

# IN SITU ELECTRICAL HEATING TECHNOLOGIES FOR ENVIRONMENTAL REMEDIATION

Tai T. Wong<sup>1</sup>, Addanki V. Krishnayya<sup>1</sup>, John G. Agar<sup>1</sup>, Barry H. Nevokshonoff<sup>2</sup>, and Randall Warren<sup>3</sup>

<sup>1</sup>O'Connor Associates Environmental Inc., Calgary, Alberta

<sup>2</sup>Currently with Sequoia Environmental Inc., Calgary, Alberta

<sup>3</sup>Shell Canada Products Ltd., Calgary, Alberta

## ABSTRACT

When contaminated soils are heated, the vapour pressure of the contaminating organic chemicals is increased. This increased volatility enhances the removal of the contaminants in the subsurface by conventional *in situ* remedial techniques such as vapour extraction and multiphase extraction. Currently, *in situ* electrical ground heating can be achieved through conventional conduction heating, electrical resistance heating and electromagnetic heating.

This paper reports the results from a pilot test using multiphase vacuum extraction enhanced by electric resistance heating. The resultant temperature pattern and distribution of contaminants in the subsurface are evaluated. Then, using a numerical model, conduction heating is compared with resistance heating. Based on these results, the efficiency of these two processes is compared. Based on the pilot test and the numerical study, practical implications for remedial system design are summarized.

## RÉSUMÉ

Quand des sols contaminés sont chauffés, la pression de vapeur des composés chimiques organiques augmente. L'augmentation de la volatilité aide à l'élimination des contaminants par des méthodes conventionnelles telles l'extraction par vapeur et l'extraction à phases multiples. On peut chauffer le sol par des méthodes électriques in-situ en utilisant le chauffage par conduction conventionnel, le chauffage électrique par résistance ou le chauffage par électromagnétisme.

Cet article rapporte les résultats d'un test pilote utilisant l'extraction par succion à phases multiples aidée par le chauffage électrique par résistance. Le patron des températures qui en résulte et la distribution des contaminants dans le sol sont évalués. Par la suite, à l'aide d'un modèle numérique, le chauffage par conduction est comparé avec le chauffage par résistance. En se basant sur ces résultats, l'efficacité des deux méthodes est comparée. À partir du test pilote et de l'étude du modèle numérique, les implications pratiques pour le design des systèmes de réhabilitation sont résumées.

## 1. INTRODUCTION

Organic contaminants, such as petroleum hydrocarbons, can exist in four different phases in the subsurface: as a separate non-aqueous phase liquid, as a dissolved in the aqueous phase, as a vapour phase in the soil gas, and as an adsorbed phase. In the adsorbed phase, the contaminant may be partitioned into the soil organic matter or adsorbed onto the soil mineral particles. In general, the non-aqueous and dissolved phases can be removed by pumping and the vapour phase removed by soil venting, the adsorbed phase usually is the most difficult to remove.

Ground heating has been identified as a potential means to enhance the recovery of organic contaminants in the subsurface (Dev et al., 1989, US EPA, 1995, Newmark and Aines, 1995). In general, an increase in temperature will increase the volatility (vapour pressure) of a contaminant, decrease its adsorption, increase its molecular diffusion in aqueous and gaseous phase, and decrease its viscosity in the liquid phase. Consequently, through heating, more contaminants are made available

for removal by conventional remediation processes such as vapour extraction.

Subsurface ground heating can be achieved through different methods such as conduction heating, electrical resistance heating, electromagnetic heating, and steam injection. Conduction heating uses electrical heaters or steam heaters inserted into the ground and heat is distributed into the surrounding soil through conduction. With electrical resistance heating, an electric current is passed between two or more electrodes installed in the ground and the intervening soil gets heated up because of its resistance to the current flow. Electromagnetic heating delivers heat energy to the subsurface by low or high frequency electromagnetic radiation. Of these three common methods, electromagnetic heating requires the most complicated equipment design and construction. In this paper, discussion will be limited to electrical resistance heating and conduction heating.

