ENHANCING VACUUM EXTRACTION OF VOLATILE ORGANICS USING ELECTRICAL HEATING

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ABSTRACT

At Lawrence Livermore National Laboratory (LLNL) we have tested the feasibility of electrical (joule) heating of the ground in engineering-scale tests for use as an adjunct to cyclic steam injection and vacuum extraction for the removal of volatile organic compounds (VOC's).

Our purposes were to 1) learn about the practical aspects of electrical heating to include details such as: selection and sizing of electrode materials and wires, and how to maintain low contact resistance between the electrodes and the ground, 2) to compare actual heating rates with those based on simple calculations, 3) to provide data for scaling the experiment up in size for application at an actual contaminated site, and 4) to provide data for estimates relating to the economics of electrical heating.

We performed an engineering-scale field test in typical Livermore Valley soils during September, 1991. We used a pattern of six heating wells equally spaces on a circle with a diameter of 6.1 m (20 ft). The electrodes were made of stainless steel tubing sections and each electrode was packed in sand with a water feed tube and electrically wired to the surface.

The heating wells were powered with 3-phase, 400 volt, 60 Hz power supplied by a 125 KVA generator. The contact resistance of the electrodes was maintained at a low value by saturating the sand pack around the electrode with water via a feed tube.

Fixed thermocouples were used to monitor the temperature as a function of time during the test. We ran the test for 10.76 days around the clock, then during the day only for 4 additional days. The currents to the electrodes, and thermocouple temperatures were monitored on a regular basis. At the end of the 24 hr/day heating period the temperature in the center of the pattern (the coldest point) at a depth of 4.88 m rose from a starting value of 19°C to 38°C. During the daytime-only heating, the temperature rose to 44°C. At this point the power was turned off and the temperature continued to rise to 54°C in a 10-day period after which we stopped temperature monitoring. Other thermocouples nearer to the periphery read as high as 73°C. These experimental results agree closely with very simple calculations based on a two-dimensional model assuming homogeneous electrical resistivity and thermal properties. Over the duration of the heating phase of the experiment, the total energy dissipated in the ground was about 15,000 KW hr.

INTRODUCTION

Recent studies have indicated that cyclic steam injection and vapor extraction can be used to rapidly remove organics from soils while producing only a small volume of highly concentrated fluids (1,2). In the laboratory complete removal of semi-volatile solvents and hydrocarbons has been demonstrated. The effectiveness of the process varies with the permeability of the soil. For a given combination of steam and vacuum extraction pressure applied to the wells, higher gas flow rates will be observed in coarser-grained sediments which have higher gas permeabilities than fine-grained sediments. Soils with lower permeabilities such as silts and clays, require a greater steam injection/vacuum pressure to induce flow through the soil. The capacity to induce flow through fine-grained materials reaches an upper limit when the required injection/vacuum capacity cannot be achieved. Remediation of fine-grained soils using steam injection and vacuum extraction may be ineffective because a closer spacing between injection and extraction wells will be required, or in fact may become impossible for soils with very low permeabilities.

Electrical heating has been proposed to enhance the efficiency of steam injection and vacuum extraction of VOC's(3). Conceptually the idea is very simple. Electrical currents at powerline frequency (60 Hz) are made to flow between electrodes embedded in the earth causing resistive or joule heating. Because current will flow most freely through high conductivity parts of the earth (typically the fine-grained soils), above the water table the current will be confined mostly to the fine-grained soils, with very little current flow in the sands and gravel. The current flow in the grained soils in turn will cause them to heat up, and thus raise the vapor pressure of the VOC's trapped within. The VOC's will then be driven by gas pressure gradients from the fine-grained soils into the more permeable parts of the formation where they can be swept out by steam injection and vacuum extraction.

Electrical heating is thus complementary to cyclic steam injection and vacuum extraction. Steam injection and vacuum extraction removes VOC's from the permeable parts of the formation (sands and gravel) where very little electrical current can flow. In contrast electrical heating works on the least permeable parts of the formation (silts and clays) where most of the current will flow.

