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**Six-Phase Soil Heating for Enhanced
Removal of Contaminants: Volatile
Organic Compounds in Non-Arid
Soils Integrated Demonstration,
Savannah River Site**

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October 1994

Prepared for the Office of Technology Development
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Pacific Northwest Laboratory
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Executive Summary

During November 1993, Pacific Northwest Laboratory (PNL) and Savannah River Site (SRS) personnel completed a field demonstration of six-phase soil heating (SPSH) at the Savannah River Site, Aiken, South Carolina. This demonstration was directed by the U.S. Department of Energy (DOE) Volatile Organic Compounds in Non-Arid Soils Integrated Demonstration (VOCs in Non-Arid Soils ID). Pacific Northwest Laboratory designed the SPSH systems for this demonstration, and Westinghouse Savannah River Company (WSRC) conducted drilling, soil sampling, construction, off-gas treatment, and contaminant analyses. The purpose of the project was to demonstrate a soil heating system that uses electricity to cost effectively heat soil and enhance the performance of conventional soil-venting techniques.

Soils at the integrated demonstration site are contaminated with perchloroethylene (PCE) and trichloroethylene (TCE); the highest soil contamination occurs in clay-rich zones that are ineffectively treated by conventional soil vapor extraction (SVE) because of the very low permeability of the clay. Specific objectives for the demonstration were to:

- demonstrate that SPSH accelerates the removal of TCE and PCE from the SRS clay soils compared with conventional SVE techniques
- quantify the areal and vertical distribution of heating as a result of SPSH under soil conditions experienced at the SRS
- provide a functional soil electrode and vent design for SPSH
- collect sufficient data to project the economic feasibility of commercial application of SPSH technology for soils and contaminants similar to those at the SRS.

To quantify the accelerated VOC removal using SPSH, pre- and post-demonstration soil characterization and monitoring activities were conducted. Testing and monitoring support was provided by the VOCs in Non-Arid Soils ID. To record soil temperature changes, thermocouples at 30 locations were installed 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 meter (foot)] from six wells before heating and adjacent to these wells after heating for direct comparison of soil parameters and changes.

The results of the SRS field demonstration indicate that SPSH is a technology capable of heating and remediating low-permeability soils containing volatile organic contaminants. Comparison of pre- and post-test soil samples show that contaminant removal from the clay zone was 99.7% (median) within the electrode array. Outside the array where the soil was heated, but to only 50°C, the removal efficiency was 93%, 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 the higher levels of soil contamination. The clay-zone temperatures increased to 100°C after 8 days of heating and were maintained near 100°C for 17 days. In addition, the electrical heating removed 72,000 L (19,000 gal) of water from the soil as steam, with peak removal rate of 5,700 L per day [1,500 gallons per day (gpd)] of condensed steam. Process automation allowed unattended operation following an initial start-up period.

The total energy applied to the soil during the demonstration was approximately 100,000 kWh. After the initial start-up, electrical power was applied to the heating pattern at an average rate of 200 kW. The volume of soil heated to above 70°C is estimated to be 1100 m³, giving an energy input of 90 kWh/m³ (70 kWh/yd³). The average voltage (line to neutral) applied to the soil was 1000 V. The voltages began at 250 V (L-N) during start-up and increased to 2400 V (L-N) at the end of the test. Based on this demonstration experience, the SPSH energy use is estimated to be approximately \$7 per cubic meter of soil at \$0.07/kWh.

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

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We would also like to thank R. L. Richardson and E. N. Greenwell, PNL, for design work; D. W. Glover, PNL, for assisting in field installation of equipment; and L. M. Peurrung, PNL, for operating a shift. For SRS on-site support, we thank Shirley Burdick, Snuffy Clark, Ken Lombard, and Randy Raymond, Bechtel Savannah River, and Marlesia Keenan, Dee Dee Stewart, and Johnny Simmons of Westinghouse Savannah River Company.

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1.0 Introduction

1.1 Demonstration Site

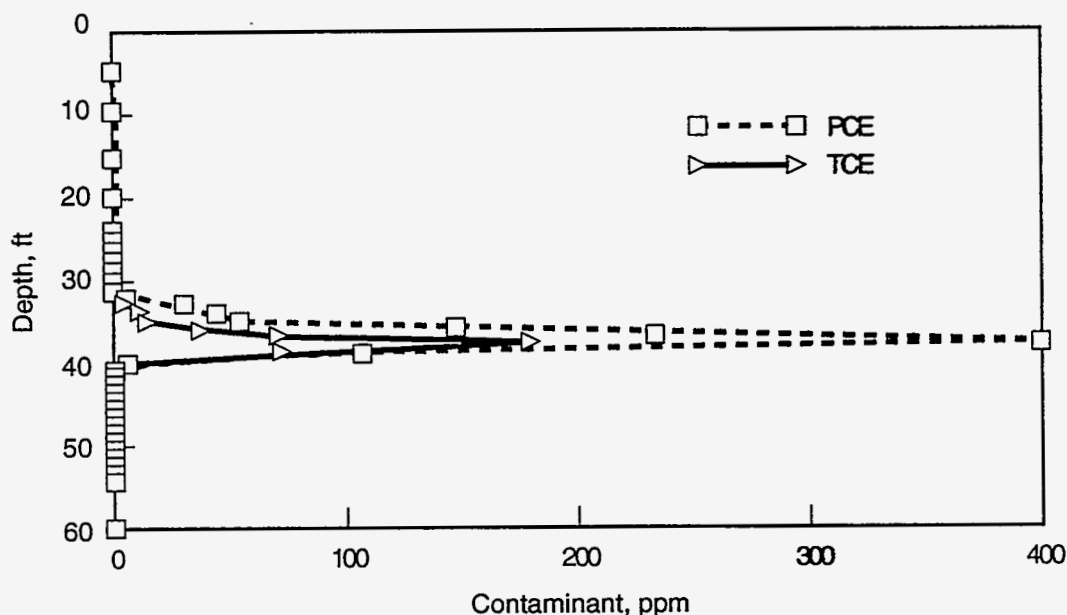
In November 1993, Pacific Northwest Laboratory (PNL)^(a) and Savannah River Site (SRS) personnel conducted a demonstration of six-phase soil heating (SPSH) at the Savannah River Site (SRS) in Aiken, South Carolina. The SRS is a 300-square-mile facility owned by the U.S. Department of Energy (DOE) and currently operated by Westinghouse Savannah River Company (WSRC). The demonstration was part of the Volatile Organic Compounds in Non-Arid Soils Integrated Demonstration (VOCs in Non-Arid Soils ID) being conducted near the M-Area operations at the SRS, along a corridor that once contained a process sewer leading to the M-Area seepage basin. In the early 1980s, this sewer line was discovered to be leaking process wastes into the subsurface and contributing to groundwater contamination in the vicinity of M-Area seepage basin. Although use of the sewer line has been discontinued, the slow release of chlorinated solvents such as trichloroethylene (TCE) and perchloroethylene (PCE) from the heterogeneous vadose zone soil continues to be a source of potential groundwater contamination.

A significant portion of the VOCs at the demonstration site are retained in low-permeability clay zones. A 3-m (10-ft) thick clay zone beginning 9 m (30 ft) from the surface is the shallowest example (Eddy et al. 1991). Figure 1.1 shows typical PCE and TCE contamination as a function of depth for a well within the zone to be treated by SPSH (MHV-38; see Section 2.0). Figures showing the pre-test soil contamination for all of the sampled wells are included in Appendix A. The data points in Figure 1.1 are averages of measurements taken on duplicate samples; all soil concentrations (parts per million) are based on the mass of wet soil. This figure shows that the majority of the PCE and TCE contamination resides in the clay zone [a few hundred parts per million (mass basis)]. We will refer to the clay zone as the depths between 9 and 12 m (30 and 40 ft). The more sandy zones above and below the clay typically have less than 1 ppm of PCE and TCE. Previous studies have shown that the rate of conventional SVE remediation of the SRS clays is quite slow; this is attributed to mass transfer limitations of the low permeability soils (Looney et al. 1991a, 1991b; Eddy-Dilek et al. 1993). The permeability of the clay is of order 10^{-12} cm², which makes this a particularly difficult interval to remediate. Thus, the challenge for SPSH is to effectively remediate this clay zone by accelerating the removal of TCE and PCE.

1.2 Background

Several candidate technologies currently exist, or are under development, to facilitate the removal of volatile contaminants from M-Area soil. Soil vapor extraction (SVE) is a proven in situ technology for removing volatile organic compounds like TCE or PCE from permeable soils. This technology succeeds when soil contaminants transfer readily into air that flows easily through the soil

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Figure 1.1. Contaminant Concentration as a Function of Depth in Well MHV-38

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 semi-volatile and the soil be permeable to the flow of air. In homogeneous and permeable soils, SVE produces rapid results with a relatively low overall cost. Conventional SVE, however, becomes infeasible when remediating low permeability non-homogeneous soils, or when low volatility contaminants are present (USEPA 1991; Pedersen and Curtis 1991).

