Soil-Heating Technology Shown To Accelerate the Removal of Volatile Organic Compounds from Clay Soils

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The Six-Phase Soil Heating (SPSH) technology was demonstrated to be capable of heating and remediating low-permeability soils containing volatile organic compounds (VOCs). Six-Phase Soil Heating accelerated the removal of VOCs from clay soils, removing over 99 percent of the contaminants in only 25 days. Soil temperature profiles showed that SPSH was successful in heating the targeted clay zone that contained higher levels of soil contamination. The success of SPSH has resulted in its planned use and consideration by potential commercial partners for use at private industrial and other government sites.

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Scientists at the DOE's Pacific Northwest National Laboratory and at Westinghouse Savannah River Company have completed the evaluation of a Six-Phase Soil Heating (SPSH) demonstration as a cost-effective technology for heating and remediating low-permeability soils containing volatile organic compounds (VOCs).

The technology was tested in November 1993 as part of the DOE's Office of Technology Volatile Organic Compounds in Non-Arid Soils Integrated Demonstration at the Savannah River Site, Aiken, South Carolina. Soil remediated at the integrated demonstration site has been contaminated with perchloroethylene (PCE) and trichloroethylene (TCE), sources of potential groundwater contamination. The highest soil contamination occurs in clay-rich zones, between 9 and 12 m (30 and 40 ft) below the surface, that could not be effectively treated by conventional soil vapor extraction.

Specific test objectives were to (1) demonstrate that SPSH accelerates the removal of TCE and PCE from Savannah River Site clay soils compared to conventional soil vapor extraction and (2) quantify the areal and vertical distribution of heating as a result of SPSH under soil conditions experienced at the Savannah River Site.

To quantify accelerated VOC removal using SPSH, pre- and post-demonstration soil characterization and monitoring activities were conducted. Thermocouples were installed at 30 locations to quantify the areal and vertical heating within the treated zone. Soil samples were collected before and after heating to quantify the efficacy of heat-enhanced vapor extraction of PCE and TCE from the clay soil. Samples were taken (essentially every one-third of a meter (one foot)) from six wells before heating and adjacent to these wells after heating for direct comparison of soil parameters and changes.

This is the first time that scientists have accomplished heating soils to these temperatures using an ohmic heating method.

Results of the Savannah River Site field demonstration indicate that SPSH technology is capable of heating and remediating low-permeability soils containing VOCs. Comparisons of pre- and post-test soil samples show that the median contaminant removal from the clay zone was 99.7 percent within the electrode array. Outside the array where the soil was heated, but to only 50°C, the removal efficiency was 93 percent, showing that heating accelerated removal of VOCs from the clay soil. The accelerated remediation resulted from effective heating of the contaminated clay zone by SPSH.

Soil temperature profiles show that SPSH was successful in heating the targeted clay zone that contained higher levels of soil contamination. The clay-zone temperatures increased to 100°C after eight days of heating and were maintained near 100°C for 17 days. In addition, electrical heating removed 72,000 L (19,000 gal) of water from the soil as steam, with a peak removal rate of 5,700 L per day (1,500 gal per day) of condensed steam. This is the first time that scientists have accomplished heating soils to these temperatures using an ohmic heating method.

The success of the SPSH technology at the Savannah River Site has resulted in its planned use at the Rocky Flats Plant and consideration by several potential commercial partners for use at private industrial and other government sites.

THE ADVANTAGE OF SOIL HEATING BY ELECTRICITY

Several candidate technologies currently exist, or are being developed, to facilitate the removal of volatile compounds from soil. Soil vapor extraction, for example, is a proven in-situ technology for removing VOCs like TCE or PCE from permeable soils. This technology succeeds when soil contaminants transfer readily into air that flows easily through the soil pore spaces. The contaminant is carried by the air through the soil to a vacuum vent and removed. Successful venting requires that the contaminant be at least semivolatile and the soil be permeable to the flow of air. In homogeneous and permeable soils, soil vapor extraction produces rapid results with a relatively low overall cost. Conventional soil vapor extraction, however, becomes infeasible when remediating low-permeability nonhomogeneous soils, such as those at the Savannah River Site or when low volatility contaminants are present (USEPA, 1991; Pedersen and Curtis, 1991).

All soil heating processes increase the temperature of the soil and contaminant, increasing the contaminant's vapor pressure and its removal rate.