We have used electrical heating at LLNL in engineering-scale tests to study some of the practical issues, and gain experience with the hardware. The site chosen is on the property of Sandia National Laboratory at Livermore, California. This "clean site" has no VOC contamination and thus we need not concern ourselves with the related complications.

HEATING RATE CALCUALTIONS

Expected heating rates can be calculated based on a simple 2d model with assumed homogeneity of electrical and thermal properties. We show some plots of calculated heating rates for three cases: 1) a 6-well pattern with 3-phase currents, 2) a 6-well pattern with 6-phase currents, and 3) a 3-well pattern with 3-phase currents. The calculations are based on equal total power inputs to the ground, and thus for cases 1) and 2) we use an electrode current of 10 amp/m while for case 3) 20 amp/m is used. The electrical conductivity is taken to be 0.1 S/m (typical for Livermore soils), and the volumetric heat capacity is $2x10^6$ joule/°C·m^3 (4). The results of these calculations are displayed in Fig. 1. The gray scale is logarithmic. Note that in each case only half of the pattern is shown. The whole pattern is easily visualized by noting that cases 2) and 3) are symmetric about their left boundary, while case 1) has three-fold symmetry about the center.

There are some notable features in these patterns. First the heating rate is the same in the center of the pattern for cases 2) and 3), and 25% less for case 1). Second the most uniform heating results from 6-spot, 6-phase heating, followed by 6-spot, 3-phase heating, and lastly 3-spot, 3-phase heating. Third for a given heating rate in the center of the pattern, the area near the electrodes will be hotter if there are only three wells instead of six. In general it can be said that the larger the number of heating wells, the more uniform the heating distribution will be. In the limit of N-phase heating for N wells, where N is a large number, the heating will be nearly uniform inside the circle.

As a practical matter, three-phase heating has advantages over six-phase heating in that the power generating and handling equipment is readily available and affordable. Three-phase power is available directly from electric utility companies and from motor-generators which one can rent or buy. The slight advantage that 6-spot, 6-phase heating has in uniformity over 6-spot, 3-phase heating may not be worth the extra investment required to produce 6-phase power.

DESCRIPTION OF EXPERIMENTS

In our engineering-scale test the electrodes were buried at a depth of about 5.18 m (17 ft) in typical Livermore valley alluvial soils which are composed of interbedded clays, sands, and gravel. The electrodes were made from stainless steel tubing, and the electrodes were packed in sand so that they could be saturated with water from the surface via a feedtube. Since the area around the electrodes gets extremely hot, the soil dries out around the electrode as heating proceeds, driving the electrical contact resistance up. Very little current will flow unless the contact resistance is reduced, and this done by saturating the sandpack around the electrode with water.

A plan view of the heating well layout is shown in Fig. 2. There are six wells equally-spaced on a 6.1 m circle. Wells