In the following sections, the performance of electrical resistance heating in enhancing *in situ* remediation at a pilot test site will be discussed. Comparison between

electrical resistance heating and conduction heating in terms of efficiency will be presented. Lastly, practical implications for the application of electrical heating will be discussed.

## 2. ELECTRICAL RESISTANCE HEATING

When an electric current is passed between two electrodes embedded in a soil strata, the intervening soil is heated as a result of the resistance to the current flow. Since the electrical conductivity of a dry soil is low, a high moisture content needs to be maintained. Consequently, the maximum temperature attainable for resistance heating is around the boiling temperature of water.

In order to evaluate the performance of electrical resistance heating in enhancing conventional subsurface remediation using soil vapour extraction (SVE) and multiphase extraction (MPE), a pilot test was carried out in 1999 at the old Canadian Force Base (CFB), Calgary.

### 2.1 Pilot Test for Electrical Resistance Heating

The pilot test was carried out on a small section of a vacant property adjacent to a former service station. Subsurface investigation using drilled boreholes indicates that the site stratigraphy is made up of approximately 2.5 m of fill material (silts, sands and gravels) overlying an 1.5 m thick layer of organic rich silt which in turn rests on silt till. The natural water table is about 3.5 m below grade. The subsurface soil and groundwater was impacted with gasoline and the contaminant of primary concern was benzene.

Prior to testing, soil contaminant levels and electrical resistivity at the site were measured and recorded to provide data for comparison. During the pilot test, power consumption, temperature distribution, water flow budget, MPE (multiphase extraction) and SVE (soil vapour extraction) operations, and contaminant levels were monitored daily.

A total of six electrodes were deployed in a rectangular pattern covering an area approximately 14 m x 9 m. Each electrode was a segmented rod 200 mm in diameter and was 6.5 m in total length. The top segment was 4 m long fiberglass pipe at the top and the bottom segment was an 1.5 m long steel rod. Each electrode was installed to a depth of approximately 4 m below grade such that the steel segment coincided with the estimated contaminated area. Along each of the 14 m sides of the rectangle, three electrodes were installed at about 7 m apart. At any one time, electric current was delivered to only three electrodes while the remaining three stayed neutral. This pattern was rotated at a 20-day period.

Heating was started on 99/02/15 and continued until 99/06/15 for a total of 115 days. The temperature at each electrode was kept below 95 °C by circulating cooling water through the electrode. The flow of cooling water to each electrode was manually adjusted. In conjunction with the heating system, an SVE and an MPE

system were operated for the removal of contaminants. From 99/02/16 to 99/05/21, a 7.5 h.p. liquid ring pump (LRP) and a 3 h.p. regenerative vacuum unit (RVU) were used together with four extraction wells. On 99/05/18, three additional extraction wells were installed. Between 99/05/21 and 99/06/21, the LRP and RVU were replaced by a 30 h.p. multi-phase vacuum unit (MPVU). A photograph of the site is shown in Figure 1.



Figure 1. CFB Pilot Test Site

In order to monitor subsurface soil temperatures 21 multi-level thermocouple probes were installed within the test area. In addition, there were 4 thermocouple/vapour sampling points, 6 dedicated soil sampling wells, and 1 groundwater monitoring piezometer. Temperature and vapour concentration readings were recorded daily while soil sampling was carried out at regular intervals. A layout of the electrodes and the locations of the soil sampling locations are shown in Figure 2.

### 2.2 Results of the Pilot Test

#### 2.2.1 Soil Temperature Distribution in the Subsurface

The average initial soil temperature was 6 °C at 3.5 m below ground surface (bgs). On the final day of heating, the average soil temperature inside the electrode array was 50°C, with soil temperatures ranging between 91°C and 28 °C. A contour plot of the temperature distribution at 3.5 m bgs is shown in Figure 3. In general, temperature was lower down the middle of the rectangle along the longer side indicating that a 9 m spacing between electrodes might be too wide for the electrodes installed.

After the deactivation of the electrodes, the site temperature remained relatively unchanged for six days. The average soil temperature then cooled to 42°C (from 50°C) in 13 days.