Soil heating can extend the effectiveness of SVE to less volatile compounds, to less permeable soils (like clays), and, potentially, to contaminant depths near or in the water table. The 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, causing an increase in 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 in situ 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 of these processes add further to the rate of contaminant removal during venting. Soil heating can provide a cost-effective alternative to conventional SVE or soil excavation followed by ex situ treatment.

Six-phase soil heating is a technique that uses common low-frequency electricity to heat soils as an enhancement to SVE (Bergsman et al. 1993a, and 1993b). The mechanism of heating is resistive dissipation of the electrical energy. SPSH 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 an SVE 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.

Figure 1.2 shows the typical heating pattern expected for application of SPSH (plan view). The heating (Q) is given in power per unit volume W/m^3 . 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 low-permeability through judicious water addition. The SPSH is also an ideal method for heating soil such as clays. The cross-sectional view in Figure 1.2 shows, as an example, a clay layer between sand zones. 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.

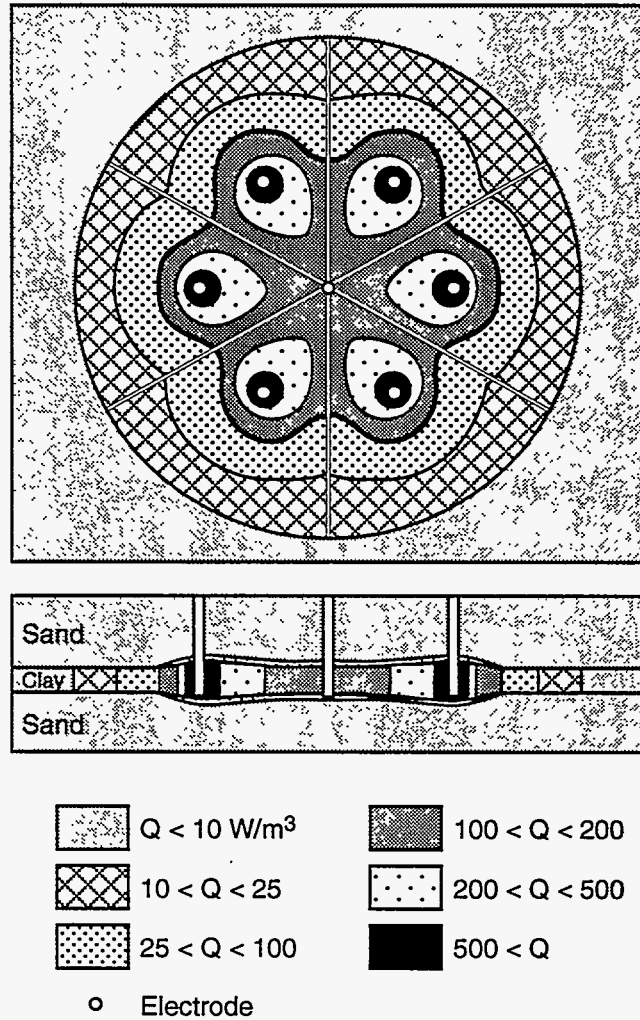
The soil heating patterns shown in Figure 1.2 were calculated by a rigorous electric field solution in a computer code called TEMPEST (Trent and Eyster 1993). TEMPEST predictions have been used to fine-tune a semi-analytical model of electrical heating as a function of water content, temperature, soil 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 and 1990). Applications of the resulting process simulator are described in more detail in Bergsman et al. (1993a, 1993b) and Heath et al. 1992.

For the SRS 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.

1.3 Objectives

The primary objective of the demonstration is to show that SPSH technology can enhance SVE in clay soils. Specific test objectives for the demonstration are as follows:

1. Demonstrate that SPSH accelerates the removal of TCE and PCE from the SRS clay soils compared to conventional SVE.
2. Quantify the areal and vertical distribution of heating as a result of SPSH under soil conditions experienced at the SRS.



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Figure 1.2. Typical Heating Pattern for SPSH with Adjacent Sand and Clay Layers. The heating (Q) is given in power per unit volume W/m^3 .

3. Demonstrate functional electrode and vent designs.
4. Collect sufficient data to project economic feasibility of commercial application of SPSH technology for soils and contaminants similar to those at SRS.

In addition to the SPSH objectives, Lawrence Livermore National Laboratory (LLNL) collected data during the SPSH test to produce electrical resistance tomography (ERT) images of the soil during the demonstration. Because temperature and water saturation each affects the soil electrical resistance, ERT records the combined effects of heating and drying.

This report presents the results of testing, data interpretation, and assessment of the SPSH field demonstration conducted at the SRS. The report's primary considerations are the removal of volatile organic contaminants by resistive soil heating and the soil heating as a result of SPSH. Section 2.0 describes the materials and methods used in the demonstration. Section 3.0 discusses project results, and conclusions are provided in Section 4.0. Appendix A provides figures showing the pre-test soil contamination for all the sampled wells.

2.0 Materials and Methods

2.1 Field Equipment and Operation

Figure 2.1 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 9.1 m (30 ft) diameter circle and had electrical contact with the soil between 7 and 13 m (23 and 44 ft). The vacuum extraction vent placed at the center of the array was also connected to the six-phase transformer (neutral). 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.

The surface equipment shown in Figure 2.1 includes a trailer-mounted 750 kVA power plant that supplied 480 V 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

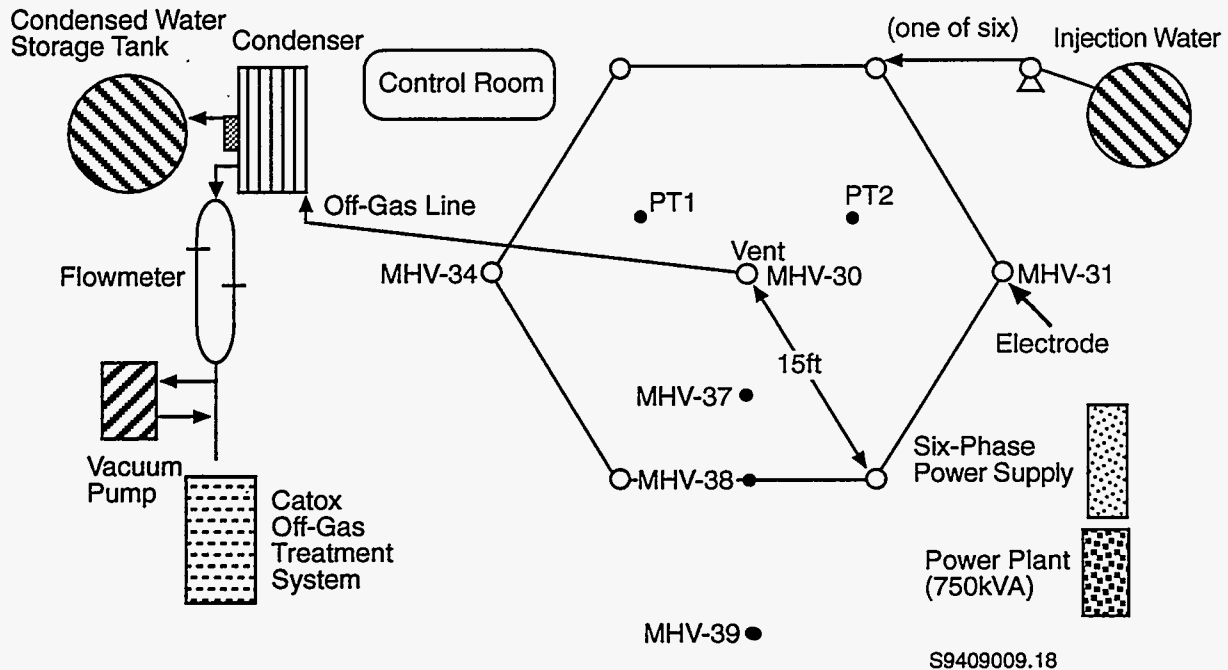


Figure 2.1. Location of Monitoring Wells, Electrodes, and Surface Equipment (well locations are drawn to scale; surface equipment is not)

2400 V [line-to-neutral (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).

Figure 2.2 shows a simple schematic of the depth from surface of two typical electrodes, the central vent, and the monitoring wells (Figure 2.2 does not show the areal position of these wells). The depths of the targeted clay zone and thermocouples are also shown. 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, and Figure 2.2 shows the location of these sandpacks. Pressure transducers located at the surface measured the pressure at these locations.