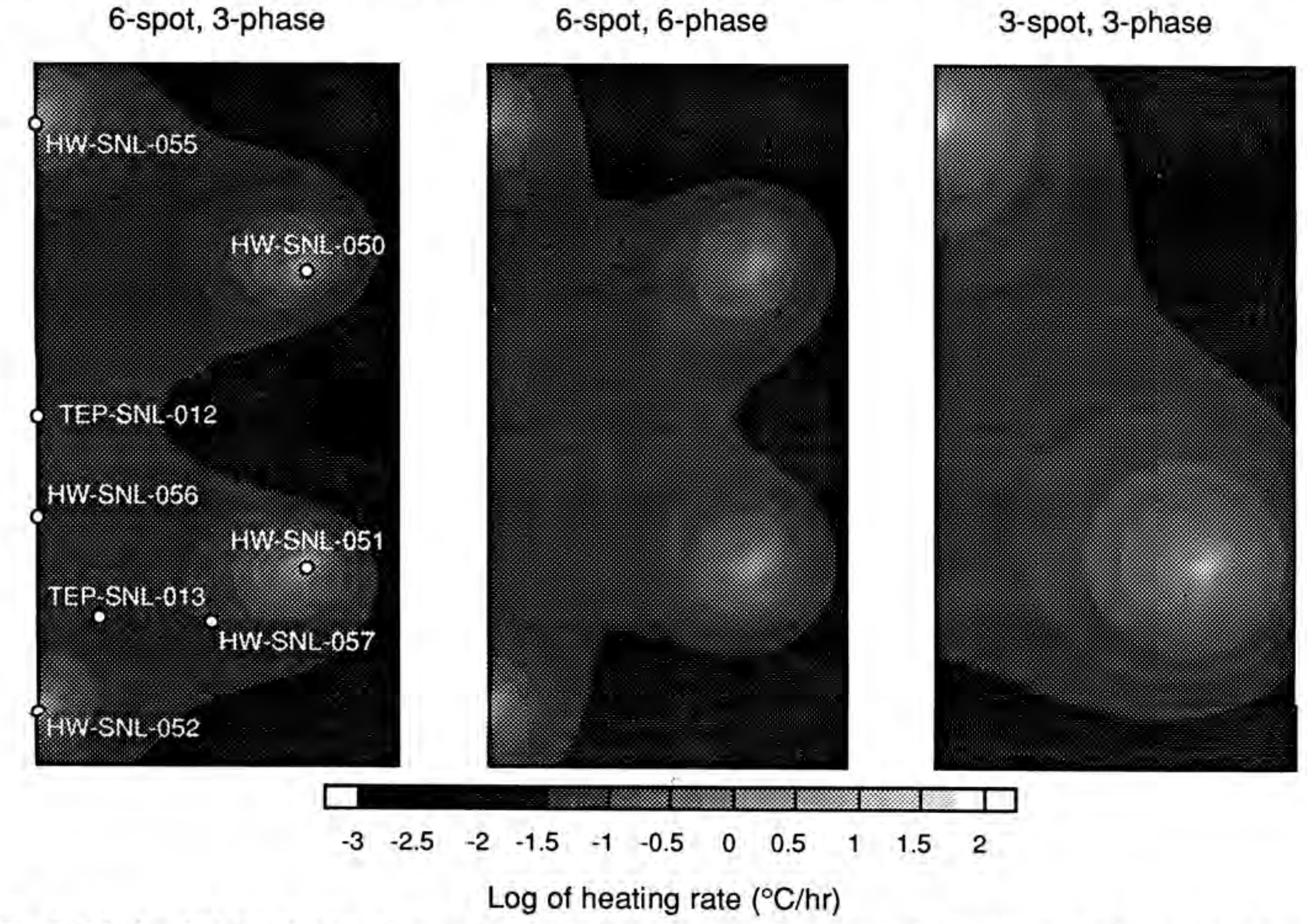

Fig. 1. Calculated 2d electrical heating rate distributions for three cases: 1) 6-spot, 3-phase, 2) 6-spot, 6-phase, and 3) 3-spot, 3-phase. Locations of some of the heating and thermocouple wells are shown superimposed on the 6-spot, 3-phase distribution.

HW-SNL-052 and 055 employ an early two-electrode design, while wells HW-SNL-050, 051, 053, and 054 use a single electrode design. Thermocouple well locations are also shown in Fig. 2. They are designated TEP-SNL-012 and TEP-SNL-013. These thermocouple wells were constructed with three thermocouples at depths of 2.44 m (8 ft), 3.66 m (12 ft), and 4.88 (16 ft) packed in fine sand inside a 2.54 cm (1 in) PVC pipe, with another thermocouple attached to the outside of the pipe at 4.88 m. Wells HW-SNL-056 and 057 (early two-electrode design) were also used for temperature monitoring since they had thermocouples at depths of 1.83 m (6 ft) and 4.28 m (14 ft).

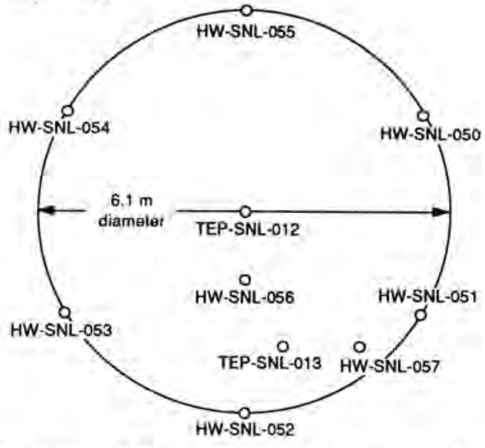

Fig. 2. Plan view of the heating and thermocouple wells for our engineering-scale test.