#### 2.2.2 Electrical Energy Consumption

Total electrical energy consumed for resistance heating was 1089 MWh in 115 days. The voltage applied to each electrode ranged from 142 to 220 VAC and the current varied between 29 to 115 Amp.

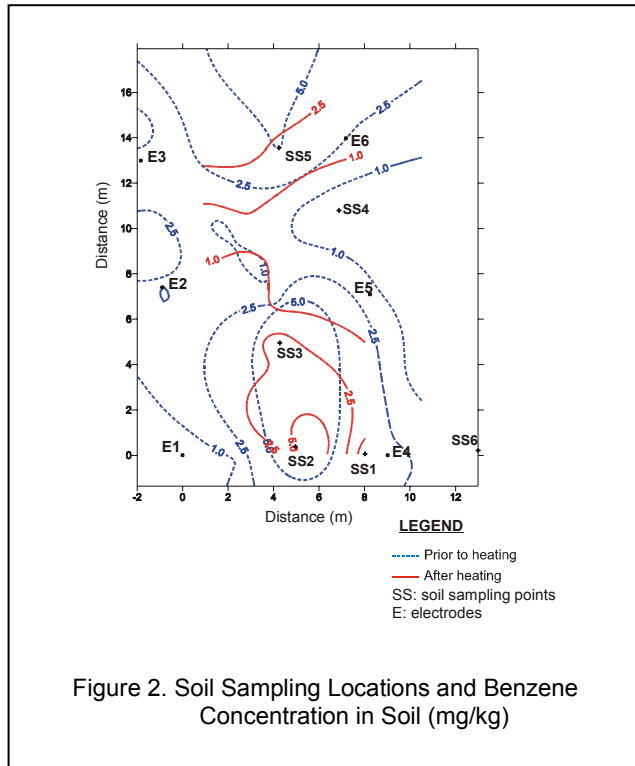


Figure 2. Soil Sampling Locations and Benzene Concentration in Soil (mg/kg)

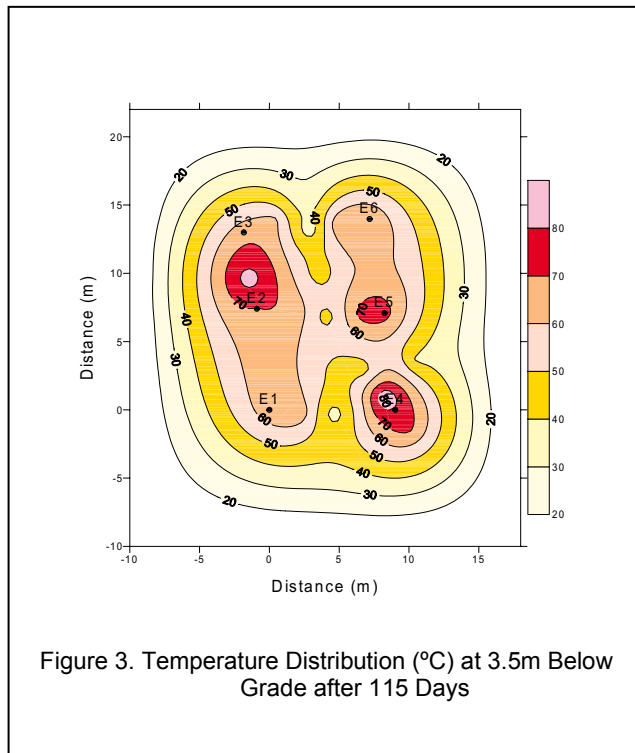


Figure 3. Temperature Distribution (°C) at 3.5m Below Grade after 115 Days

### 2.2.3 Effect on Groundwater

The initial groundwater table was located at approximately 3.2 m below grade. Between 99/02/16 and 99/05/20, due to pump capacity only 2 of the 4 extraction wells could be connected to the extraction system at any one time. Consequently, the volume of cooling water leaked often exceeded the volume of groundwater recovered, and the groundwater level within the electrode array rose to within 0.7 m below grade in wells not connected to the extraction system. This would have restricted the soil volume through which vapour could travel thus reducing the vapour extraction rate. Detailed water budget has yet to be extracted from the test records.