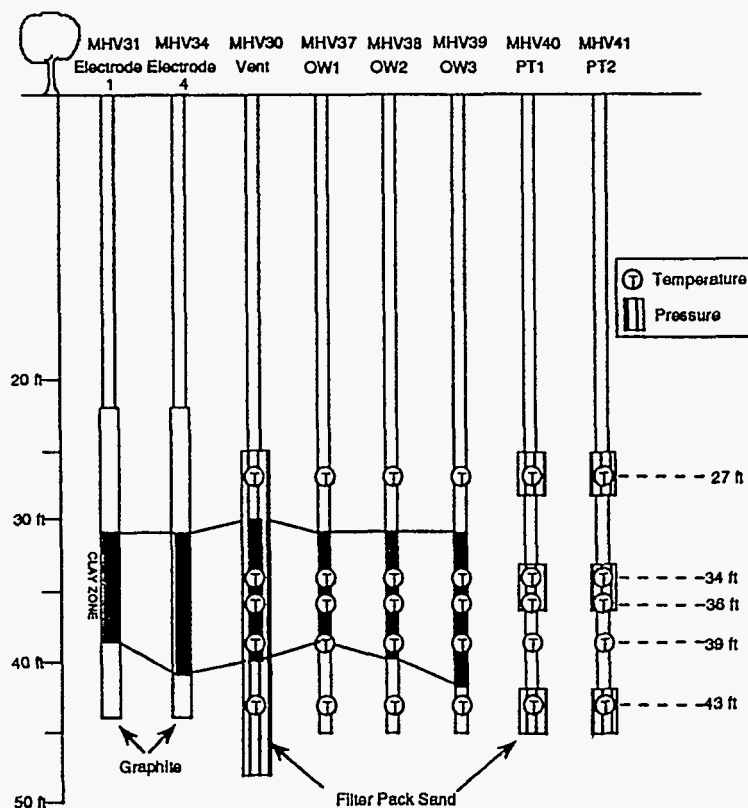


Figure 2.2. Subsurface Depth for Two Typical Electrodes, Central Vent, and Monitoring Wells. The clay zone is indicated by the shaded region for the wells that were cored and logged; the clay zone was continuous through the test area. The symbols show the depth of temperature and pressure measurements.

An extensive program of subsurface monitoring 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 prior to heating and adjacent to these wells after heating. The difference between the pre- and post-test samples, which gives critical information for assessing the efficacy of SPSH, is discussed in Section 3.2. 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 meter (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).

2.2 Demonstration

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. Figure 2.3 shows the power applied to the six electrodes during the heating phase. 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 1000 V. Figure 2.4 shows the mean voltage (I-n) applied to the electrodes. The transformer and surface equipment were automated, and the SPSH system operated unattended beginning November 19, 1993. Toward the end of heating, the soil resistivity increased,

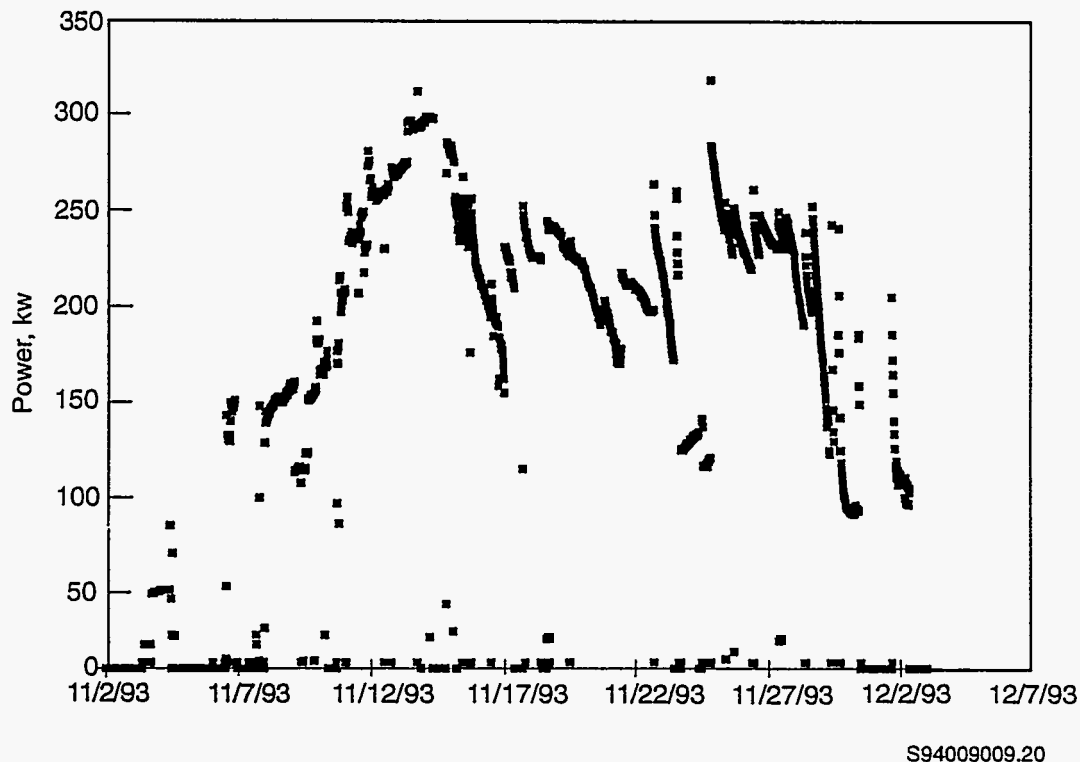
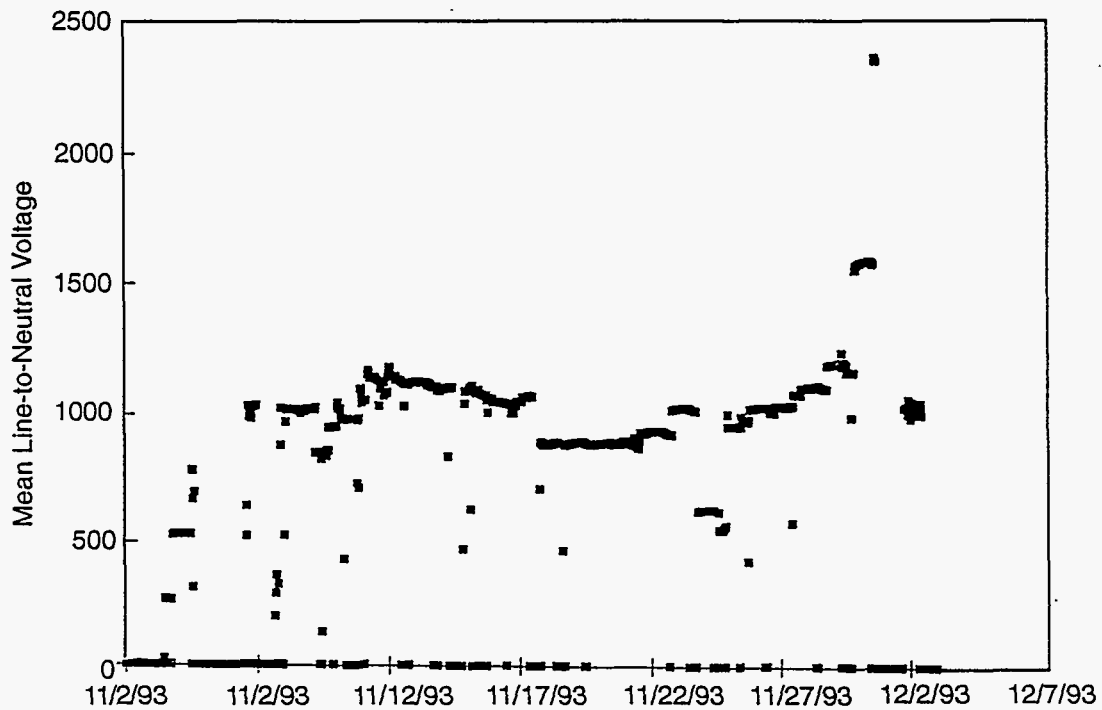