Soil heating can extend the effectiveness of soil vapor extraction to less volatile compounds, to less permeable soils, and, potentially, to contaminant depths near or in the water table. Principal processes for soil heating are resistive heating, radio frequency heating, and steam injection (Smith and Hinchee, 1993). All soil heating processes increase the temperature of the soil and contaminant, increasing the contaminant's vapor pressure and its removal rate. However, compared to heating by steam or hot air injection, applied electrical fields have the advantage of heating soils internally. Thus, low-permeability zones or complex heterogeneous soils can be treated. Electrical heating also provides an insitu source of steam to accelerate further removal of volatile organics from soils. This enables higher molecular weight compounds that are not very volatile to be removed by simple venting. Removal of soil moisture (as steam) also tends to increase the gas permeability of soils and can reduce the mass transfer limitations associated with low-permeability soils (Gierke et al., 1990; Rodriguez-Maroto and Wilson, 1991). Both processes further add to the rate of contaminant removal during venting. Soil heating can provide a cost-effective alternative to conventional soil vapor extraction or soil excavation followed by ex-situ treatment.

HOW SIX-PHASE SOIL HEATING WORKS

SPSH uses common low-frequency electricity to heat soils as an enhancement to soil vapor extraction (Bergsman et al., 1993a, 1993b). The mechanism of heating is resistive dissipation of the electrical energy. The SPSH technology uses conventional single-phase transformers to convert standard three-phase electricity into six-phase electricity.

Electrodes are inserted into the ground in one or more circular arrays of six per array. Each electrode is connected to a separate transformer wired to provide it with a separate current phase. A seventh, electrically neutral electrode located at the center of the array doubles as a soil vapor extraction vent. The six-electrode array was chosen because it provides a more uniform distribution of electrical currents in the soil than other geometries. The SPSH electrode system is typically installed using common drilling equipment and constructed of modified well-casing materials. SPSH uses conventional nonspecialized utility transformers, resulting in low capital cost.

Although more heating occurs near the electrodes, the six-phase pattern produces a relatively uniform heating pattern. Excessive drying can occur near the electrodes, but these regions can be managed through judicious water addition. The SPSH technology is also an ideal method for heating low-permeability soils such as clays. Because of the clay layer's relatively high electrical conductivity, it receives the majority of the current and is where most of the energy is dissipated.

Soil heating patterns were calculated by a rigorous electric field solution in a computer code called TEMPEST (Trent and Eyler, 1993). TEMPEST predictions have been used to fine-tune a semi-analytical model of electrical heating as a function of water content, temperature, soil type, and location within the SPSH array. This model was incorporated into a modified version of the TOUGH2 code (Transport of Unsaturated Groundwater and Heat), a thermal, porous media code capable of predicting the movement of air and water in soils (Pruess, 1987, 1990). Applications of the resulting process simulator are described in more detail in Bergsman et al. (1993a, 1993b) and Heath et al. (1992).

The process simulator was used to help make a number of design decisions.

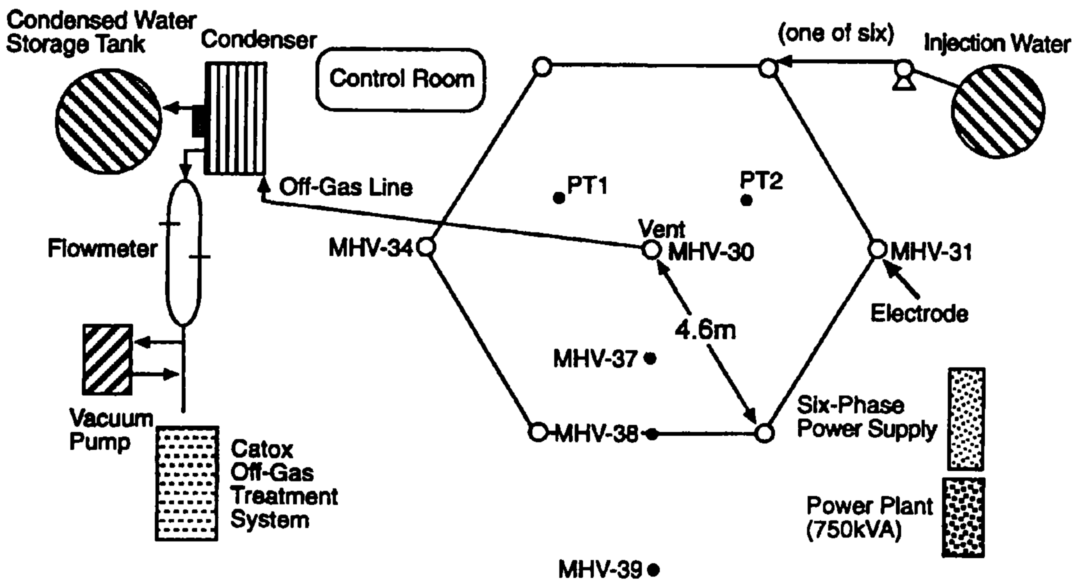
For the Savannah River Site demonstration, the process simulator was used to help make a number of design decisions. These decisions included choosing the best power level and array diameter and selecting the best location for the thermocouples. Also, the simulator helped predict the effect of water addition at the electrodes and determine the effectiveness of the venting.