From 99/05/21, the MPVU managed to maintain the groundwater level at the extraction wells at about 5 m below grade. With this lowered groundwater level and higher operating vacuum pressure, the sub-surface air flow rate was increased by about 3.5 times.

### 2.2.4 Effect on Contaminant Concentration in Soil

Soil samples collected during the pilot test were also tested for benzene concentrations. The time variation of average benzene concentration in soil is as follows:

March 99	4.0 mg/kg
Apr-May 99	3.7 mg/kg
June 99	1.7 mg/kg

Significant reduction in benzene concentration was only achieved after the groundwater level had been lowered significantly using the 30 hp MPVU. Contours of the pre-heating and post-heating benzene concentration in soil are shown in Figure 2.

The maximum initial benzene concentration in soil was 8.5 mg/kg and the maximum final benzene concentration in soil was 7.3 mg/kg. These were located in the cooler region of the test area. It was estimated that approximately 73% of the mass of benzene were removed from the area bounded by the electrode array in 130 days of remediation operations.

### 2.2.5 Subsurface Vapours

During the pilot test, subsurface vapours were monitored at six soil sampling locations distributed within the electrode array (Figure 3). At these locations, the following gases were detected: petroleum hydrocarbon (TPH) vapour, methane (CH<sub>4</sub>), hydrogen sulphide (H<sub>2</sub>S), carbon monoxide (CO), carbon dioxide (CO<sub>2</sub>), and oxygen (O<sub>2</sub>). Typically, methane, hydrogen sulphide, carbon dioxide and oxygen are products of biodegradation of hydrocarbons; and methane and hydrogen sulphide are only generated under anaerobic conditions. Carbon monoxide is usually generated when carbon is oxidized in an oxygen-deficient environment. CH<sub>4</sub> and H<sub>2</sub>S might have also been generated when organics (roots and fibers) in soils decomposed. A correlation between respective concentration of TPH, CH<sub>4</sub> and H<sub>2</sub>S vapours and soil temperature cannot be established.

H<sub>2</sub>S was first detected at a sampling location (SS1, see Figure 2) closest to an electrode after 32 days of heating. Concentrations higher than 10ppm (Alberta Occupational Exposure Limits for 8 Hours) were recorded at four of the six sampling locations. The highest concentration recorded was >200 ppm. The occurrence of high concentration of H<sub>2</sub>S only coincided with low O<sub>2</sub> level at the beginning of the pilot test. After 80 days of heating, H<sub>2</sub>S was only detected at SS1 and persisted for the remainder of the pilot test.

After 32 days of heating, CH<sub>4</sub> were detected at all six soil sampling locations throughout the test. The highest concentration was >100% LEL (the limit of the monitoring equipment). It appeared that higher CH<sub>4</sub> concentrations coincided with low O<sub>2</sub> concentrations.

The generation of CH<sub>4</sub>, CO<sub>2</sub>, and hydrogen sulphide may indicate the anaerobic microbial decomposition of organic material (Wardwell *et al*, 1983). These bacteria are usually mesophilic and, in the range of temperatures from 15 to 45 °C, their activity may increase 2 to 3 times for each 10 °C rise in temperature.

### 2.2.6 Effect of Soil Temperature on Microorganism Population

Microorganism population counts were performed on groundwater samples collected from locations within the electrode array. The total heterotrophs count ranged from 2.0x10<sup>3</sup> to 2.0x10<sup>5</sup> colony forming units (CFU)/ml while the total gasoline degraders count ranged from 5.1x10<sup>2</sup> to 5.1x10<sup>4</sup> CFU/ml. It appeared that these counts had decreased with increasing temperature. However, an oxygen-deficient environment and the possible lack of nutrients may also have limited the population of heterotrophs and gasoline degraders as the test progressed.

### 2.2.7 Soil Properties

Laboratory tests were carried out to measure some of the hydraulic and thermal properties of the organic silt at the pilot test site. Typical properties for this silt are summarized in Table 1. Electrical conductivity was determined using both laboratory and *in situ* methods.