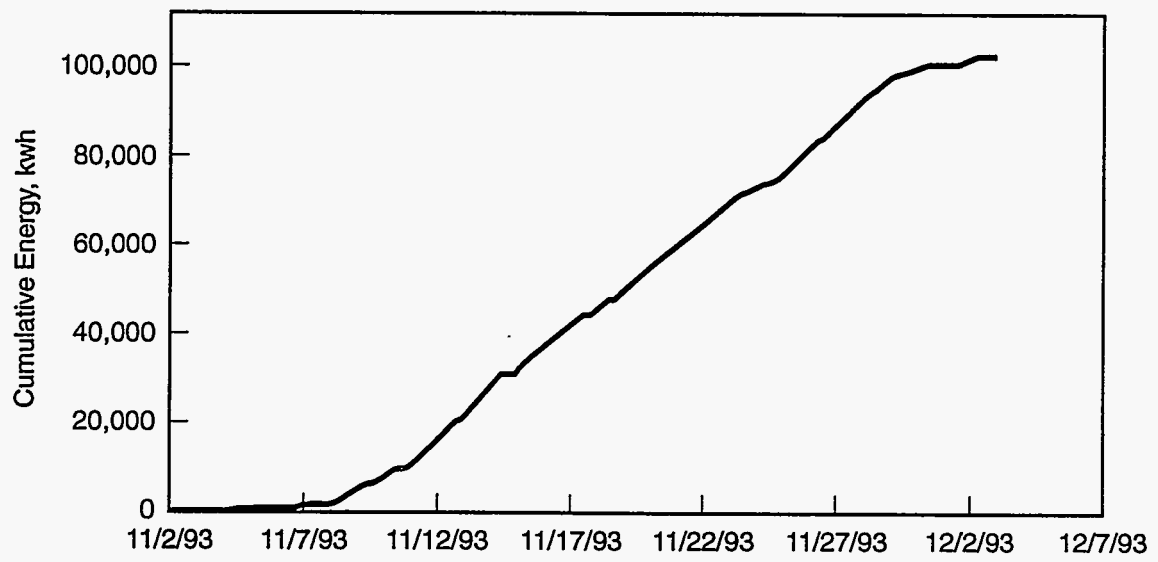
Figure 2.3. Power Applied to SPSH Array



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Figure 2.4. Mean Voltage Applied to SPSH Electrodes

so the voltage was increased to 2400 V (l-n) to maintain power input levels. Periods when the mean voltage (and power) are zero represent periods of power shutdown for maintenance and data gathering (i.e., LLNL conducted measurements for ERT, collection of soil gas samples, etc.). Figure 2.5 shows the energy applied to the soil. At the end of the test, 100,000 kWh of energy had been applied.



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Figure 2.5. Energy Applied to Soil

3.0 Results and Discussion

3.1 Soil Heating Measurement and Results

Quantifying the areal and vertical soil heating was one of the main objectives of this demonstration. As shown in Figure 2.2, thermocouples were placed at different depths to determine the vertical heating distribution. The areal variation was obtained by placing thermocouples in different wells. Figure 3.1 shows the temperature in MHV-38, which is the observation well located between two electrodes. Figures 3.2 - 3.6 show temperatures measured at other wells. 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. Figure 3.1 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 the modeling results given in Figure 1.2.

The temperature in the clay zone rose to 100°C (MHV-40 and MHV-41 peaked at 105° to 110°C) after 8 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.

Figure 3.7 shows the areal uniformity of the temperature within the array during SPSH. The temperatures are for thermocouples within the clay zone (34 and 36 ft) in the central vent (MHV-30) and monitoring wells MHV-37, MHV-38, and MHV-39. The temperature at the central vent is slightly less because the vacuum applied to this vent lowered the vapor pressure (boiling point) of water at this location. The temperature rise in MHV-39 is much less because it is located outside the electrode array. This initial temperature rise agrees with modeling results shown in Figure 1.2.

3.2 Effect of Heating on Soil Remediation

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. Figure 3.8 shows the pre- and post-test soil measurement for PCE in 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. (Figures comparing pre- and post-test soil measurements for all the sampled wells are included in Appendix A.) 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.

Figure 3.9 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

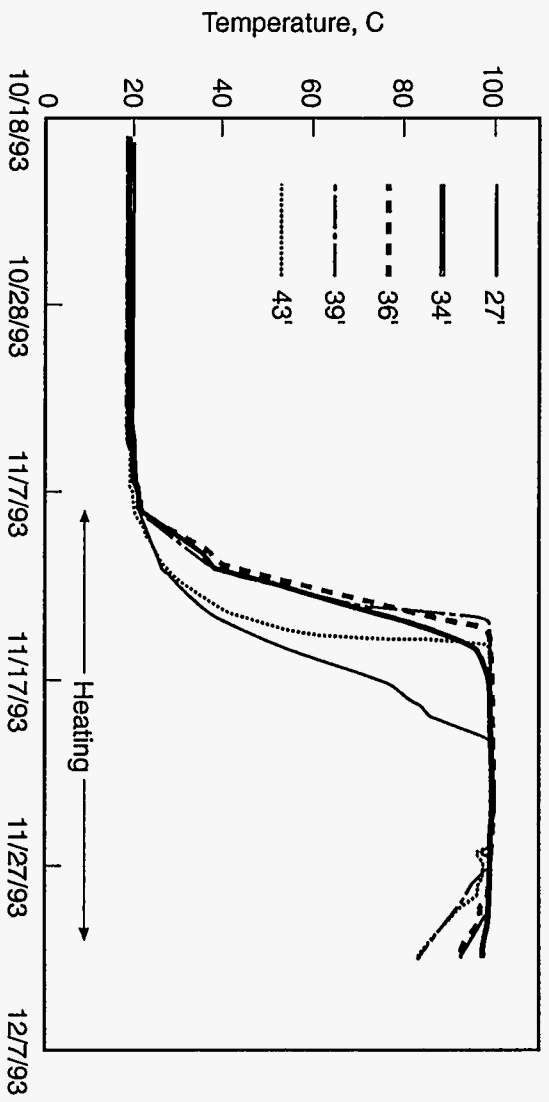


Figure 3.1. Temperature in Well MHV-38

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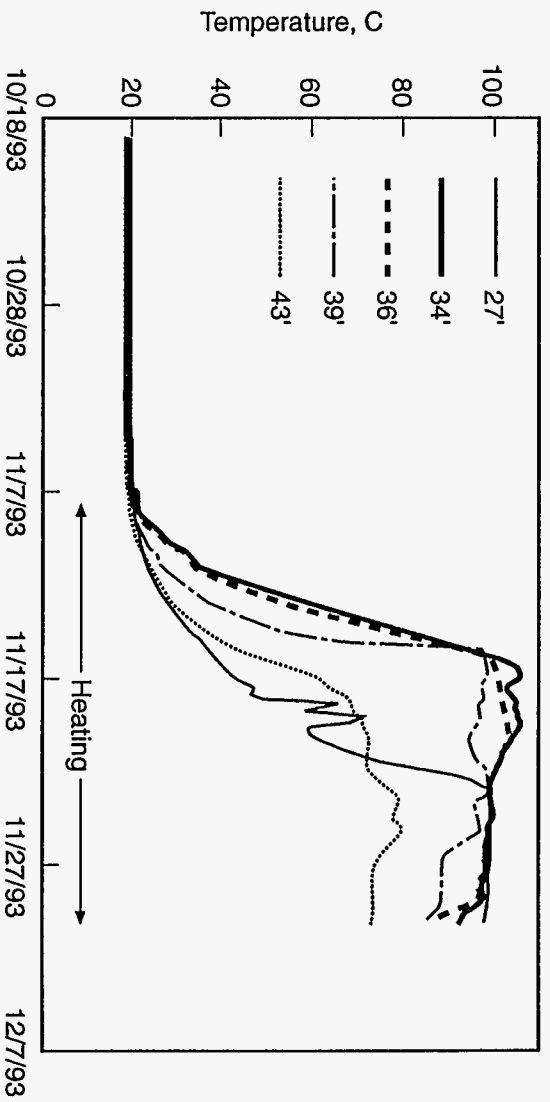
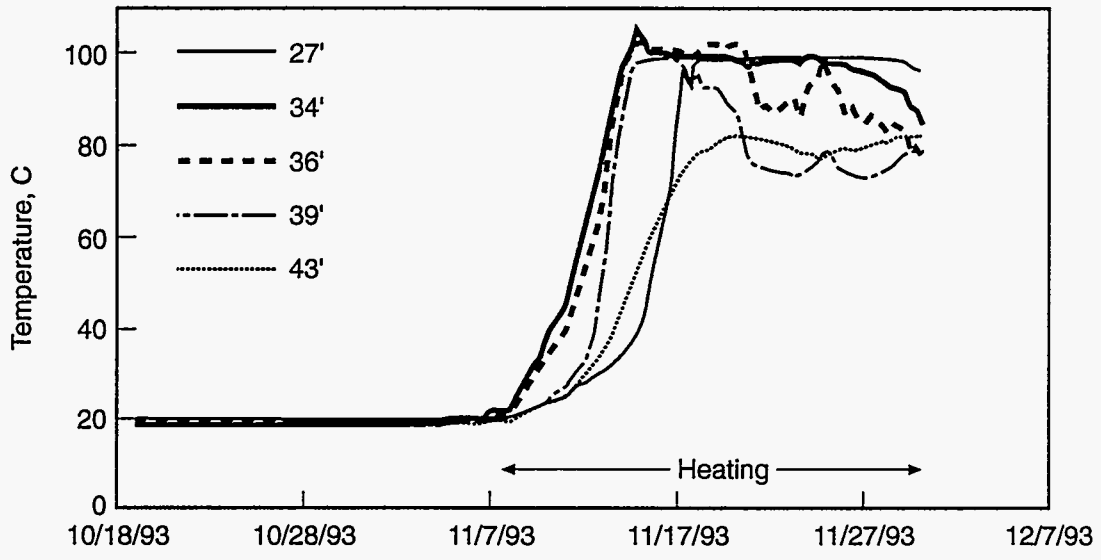