DEMONSTRATING THE TECHNOLOGY

The demonstration consisted of five phases: (1) pre-test drilling and soil sampling; (2) baseline SVE test without heating; (3) SPSH with venting; (4) venting after heating; and (5) post-test soil sampling. The baseline venting spanned 12 days, and the heating covered 25 days. Electrical heating began on November 3, 1993, with a few days of system testing at lower power levels. Between November 7, 1993, and December 2, 1993, an average power of 200 kW was applied to the electrode array, and the mean voltage was about 1,000 V. The transformer and surface equipment were automated, and the SPSH system operated unattended beginning November 19, 1993. Toward the end of heating, soil resistivity increased, so voltage was increased to 2,400 V (line-to-neutral (l-n)) to maintain power input levels. By the end of the test, 100,000 kWh of energy had been applied.

Exhibit 1 shows the electrode array, the location of the monitoring wells, and principal surface equipment used for the SPSH demonstration. The electrodes were positioned on a circle with 9.1-m (30-ft) diameter and had electrical contact with the soil between 7 and 13 m (23

Exhibit 1. Location of Monitoring Wells, Electrodes, and Surface Equipment



Note: Well locations are drawn to scale; surface equipment is not.

and 44 ft). The vacuum extraction vent placed at the center of the array was also connected to the six-phase transformer (neutral).

The surface equipment shown in Exhibit 1 includes a trailer-mounted 750 kVA power plant that supplied 480V of three-phase power to a six-phase power transformer. The six-phase transformer was rated at 950 kVA and used a remote computer to control the output voltages for each electrode. The power transformer used multiple link-tap changes to attain discrete voltages between 300 and 2,400 V (l-n); silicon control rectifiers allowed further adjustment of voltages. The electrodes were connected to the transformer via insulated power cables lying on the soil surface. The soil surrounding each electrode was supplied with water through a drip system to the electrified regions that spanned the clay zone. A vacuum system pulled air and contaminant vapors from the soil and through a condenser to remove the steam generated by heating. Water that collected in the vent well was removed by an air-actuated piston pump with remote speed control (Hydrostar 8001, Instrumentation Northwest).

For each monitoring well, the placement of the thermocouples was chosen to give measurements in the sand above and below the clay, two measurements within the clay, and one measurement in the sand adjacent to the clay. Sandpacks around slotted pipes were used for pressure communication with the soil. Pressure transducers located at the surface measured the pressure at these locations.

A number of monitoring wells were drilled for soil sampling and for temperature and pressure monitoring in the soil. The soil sampling program was designed to quantify removal of PCE and TCE from the soil and the extent of soil drying. Soil samples were taken, essentially every foot, from six wells before heating and adjacent to these wells after heating (MHV-30, MHV-31, MHV-34, MHV-37, MHV-38, MHV-39). The difference between the pre- and post-test samples was used to quantify the efficacy of the SPSH process. For soil sampling from wells, continuous cores were taken with a split spoon sampler using hollow steam auger drilling methods. Duplicate samples were taken every one-third of a meter (one foot) from 7.6 to 16.8 m (25 to 55 ft); above 7.6 m (25 ft), samples were taken every 1.5 m (5 ft). Additional details on sampling and analysis are described elsewhere (Eddy-Dilek et al., 1994; Eddy et al., 1991; and Eddy-Dilek et al., 1993).

RESULTS OF SPSH DEMONSTRATION

The following sections discuss the key results from the SPSH demonstration including observed heating, contaminant removal, and changes in soil permeability.

Soil Heating

Quantifying areal and vertical soil heating was one of the main objectives of the SPSH demonstration. Thermocouples were placed at different depths to determine the vertical heating distribution. The areal variation was obtained by placing thermocouples in different wells.