## 2.3 Effect of High Organic Contents

From the performance observed during the pilot test, it appears that that high organic content of the CFB silt has slowed down the remediation processes. Its low hydraulic conductivity and high moisture content reduce both air and water flow rates and make vapour extraction difficult. In addition, it may decompose at higher temperature to give out methane and hydrogen sulphide.

Table 1. Properties of Organic Silt at Pilot Test Site

Specific gravity of soil grain	2.47
<i>In situ</i> total density (kg/m <sup>3</sup> )	1390 - 2100
Dry density (kg/m <sup>3</sup> )	1200 – 1980
Natural moisture content	10.0% - 32.0%
Hydraulic conductivity at 20 °C (m/s)	1.24x10 <sup>-11</sup>
Average electrical conductivity (S/m)	0.042
Thermal conductivity (W/m-K)	0.6
Total organic carbon	1.7% - 4.8%

In a soil, a contaminant may partition into four possible phases, namely: soil gas, soil water, adsorbed, and free liquid. Table 2 presents the results of a parametric study on the phase distribution of benzene due to contamination by weathered gasoline in a soil with two total organic carbon (TOC) ents: 0.1% (low) and 3.3% (high). The high TOC soil may be considered similar to the CFB silt. The percent mass of benzene in various phases was calculated assuming equilibrium conditions among the phases. The results are presented for temperatures of 10 °C and 80 °C and moisture contents of 10% and 20%. The purpose of this parametric study was to indicate the effectiveness of heating and vapour extraction in

Table 2. Phase Distribution of Benzene in Soil Due to Gasoline Contamination

TOC Content	Gravimetric Water Content	Soil Temperature: 10 °C				Soil Temperature: 80 °C			
		Percentage of Benzene in				Percentage of Benzene in			
		Gas	Water	Adsorbed	Free	Gas	Water	Adsorbed	Free
3.3 %	20%	0.07	6.72	92.3	0.95	0.94	6.70	92.0	0.33
	10%	0.48	3.48	95.2	0.85	5.88	3.32	90.8	0.00
0.1%	20%	0.36	34.5	14.4	50.8	4.70	34.9	14.5	45.9
	10%	2.84	20.9	17.3	58.9	31.4	17.9	14.8	35.9

remediating soils with high TOC.

In soils with high TOC, benzene partitions predominantly into the adsorbed phase. Even at elevated temperatures, only a small proportion of the adsorbed benzene will be released into the gas and dissolved phase. In soils with low TOC, the majority of the benzene partitions into the free and dissolved phase. Only at high temperatures and low moisture content, a significantly higher proportion of benzene will partition into the gas phase.

### 2.3.1 Cost of Remediation

The volume of soil effectively heated was estimated to be around 490 m<sup>3</sup>. This volume was obtained by using the area bounded by the 40 °C contour and the length of the electrode (1.5 m)

The soil treatment cost in this pilot test was approximately \$253/m<sup>3</sup> of hydrocarbon-affected soils. The estimated cost for a 95% removal of the hydrocarbon mass was \$265/m<sup>3</sup>. This cost includes equipment and operating costs, but does not include drilling and monitoring costs.

## 3. CONDUCTION HEATING

Electrical resistance heating requires the addition of water to the soil to be heated in order to maintain good electrical conductivity as well as the supply of cooling water to the electrodes for cooling. This additional amount of water will also be heated and add to the energy consumption. Soil heating mainly by heat conduction with the use of electrical heaters does not require the addition of water thus resulting in more efficiency use of electrical energy.

In the following sections, the simulation of soil heating by conduction using a numerical model is described. The heating rates and energy costs are compared with those reported for electrical resistance heating. Since the interpretation of the CFB pilot test is complicated by the presence of organic soils and still incomplete, results of resistance heating reported in the literature are used as a basis for comparison.