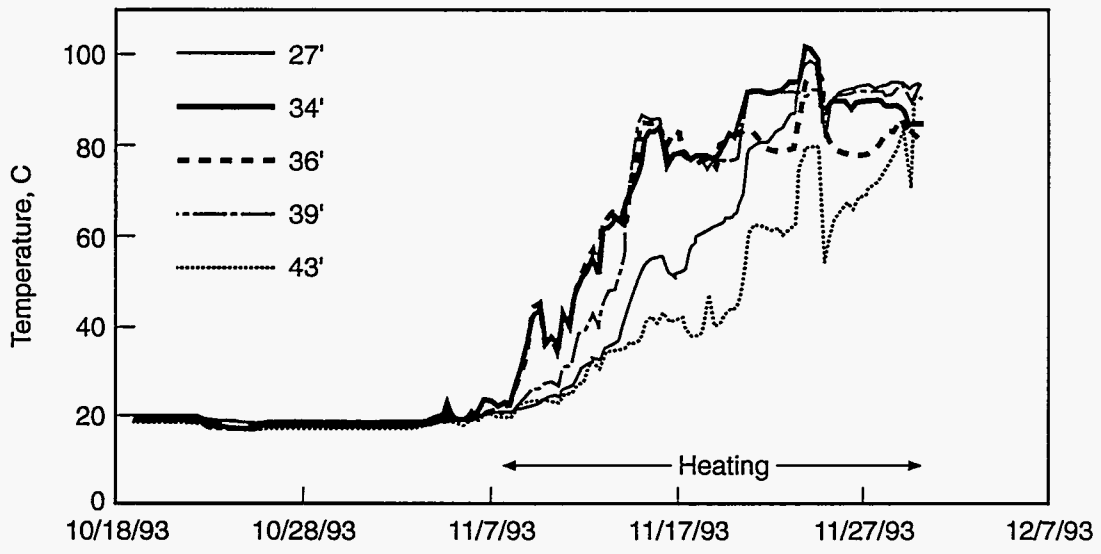
Figure 3.2. Temperature at Well MHV-40

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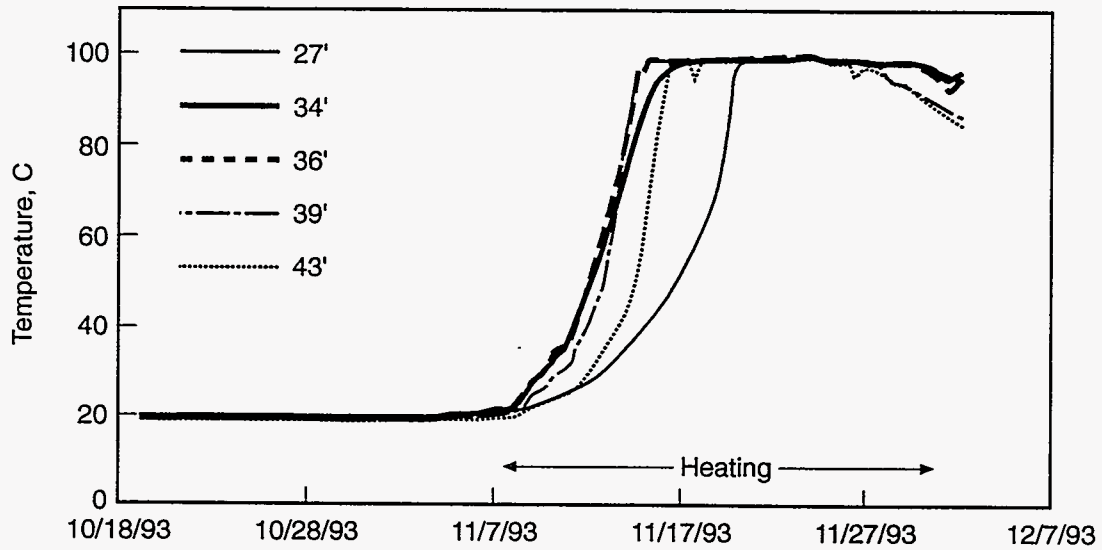
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Figure 3.3. Temperature at Well MHV-41



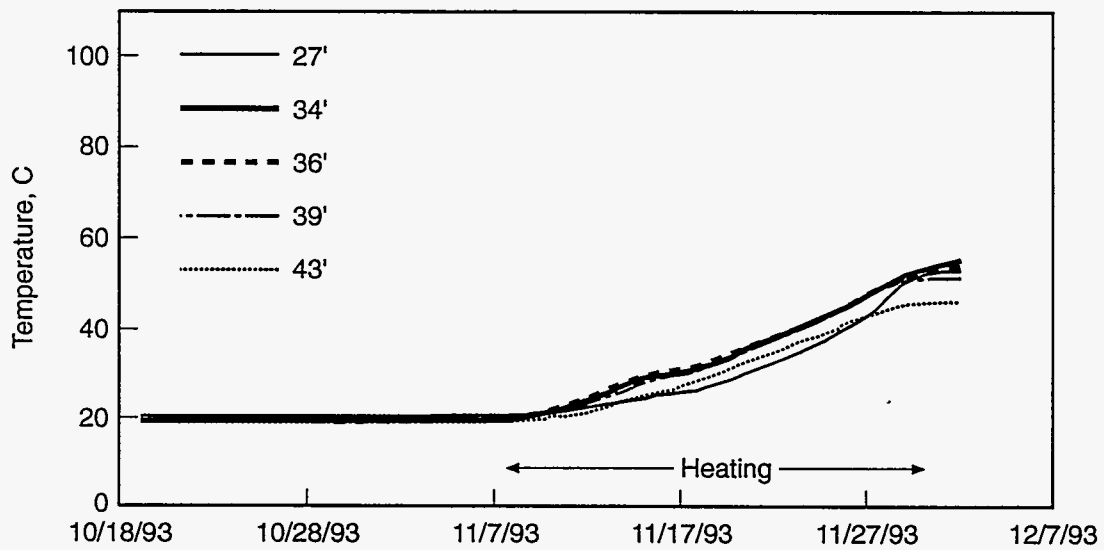
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Figure 3.4. Temperature at Well MHV-30



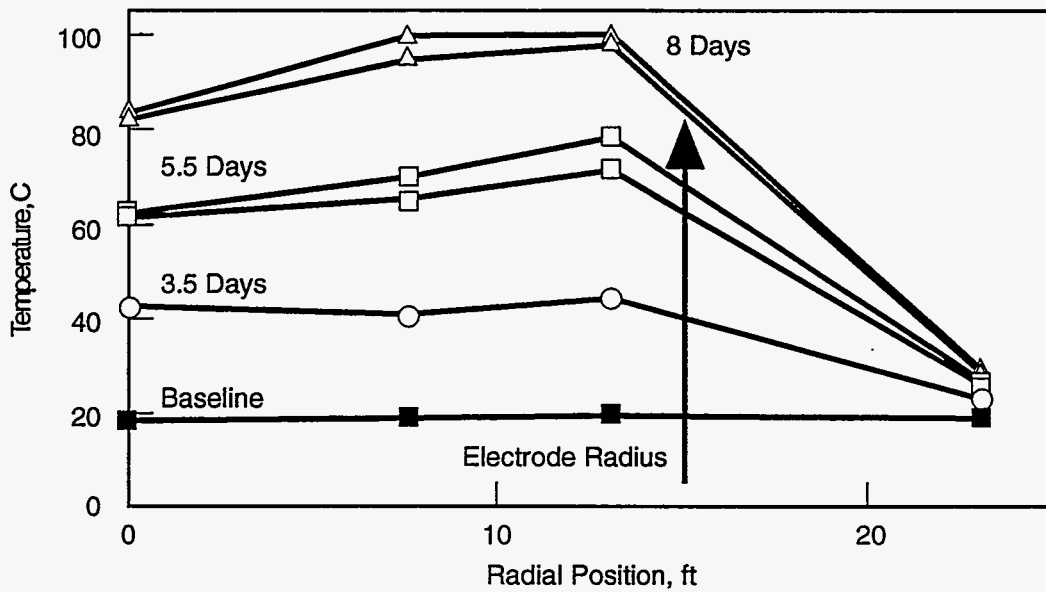
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Figure 3.5. Temperature at Well MHV-37