Exhibit 2. Temperature in Well MHV-38

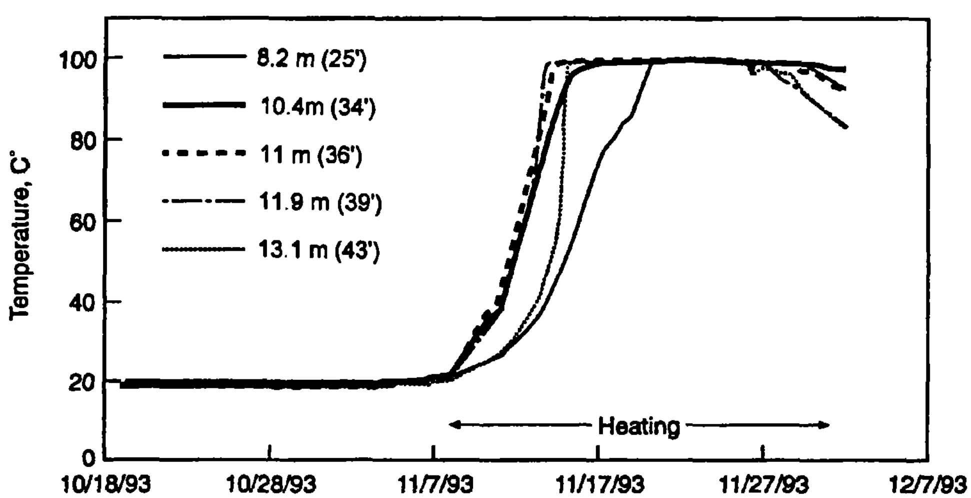


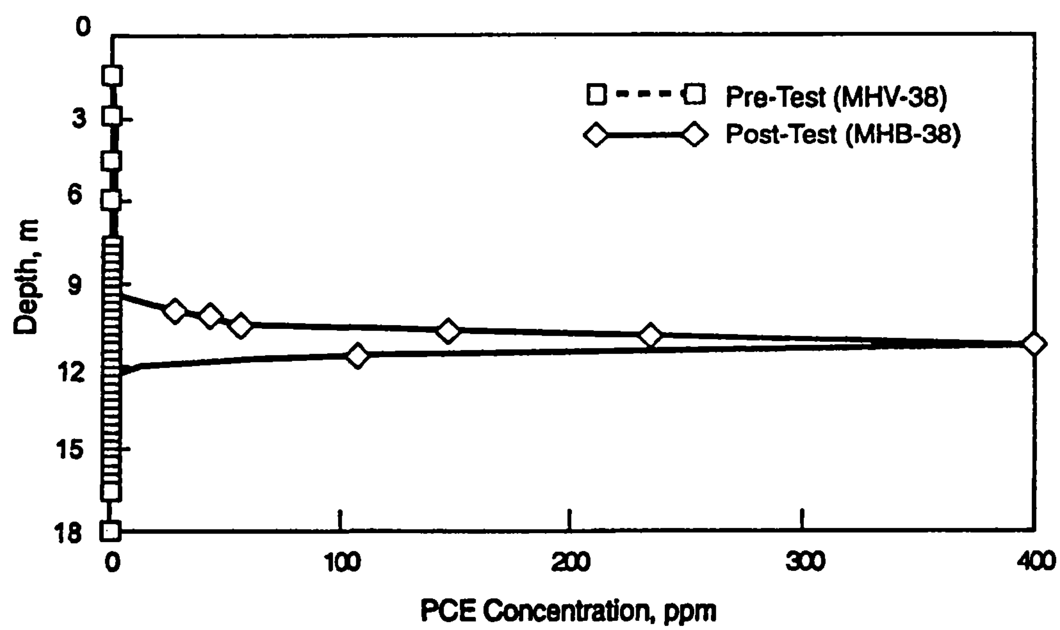
Exhibit 2 shows the temperature in MHV-38, which is the observation well located between two electrodes. An important attribute of electrical resistive heating is its ability to heat low-permeability soils. The clay-zone temperatures are represented by the thermocouples at depths of 10.4 and 11 m (34 and 36 ft) and the sand above and below the clay by the thermocouples at 8.2 and 13.1 m (27 and 43 ft), respectively. Exhibit 2 shows that the clay-zone temperature increased rapidly to 100°C, confirming the effective heating of the clay. The more rapid rise in the clay-zone temperature compared to the adjacent sands results from the clay being more electrically conductive than the sand and agrees with modeling results.