### 3.1 Case Histories of Electric Resistance Heating

Electrical resistance heating tests have also been conducted by the Lawrence Livermore National Laboratory (LLNL) in California (Buettner et al., 1992) and by the Pacific Northwest Laboratory (PNL) in Washington (Bergsman et al, 1993). In both tests 6, electrodes each 3.05 m (10 feet) in length were used to heat up 89 m<sup>3</sup> of soil. The electrodes were arranged at the vertices of a regular hexagon circumscribed by a 6.1m (20 feet) diameter circle, which is different from the rectangular pattern used in the CFB pilot test.

The LLNL heating system was powered by a 3-phase electricity supply provided by a 125 kV-A generator operating at nominal voltage of 400 VAC. Water was added to the electrodes to keep the contact resistance between the electrodes and the soil at a reasonably low

level. The test was run for 15 days during which 14 920 kWh of electricity was dissipated in the soil. Temperature at the centre of the electrode array rose from 19 °C to 44 °C by the end of the heating period but continued to rise for several days afterward to a peak of 54 °C (Buettner and Daily, 1995).

At the PLN site, 6-phase electrical power were used with the maximum voltage rated at 2400 V. The test lasted 50 days. Initially the power was maintained at 25 kW and the increase in soil resistance was controlled by adding water to the electrodes at a rate of 0.18 m<sup>3</sup>/d (2 USgal/h). After one week the power was increased and maintained between 30 kW and 35 kW for the remainder of the test. The total energy delivered to the system was 34 000 kWh. The temperature at the centre of the electrode array and at 0.6 m (2 ft.) depth steadily rose from 18 °C and levelled off at approximately 80 °C late in the test.

### 3.2 Numerical Simulation of Conduction Heating

An in-house finite element model, ADHEAT, formulated for heat transport in both conduction and advective modes was used to simulate conductive heating using heaters arranged in a similar hexagonal pattern. The soil properties used in the analysis are summarized in Table 3.

Table 3. Soil Properties Used in Conduction Heating Simulation

Soil thermal conductivity at temperatures ≤ 100 °C (W/m-K)	1.364
Soil thermal conductivity at temperatures > 100 °C (W/m-K)	0.268
Soil volumetric heat capacity at temperatures ≤ 100 °C (MJ/m <sup>3</sup> -K)	2.00
Soil volumetric heat capacity at temperatures > 100 °C (MJ/m <sup>3</sup> -K)	1.21
Latent heat of vaporization (MJ/m <sup>3</sup> )	617.03
Phase change temperature (°C)	100
Soil porosity	0.36
Volumetric water content	27.4%

Temperature boundary conditions were prescribed at the heater locations to simulate constant temperatures of 100 °C, 300 °C, 500 °C, and 900 °C throughout the heating period. Heat transport by conduction alone was considered in the present analysis. Figure 4 shows the soil temperature along a radial line extending from the centre of the heater array to one the heaters for the various applied temperatures. It can be seen that for

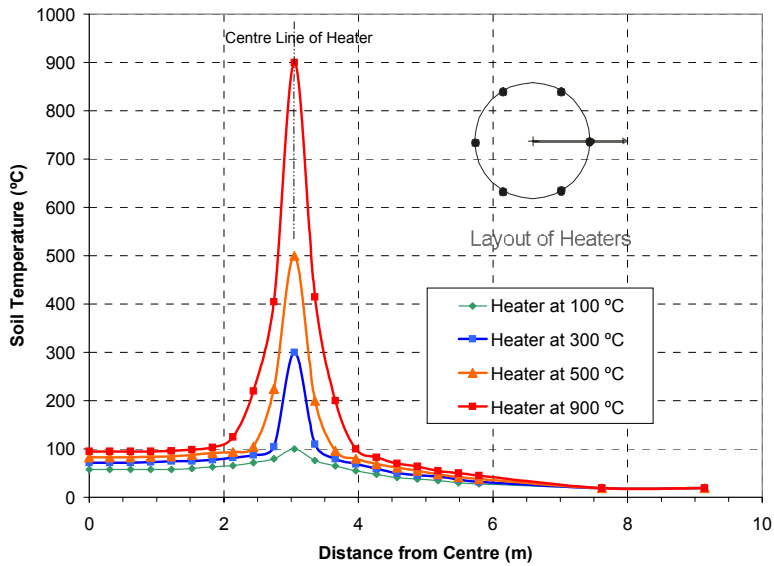


Figure 4. Soil Temperature after 90 Days of Conduction Heating

heater temperatures higher than 500 °C, the increase in soil temperature and the soil temperature within the heater array is not uniform with sharp peaks centred on each heater.