Three-phase electrical power for heating was supplied by a 125 KVA diesel generator operated at a nominal voltage of 400 VAC between the phases. Safety was a major concern so we made every effort to reduce the hazards involved. Each phase of the system was protected with 100 A fuses, and all wires were carried in PVC conduit along the ground to an insulating distribution box in the center of the pattern. From this box power was carried in PVC conduit to the individual wells. During electrical heating an insulating keep-out fence was in place around the test area, and all power was shut off before entering the field to monitor thermocouple readings.

RESULTS

The experiment began on September 13, 1991 and continued 24 hours per day until September 23 when we started heating during the day only. The power was turned off at the end of the work day on September 27. We continued to take thermocouple readings until October 7.

The results for the central thermocouple well, TEP-SNL-012, are shown in Fig. 3. Note that the time scale on the plot is such that the first data point is during the morning of September 13, 1991. The temperature of the thermocouple at 4.88 m depth rises steadily from 19°C to 38°C during the 24 hr/day heating period, to 44°C during the day-only heating period, and continued to rise to 54°C even after the power had been turned off. The other thermocouples in this well (packed in sand on the inside of the PVC pipe) were installed at the end of the fourth day, and we note that some few days were required for them to equilibrate. During the first 10 days the heating rate at 4.88 m depth is 1.6°C per day.

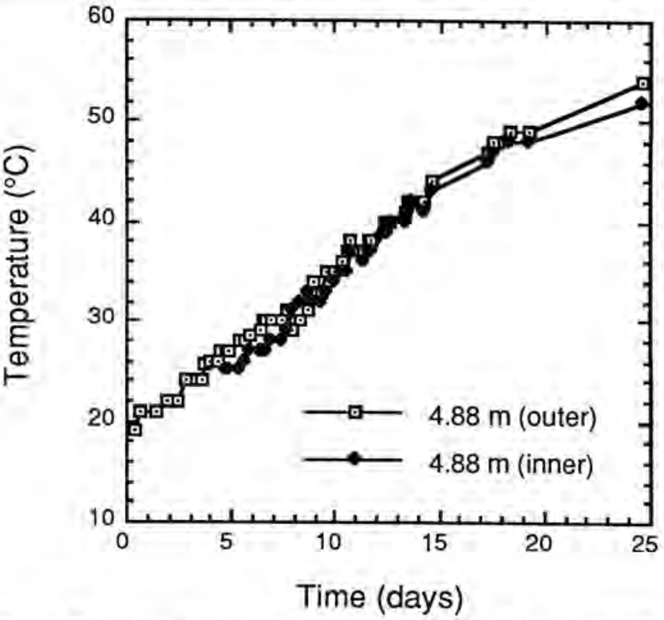

Fig. 3. Temperature vs. time for thermocouples in well TEP-SNL-012.

The temperatures in well HW-SNL-057 (closest to any electrode) are plotted in Fig. 4. The lower and upper thermocouples are at a depths of 4.28 and 1.83 m respectively. At the end of the 24 hr/day heating period the temperatures are 72°C and 54°C respectively. During the day-only heating they peak at 73°C and 56°C and end up at 72°C and 54°C. By the end of the experiment they had fallen to 54°C and 48°C.

Comparisons between heating rates based on the simple model and experimental data can be made base on the heating rate distribution of Fig. 1 for the 6-well, 3-phase case (left-most plot). Note that locations of some of the heating and thermocouple wells have been superimposed on the heating rate distribution.