The temperature in the clay zone rose to 100°C (MHV-40 and MHV-41 peaked at 105° to 110°C) after eight days of heating. Most of the data show the temperature of the sand above and below the clay also rising to essentially 100°C after 10 to 15 days of electrical heating. Electrical heating continued after reaching 100°C to boil the moisture within the soil.

Contaminant Removal

For pre- and post-test soil drilling and coring, samples were taken at the same depth for each well pair. The difference between the pre- and post-test samples shows how well the soil was remediated. **Exhibit 3**

Exhibit 3. Comparison of Pre- and Post-Test PCE Contamination in the Soil for Well MHV-38



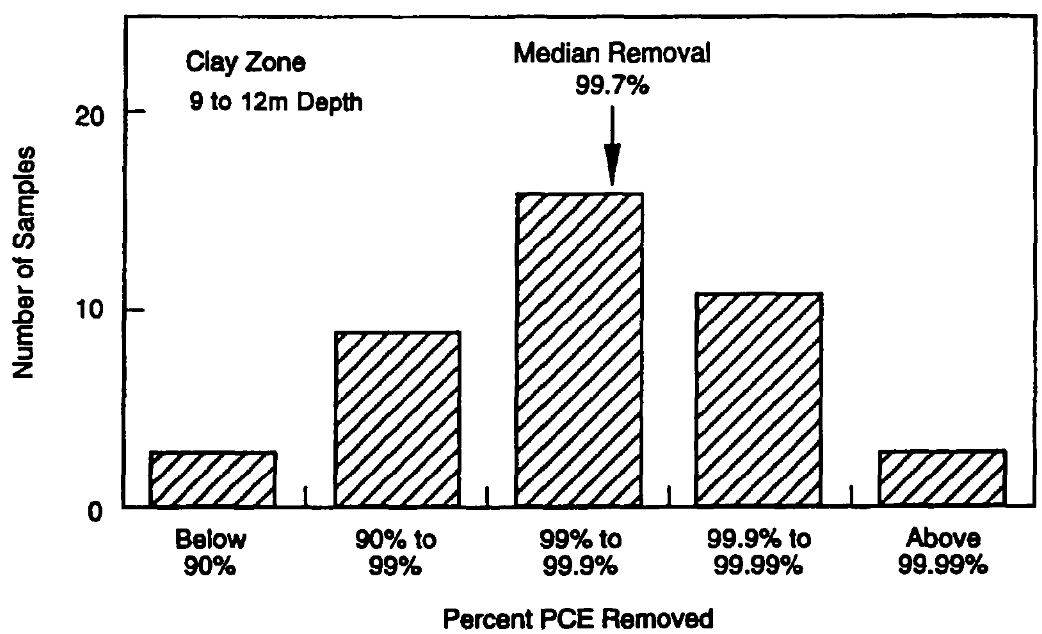
Note: The post-test well (MHB-38) was drilled 1 m (3 ft) from the pre-test well.

shows the pre- and post-test soil measurement for PCE in test well MHV-38. This well was located within the heated zone and directly between two electrodes. These data show the substantial reduction in the clay-zone concentration of PCE. Because samples were taken from the same depth in adjacent wells, we did not interpolate between data or average data before calculating differences between pre- and post-test samples. In a number of cases, soil samples at the same depth from adjacent wells had much different soil types because of soil heterogeneity.

Exhibit 4 shows the percent of PCE removed in all the clay-zone samples (9 to 12 m), excluding the samples from MHV-39, which is outside the electrode array. The median removal efficiency is 99.7 percent for these samples. Although the data have a wide range in removal efficiency, the distribution is reasonable. The main reasons for the variation are soil heterogeneity and the fact that samples taken at the same depth in adjacent wells varied in clay content.

Analysis of remediation and heating in well MHV-39 shows that heating accelerated PCE removal from the clay. MHV-39 was located outside the electrode array at a radius of 7 m (23 ft). This location, which was heated much less than inside the array, was chosen to quantify the effect of heating on the remediation. The temperature at MHV-39 rose to 50°C at the end of heating (25 days), while the temperature within the array reached 100°C after eight days of heating. The median removal of

Exhibit 4. PCE Removal Efficiency after Treatment with SPSH



PCE at MHV-39 was 93 percent at the end of the test, which is appreciably less than the 99.7 percent removal within the array discussed above. At a 23-foot radius, the predicted heating rate as a result of SPSH is about 10 to 20 percent of the heating rate within the electrode array (MHV-30, MHV-37, and MHV-38).