### 3.3 Comparison between Resistance Heating and Conduction Heating

Figure 5 summarizes the temperature variation with time at the centre of the heater array for the present analysis and the LLNL and PNL heating tests. The energy consumed in each case was also noted in this figure.

At first glance, it appears that energy consumption may be considerably higher for electrical resistance heating than for conductive heating. To attain the same temperature at the centre, the ratios of the total power consumed by resistance heating to that used by conduction heating are 2.0 (LLNL Test) and 2.5 (PNL Test) respectively. However, if an efficiency of 60% is assumed for the conduction heaters, these ratios drop to 1.2 and 1.5. The higher energy consumption in resistance heating is due to the addition of moisture around the electrodes in order to maintain an acceptable flow of electric current.

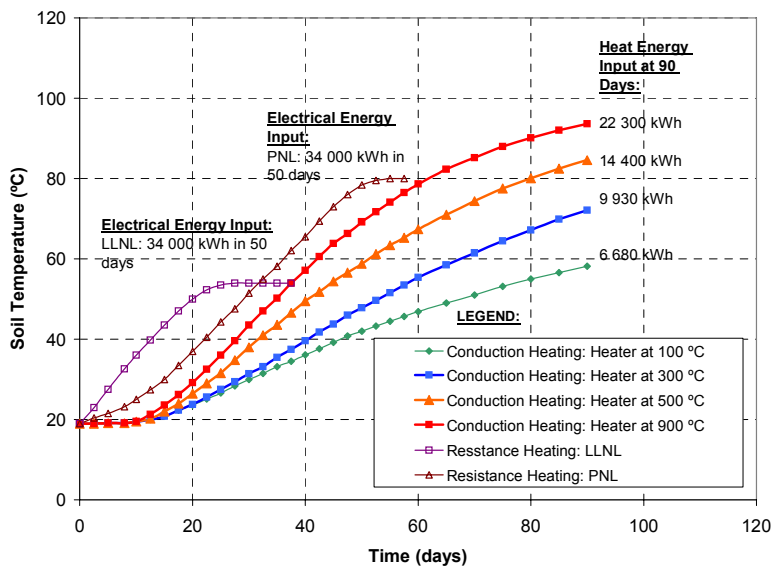


Figure 5. Time History of Soil Temperature at Centre and Energy Consumption

Figure 5 also shows that resistance heating will heat up a site much quicker than conduction heating. For example, when the conduction heater was set at 500 °C, resistance heating would achieve a similar central temperature in about half the time required for conduction heating.

#### 4. CONCLUSION

The CFB pilot test results show that soil heating can accelerate the removal of gasoline contamination from subsurface soils using multi-phase extraction. However, they also indicate that the increase in vapour pressure with temperature is not the only factor controlling the effectiveness of soil heating. The nature of the soil, especially its organic carbon contents, needs also be considered. In this study, the high TOC has enabled a higher proportion of contaminants to be adsorbed in the early stage of the test. Other operational concerns include adequate control of water flow to and from the site, the proper spacing between electrodes, and the avoidance of electrical hazards. For example, a portion of the chain-link fence around the site was replaced by wooden fence for safety reasons.

Comparison between conduction heating and electrical resistance heating demonstrates that conduction heating is more energy efficient but may take more time in achieving the same temperature. In order to maintain the flow of electrical current for resistance heating, high moisture content in the heated soil needs to be maintained. This high moisture content may reduce the pore space for air flow and, consequently, the effectiveness of soil vapour extraction.

Further studies on the thermal properties and behaviour of organic soils as well as the applicability of conduction heating are still being carried out in the laboratory at O'Connor Associates (OAEI).

#### 5. ACKNOWLEDGEMENT

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