The actual calculated value in the center of he pattern (TEP-SNL-012) is 0.033°C/hr. In our experiment, the average current per phase was 73 amps during the 24 hr/day heating period which results in a current per electrode of 12 amp/m. Since the heating rate is proportional to the square of the current, the heating rate of 0.033°C/hr should be scaled by the

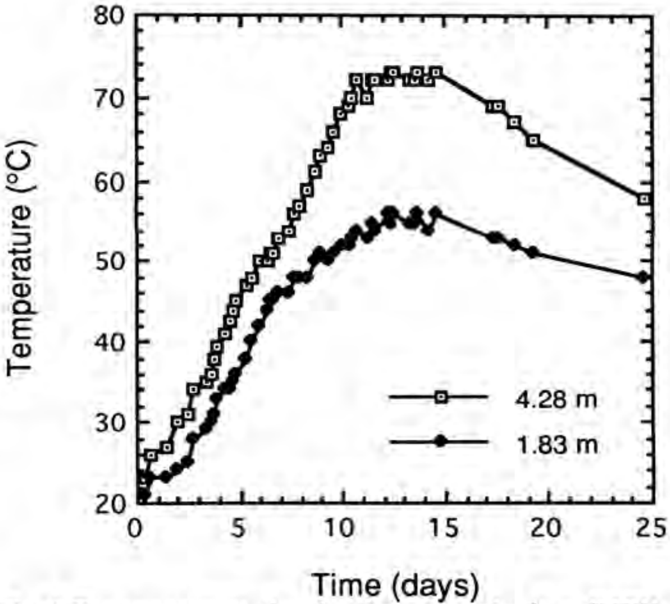

Fig. 4. Temperature vs. time for thermocouples in well HW-SNL-057.

factor $(12/10)^2$, which results in a heating rate of 0.047°C/hr or 1.14°C/day. This compares with an actual rate of 1.60°C/day based on a linear curve fit to the data of Fig. 3.

At well HW-SNL-057 the calculated rate is 2.05°C/day and the measured rate is 4.65°C/day. Considering the assumptions we have made and the simplicity of the calculations, the agreement is quite good.

A final interesting result is shown in Fig. 5 where the total energy deposition is plotted. The final value is 14 920 KW · hr, and the deposition rate is nearly linear during the 24 hr/day heating period. The "stairsteps" in the energy deposited are a result of the "day-only" heating at the end of the experiment.

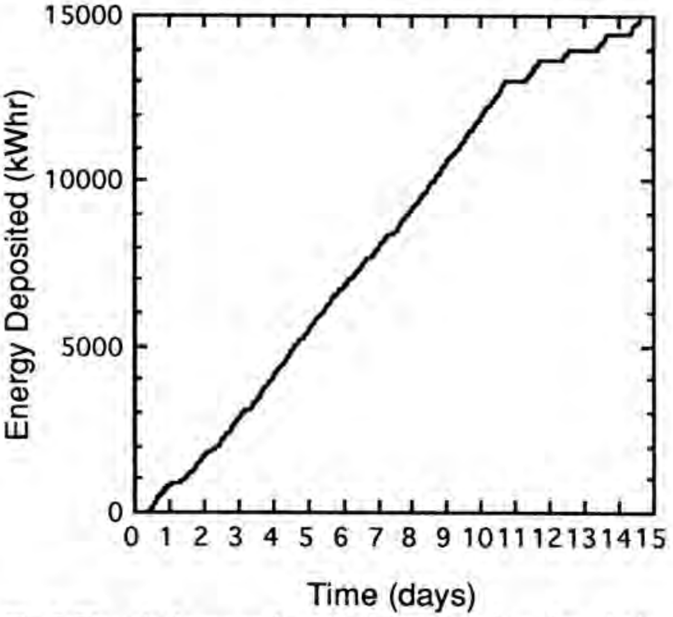

Fig. 5. Electrical energy deposited in the earth vs. time during the heating test.

CONCLUSIONS

Powerline-frequency electrical energy can be used effectively for heating soils. We raised the temperature of about 300 m^3 (393 yd^3) of soil by 37°C in 25 days using electrical heating. This was done by heating 24 hr/day for 10.76 days, then 4 days during the day only, and finally letting the soil come to equilibrium for another 10 days. the total energy required was about 14920 kW · hr. This results in a figure of merit for the process of 1.34 kW · hr/°C · m^3 (1kW · hr/°C · yd^3). The heating rates agreed well with those predicted based on very simple calculations.

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