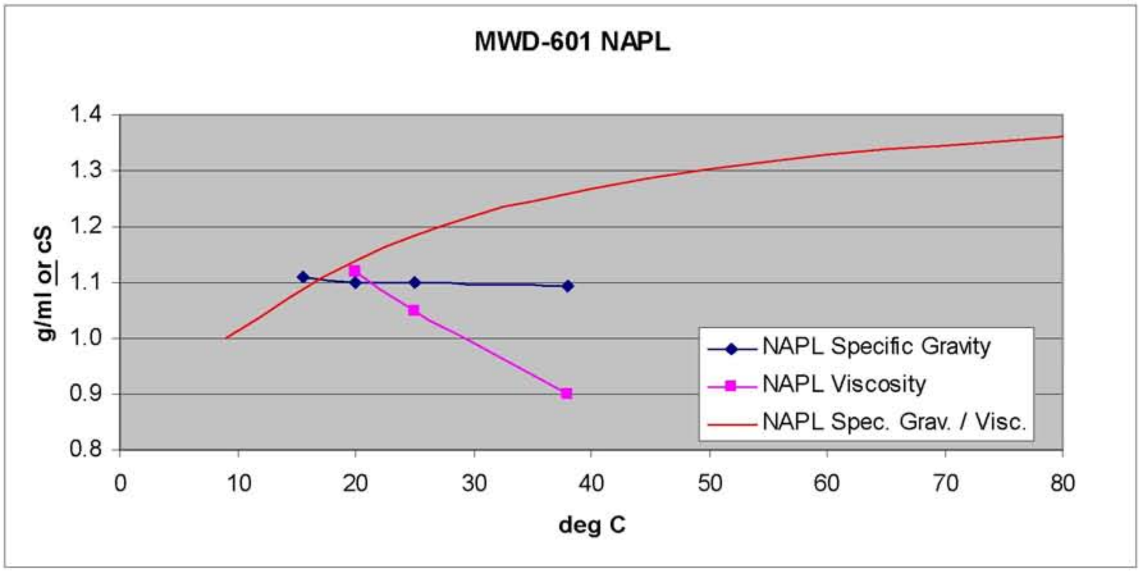
When considering whether or not a thermal barrier is appropriate for the SRSNE site, the evaluation should include the three factors outlined at the beginning of this document.

SRSNE NAPL Characteristics

The NAPL that is present in the overburden unit today is not pure chlorinated solvents, rather it is a mixture of chlorinated solvents and other compounds that are less dense than water. Because of this mixture, the overburden NAPL is far less dense than pure TCE. The density of NAPL in the overburden is only slightly greater than that of water and the liquid contamination can be considered to be of essentially neutral buoyancy. For this reason, it might not be appropriate to refer to the overburden NAPL as a *Dense* NAPL.

It is highly probable when considering the site history that portions of the SRSNE site likely had VOC mixtures with a greater fraction of chlorinated VOCs and greater than neutral density. It is also highly probably that those dense solvent mixtures moved rapidly downward and are probably the source of the present day bedrock contamination. What remains in the ONOGU today appears to be the NAPL mixtures that are near neutral buoyancy.

Measured NAPL characteristics from MWD-601 are shown below:

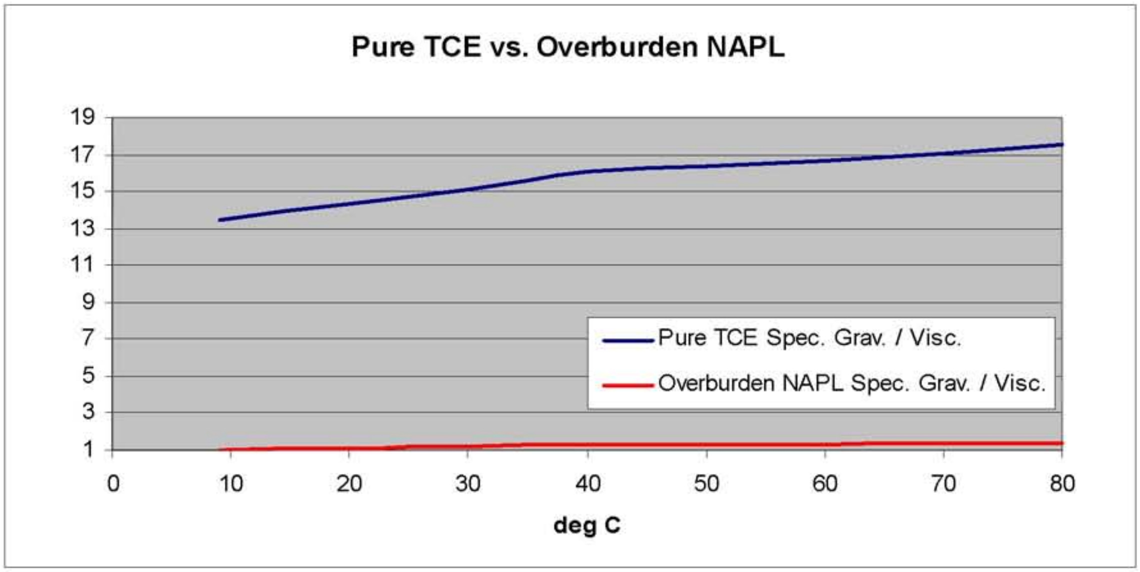


As the NAPL is heated, the viscosity and density both decrease slightly. Reduced viscosity makes it easier for the NAPL to move. However, the density of the NAPL relative to water (specific gravity) also decreases as the NAPL is heated, reducing the force that could cause downward movement. The counterbalance between NAPL specific gravity and NAPL viscosity is graphed as the red line above. Specifically, the red line is the difference between the densities of NAPL and water, divided by the NAPL viscosity, and normalized to unity at the site ambient temperature of 9 degrees Celsius (°C). The red line indicates that the overall effect of heating on liquid NAPL is a slight increase in its potential for downward mobility; however, the downward force remains very small at all temperatures because the NAPL is so close to neutral buoyancy.

The dense chlorinated solvents in the NAPL mixture have lower boiling temperatures than the lower density hydrocarbons in the mix. If the subsurface were heated, the chlorinated solvents would begin preferential evaporation near 80°C and the density of any NAPL would be very rapidly reduced to less than the density of water. As a result, any downward NAPL movement should be essentially impossible after the site reaches 80°C.

As shown in the graph above, the characteristics of the overburden NAPL would make it slightly more likely to move deeper during heating until the chlorinated solvent fraction begins to boil near 80°C. In a typical thermal remediation, the time spent in the hot, but not yet boiling regime is less than one month. If the NAPL has not moved downward over a period of decades, it seems unlikely to move down over a period of a month.

To put the overburden NAPL characteristics in perspective, the downward movement risk of pure TCE over the same temperature range would be 13 to 18 times greater (see chart below).



For the reasons previously detailed, the overburden NAPL has characteristics that make the risk of downward movement minimal.

SRSNE Geologic Setting

The overburden soils at the SRSNE site can be broadly characterized as moderately permeable interbedded sands and silts. A low permeability till layer generally separates the overburden soils from bedrock and often serves as an effective barrier to NAPL migration; however, there are several locations where the till is absent and the overburden is in direct contact with underlying bedrock. The top of bedrock is highly weathered while the deeper bedrock is fractured. As a result, the overall bedrock permeability could be described as moderate.

Although the till seems to be an effective barrier to NAPL migration where present, there are several locations where *moderately* permeable overburden is in contact with the *moderately* permeable bedrock. Therefore, the SRSNE geologic setting would be a moderate risk and should be considered neutral in regards to the requirement for a thermal barrier.

SRSNE Environmental Setting

The bedrock immediately beneath the SRSNE site is highly contaminated with concentrations indicative of NAPL presence. Because of this pre-existing contamination, it would be difficult to detect if a minor additional amount of NAPL were to enter the bedrock from the overburden, much less predict any change in health risk. Based on evaluation of the information provided, the SRSNE environmental setting appears to pose minimal risk.

Summary

The balance of the aforementioned factors leads to the recommendation that a thermal barrier is not required at SRSNE.

For comparison, the factors necessary for the decision-making process to evaluate the need for thermal barriers at the Portland site and the SRSNE site are summarized below:

Factors	Portland Site Rating	SRSNE Site Rating
NAPL Characteristics	severe factor	minimal factor
Geologic Setting	extreme factor	moderate factor
Environmental Setting	severe factor	minimal factor
Thermal Barrier	successfully used	not recommended

Previous Evaluations

An evaluation of the risk of vertical NAPL mobilization was included as Appendix W of the Feasibility Study. The evaluation focused primarily on the use of steam injection as a method of thermal remediation and much of the discussion in that document is not relevant to ERH in particular.

During ERH, the entire treatment zone is heated simultaneously. To help visualize the process, imagine placing a large pot of water on your stove and adjusting the burner so low that it takes two weeks to reach boiling. Once the water in the pot does begin to boil, the process is gentler than the mildest “simmer”.

During the simultaneous heating achieved with ERH, there are no “steaming zones” and no “condensation” zones. There is no significant lateral flow of any kind and there are no steam fronts. NAPL will not accumulate anywhere, and there are no “NAPL banks”. Co-injection of air is not required during ERH.

The Appendix W conclusion used previous analysis based on steam injection to argue that all thermal remediation techniques have a risk of vertical mobilization. It should be noted that ERH processes were not evaluated in sufficient detail in that document to allow formation of its “broad brushstroke” conclusion regarding in situ thermal remediation technologies.