The temperature data confirm this prediction and give an initial increase in temperature at MHV-39 of about 15 percent of the temperature rise for wells MHV-30, MHV-37, and MHV-38. These data show that MHV-39 was heated less and remediated less than the soil within the array. Consequently, heating accelerated PCE removal from the clay. Results for TCE removal are equivalent.

Removal of volatile contaminants from low-permeability soil should be greatly accelerated by steam creation within the soil, which convects the contaminant out of the low-permeability region. Accordingly, removal of soil moisture should correlate with the effectiveness of contaminant removal from the clay. For soil vapor extraction, the rate of contaminant removal is typically proportional to the concentration of the contaminant. Thus, it becomes progressively more difficult to remove the contaminant as its concentration approaches zero. For comparison with moisture removal, the fraction of contaminant remaining after treatment is a good measure of effectiveness.

Soil Permeability Changes

One objective of electrical soil heating is increasing the air permeability of the soil by drying the soil. Substantial water removal did not occur until the soil reached essentially 100°C. At the end of electrical heating, 61,000 L (16,000 gal) of water had been removed through the vent. Because the soil was hot at the end of electrical heating, venting continued without heating into January 1994, excluding the two-week break for post-test drilling and soil sampling in December 1993. At the end of venting, 72,000 L (19,000 gal) of condensate had been removed (11,000 L attributed to venting after electrical heating had been completed). For comparison, the electrode drip system, which operated essentially continuously during the heating phase of the demonstration, added about 21,000 L (5,500 gal) of water (approximately 1 to 2 gph per electrode). A small amount of table salt was added to this water to increase its conductivity. The salt concentration was within potable water standards (500 mg/L); a total of 11 kg (24 lb) of table salt was injected.

The permeability of the vented sandy soil can be determined from the flow of air and steam into the vent and the pressure at the vent. The steam flow was calculated from the rate of condensate collection assuming an ideal gas, and the air flow was measured by two orifice meters. During the heating phase, the majority of gas flow from the vent was steam. Determining the permeability of the soil is complicated because the steam is generated within the soil. However, the change in permeability can be determined qualitatively by calculating the ratio of total flow over an appropriate pressure drop. Clearly, the permeability increased during the demonstration. Soil sampling has shown that SPSH dried the

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sand intervals, so reducing the moisture content of the soil is the most likely cause of the increased permeability. The soil samples were visually inspected during drilling and soil sampling. Although drying made the clay-zone samples dry and brittle, they showed no evidence of fracturing and still appeared much less permeable than samples from the adjacent sand zones. This supports the conclusion that the permeability increase resulted from drying of the sand zones.

SPSH COSTS

On a cubic-yard basis, the cost of SPSH technology is roughly equal to the baseline cost of SVE remediation. For example, at a typical industrial site, the estimated added cost for SPSH is between $50 and $80 per cubic yard of soil treated. This cost estimate is based on a typical (one acre) site, employing SVE remediation of a volatile organic constituent like PCE, in sandy or clay soils contaminated from the surface to a depth of approximately 20 feet.

As one might expect, energy consumption is another important factor in considering the economic feasibility of SPSH technology. To address this project objective, data obtained from the field demonstration were used to estimate the electrical energy usage per cubic meter of soil treated. By using the thermocouple data on vertical and areal heating, it is estimated that approximately 1,100 m^3 of soil was heated to above 70°C. At the end of the test, 100,000 kWh of energy had been applied to the soil. Combining this energy usage with the rough estimate of the heated volume gives an energy usage of 90 kWh/m^3, or $7/$m^3$ at $0.07/kWh. As with most heating methods, the energy cost to heat the soil was small when compared to the costs for the capital equipment for the electrical system, the off-gas destruction system, and the operator time.

SPSH should be able to reduce the time of traditional SVE from years to months or weeks.

Some of the greatest benefits to be gained from the use of SPSH technology come from the reduction in the time for remediation and the confidence to meet required cleanup goals. Depending on the individual application involved, SPSH should be able to reduce the time of traditional SVE from years to months or weeks. For most applications, this should result in reduced operational costs that will more than offset the expense of the SPSH enhancement to SVE. It is also expected that SPSH will increase the certainty of SVE remediation. As with the demonstration at SRS, the remediation of VOCs or even DNAPLs in low-permeability soils can be approached with greater assurance that regulatory goals can actually be met. Finally, SPSH is envisioned to provide new hope for those SVE applications which have long since been abandoned because of their marginal economic feasibility or as a result of their critical time constraints for remediation. ❖

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