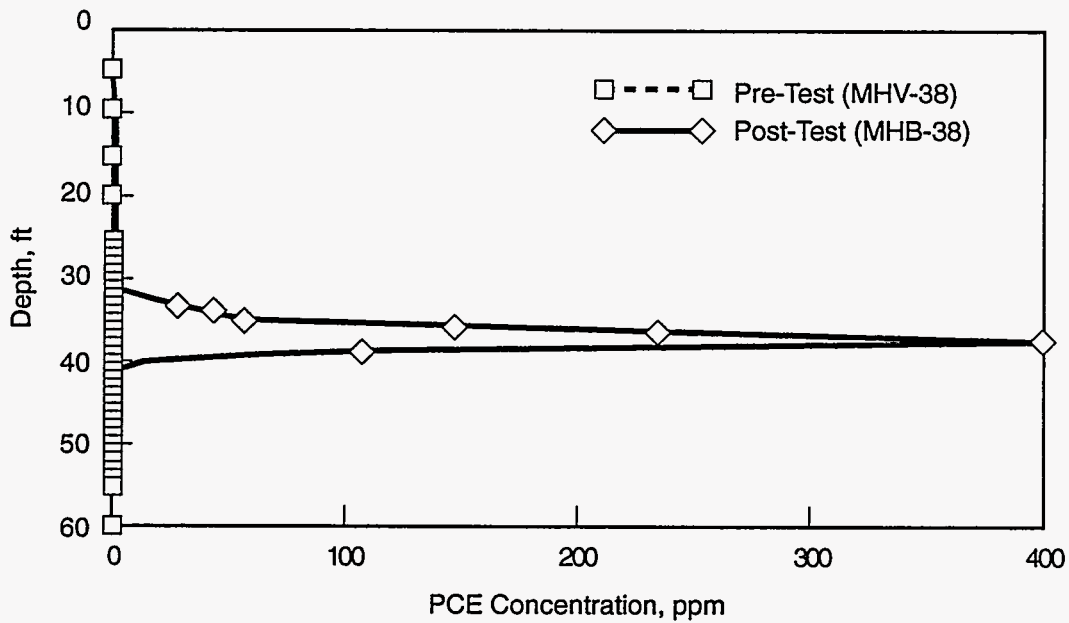
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Figure 3.6. Temperature at Well MHV-39



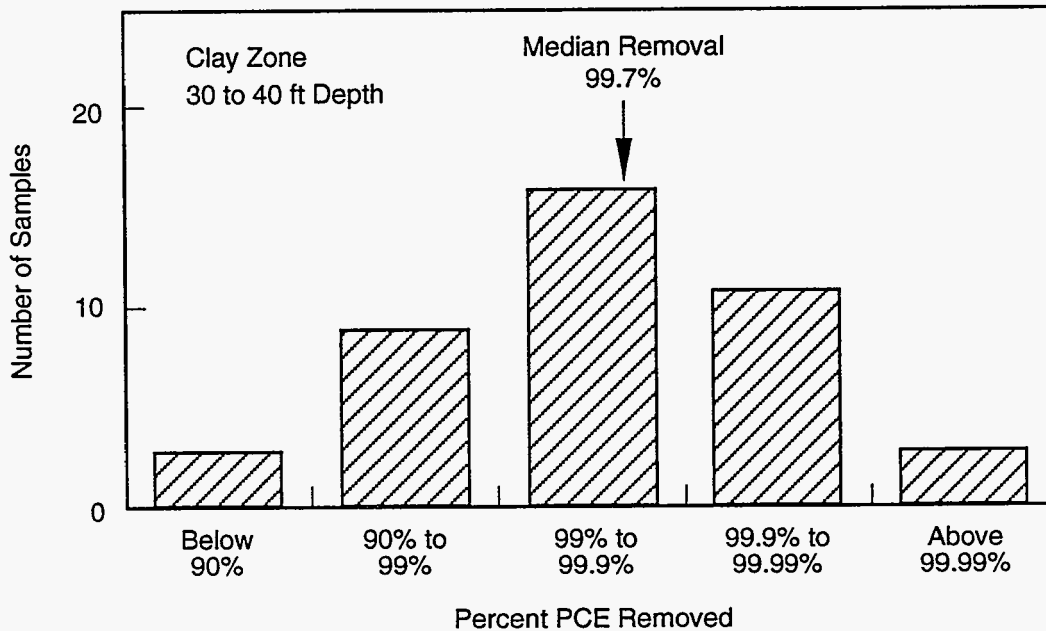
S9409009.9

Figure 3.7. Areal Uniformity of Temperature



S9409009.10

Figure 3.8. Comparison of Pre- and Post-Test PCE Contamination in the Soil for Well MHV-38. The post-test well (MHB-38) was drilled 1 m (3 ft) from the pre-test well.



S9409009.11

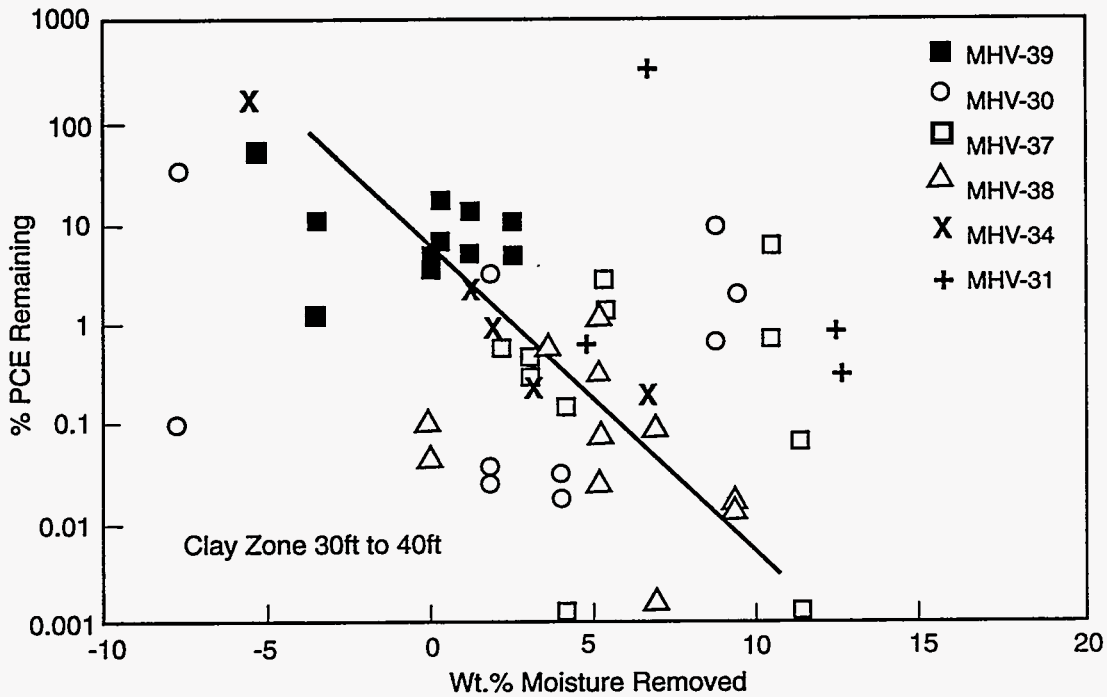
Figure 3.9. PCE Removal Efficiency After Treatment with SPSH

is 99.7% 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 that samples taken at the same depth in adjacent wells varied in the clay content. The data in Appendix A show that the contamination in the clay zone was consistently reduced in all the wells within the electrode array. For the sand above the clay, which is outside the heated zone, the contamination was reduced but to a lesser extent. For the sand below the clay, the data are quite noisy, and no trend is readily apparent. The noise in the measured soil contamination is mostly due to the heterogeneity of the soil.

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 8 days of heating. The median removal of PCE at MHV-39 was 93% at the end of the test, which is appreciably less than the 99.7% removal within the array discussed above. At a 23-ft radius, as shown by Figure 1.2, the predicted heating rate as a result of SPSH is about 10 to 20% of the heating rate within the electrode array (MHV-30, MHV-37, and MHV-38). The temperature data shown in Figure 3.7 confirm this prediction and give an initial increase in temperature at MHV-39 of about 15% 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 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.

Figure 3.10 shows the effect of moisture removed on the fraction of contaminant remaining after treatment with SPSH. These data are shown only for the clay interval at depths between 30 and 40 ft. Although the data have substantial scatter, the expected trend of less PCE remaining with a greater removal of moisture is clear. The solid symbols are for MHV-39, which was heated less. As seen in Figure 3.10, the wells within the array, as compared to MHV-39, had greater moisture removal and better contaminant removal. This shows that drying as a result of heating correlates with the accelerated removal of VOCs from clay soils.



S9409062.1

Figure 3.10. Effect of Moisture Removal on the Efficiency of PCE Removal from the Clay Zone. The solid symbols are for MHV-39, which was located outside the electrode array (cooler). The wells inside the array, which were hotter than MHV-39, show greater PCE removal.

3.3 Effect of Heating on Permeability

One objective of electrical soil heating is increasing the air permeability of the soil by drying the soil. Figure 3.11 shows the water removed from the central vent as condensed steam. 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 2-week

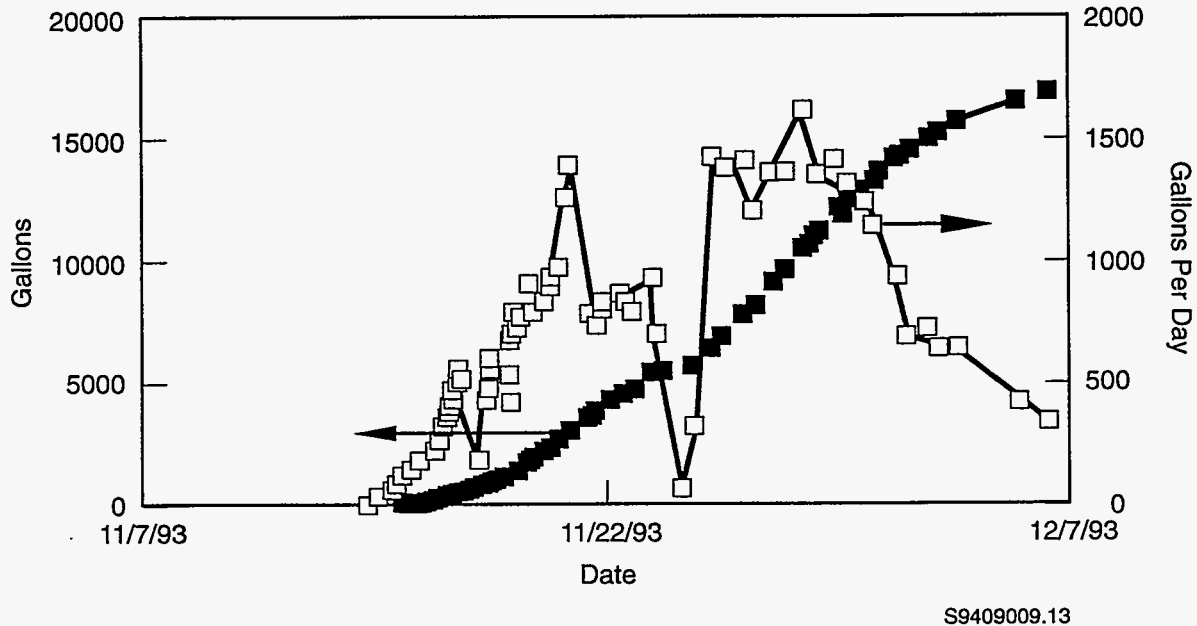
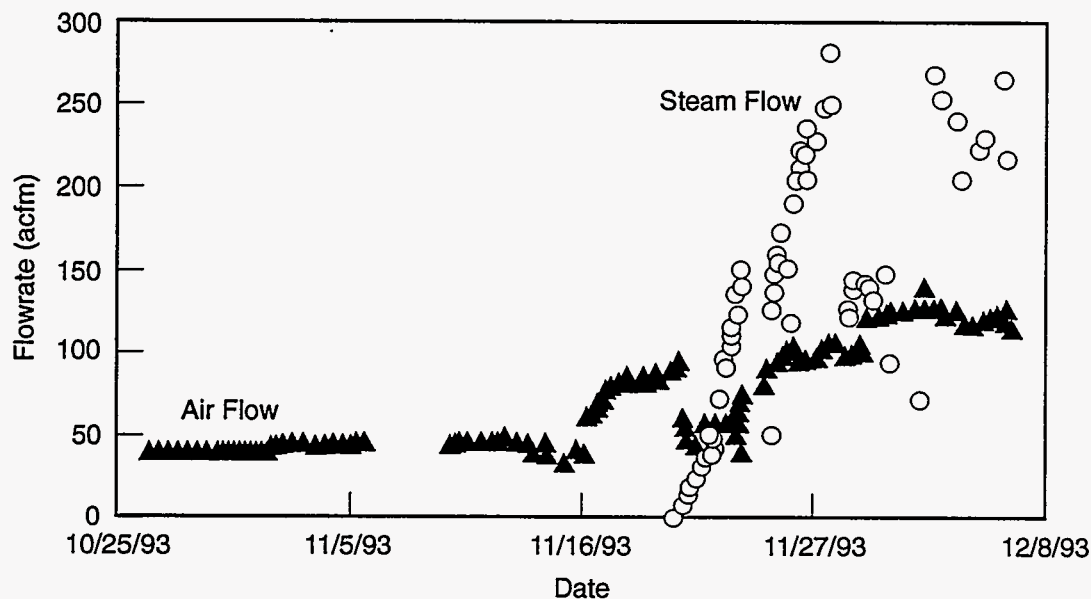


Figure 3.11. Condensed Steam Removed from the Vacuum Extraction Vent During Heating

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. Figure 3.12 shows the flow entering the well in actual cubic ft/minute (acfm). 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, as shown in Figure 3.12. 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



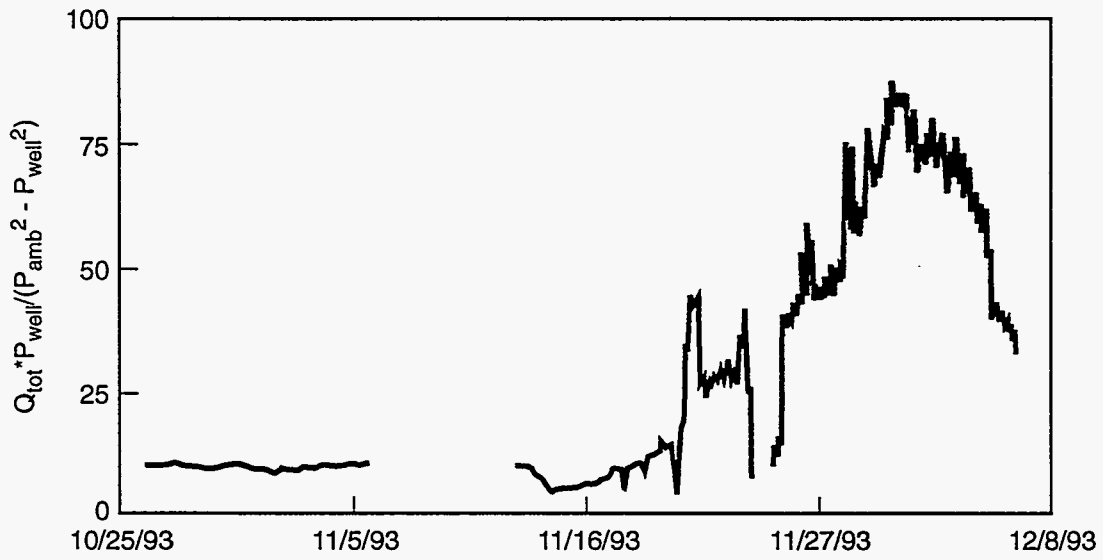
S9409009.14

Figure 3.12. Flow Rate of the Combined Air and Steam at the Vent in Actual Cubic Feet/Minute

pressure drop. Figure 3.13 shows this ratio with the pressure drop appropriate for compressible gas flow (Dullien 1992). Clearly, the permeability increased during the demonstration. Soil sampling has shown that SPSH dried the 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. The peak in Figure 3.13 coincides with the peak steam flow given in Figure 3.12. The decrease following the peak in Figure 3.13 results partly from the decreasing steam flow shown in Figure 3.12.

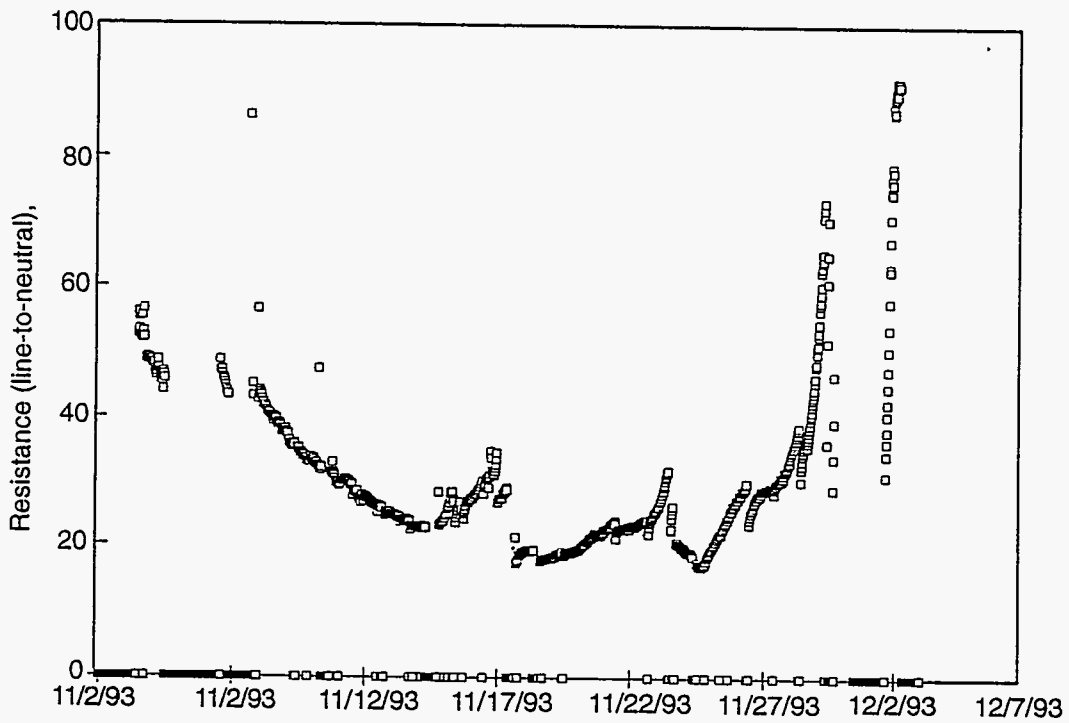
3.4 Effect of Heating on Soil Electrical Resistance

Soil heating also affects the electrical resistance of the soil. Initially, the resistance decreases with increasing soil temperature. However, as the soil dries, the resistance increases. Figure 3.14 shows the results for the mean resistance of the six electrical phases. Between November 7, 1993, and November 14, 1993, the resistance decreased smoothly; during this period, the soil temperature rose to 100°C. Between November 15, 1993, and November 24, 1993, the resistance went through a series of slow increases and drops. The increases are likely due to soil drying near the electrodes. The drops resulted from process changes that included adjustments of the water addition rate and voltage at individual electrodes. After November 24, 1993, the resistance increased steadily. The electrode drip system was stopped on November 29, 1993, but the power level was maintained, causing a rapid increase in resistance due to soil drying near the electrodes.



S9409009.15

Figure 3.13. Effect of Heating and Drying the Permeability of the Vented Soil



S94009009.19

Figure 3.14. Average Phase Resistance

3.5 Effect of Heating on Off-Gas Concentration

The ability of temperature increases to accelerate remediation varies depending on the mechanism limiting the rate of contaminant mass transfer within the soil. At the Savannah River Site, the thick clay zone can impart tremendous mass transfer resistances for removing contaminants from the clay. Without heating, remediation of the clay is expected to be limited by diffusion of contaminant through water within the clay to the more permeable sand layers where the contaminant can be swept away. After heating and partial drying, steam will occupy a portion of the clay pore space. At this point, contaminants may transfer from the water into this steam and move within the gas phase to the permeable sand layer. Contaminant movement within the gas space may still be diffusion limited, or if sufficient water volatilization occurs, convection of contaminant by in situ steaming will occur. In addition to altering the dominant mass transfer resistance, heating the soil also raises the concentration of the contaminant in air passing through the soil.

A variety of data can be used to quantify accelerated removal of contaminants from the soil as a result of heating. Comparison of soil samples taken from wells inside (hot) and outside (warm) the electrode pattern have shown that heating accelerated the removal of PCE and TCE from the clay (see Figure 3.10). It was also expected that contaminant concentration in the air drawn from the central vent would respond to changes in soil temperature. Figure 3.15 shows the PCE and TCE concentration in the off gas. Also shown is an extrapolation of the PCE baseline data without heating. The difference between the baseline extrapolation and the off-gas concentration during heating indicates the degree of acceleration. Although the data in Figure 3.15 show little acceleration, a number of

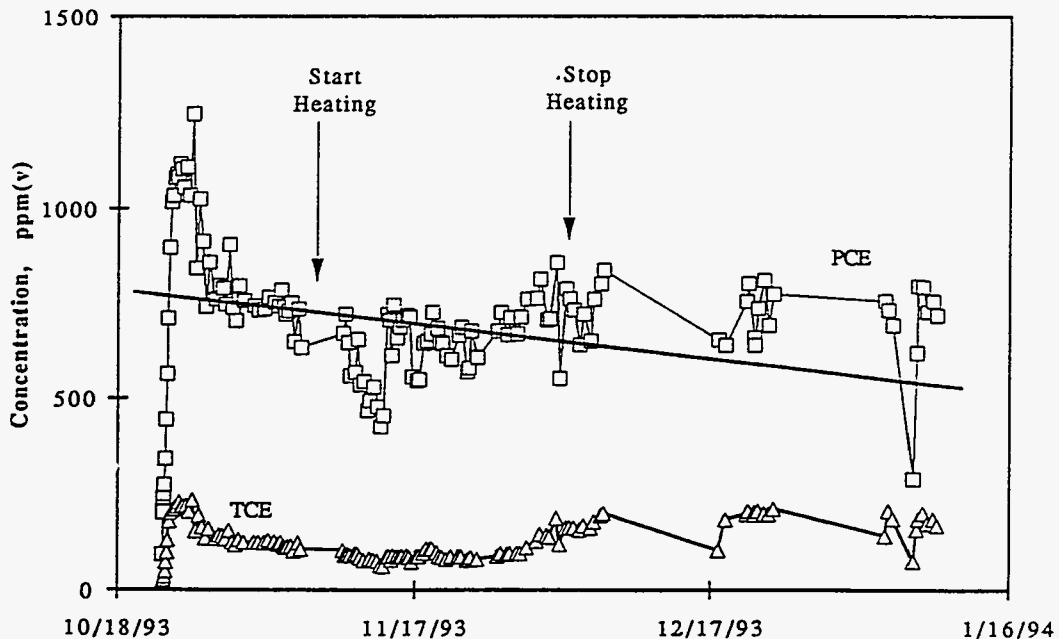


Figure 3.15. Concentration of PCE and TCE in the Vent Gas Downstream of the Condenser

observations make these data difficult to interpret. In particular, it appears that a more highly contaminated region within the influence of the vent, but outside the heated zone, greatly affected the off-gas concentrations. This interpretation is consistent with the uneven soil contamination at the VOCs in Non-Arid Soils ID Site.

Because the permeability of the soil increased as a result of soil drying, the mass rate of contaminant removal increased even though the off-gas concentration varied little. Figure 3.16 shows the removal rate of PCE increased from an initial rate of about 5 g/min to 15 g/min. The cumulative removal as of December 6, 1993, which was just before the majority of the post-test soil sampling, was 475 kg for PCE and 107 kg for TCE.

The difference between the pre- and post-test soil samples can also be used to calculate the amount of contaminant removed from the soil and can be compared to the amount removed in the off-gas stream. As mentioned previously, the contaminant was being drawn from beyond the heated region, so the amount removed from the vent should be greater than the amount removed based on soil measurements. The difference between the pre- and post-test soil samples was integrated over the sampled region to give the mass removed based on the soil samples. A number of assumptions were necessary to integrate the soil data. To perform the integration, we assumed a uniform soil bulk density of 1.9 g/cm³ (120 lb/ft³), applied the contaminant removal results from each sampled well to an appropriate area, and then integrated with a trapezoid rule over the depth. Results for MHV-30 were applied to the soil up to a radius of 1.2 m (4 ft); MHV-37 between radii of 1.2 and 3.0 m (4 and 10 ft); MHV-38 between radii of 3.0 and 5.2 m (10 and 17 ft), excluding 1.14 m (3.75 ft) radius zones about the electrodes; MHV-39 between radii of 5.2 and 7.9 m (17 and 26 ft); MHV-31 for a

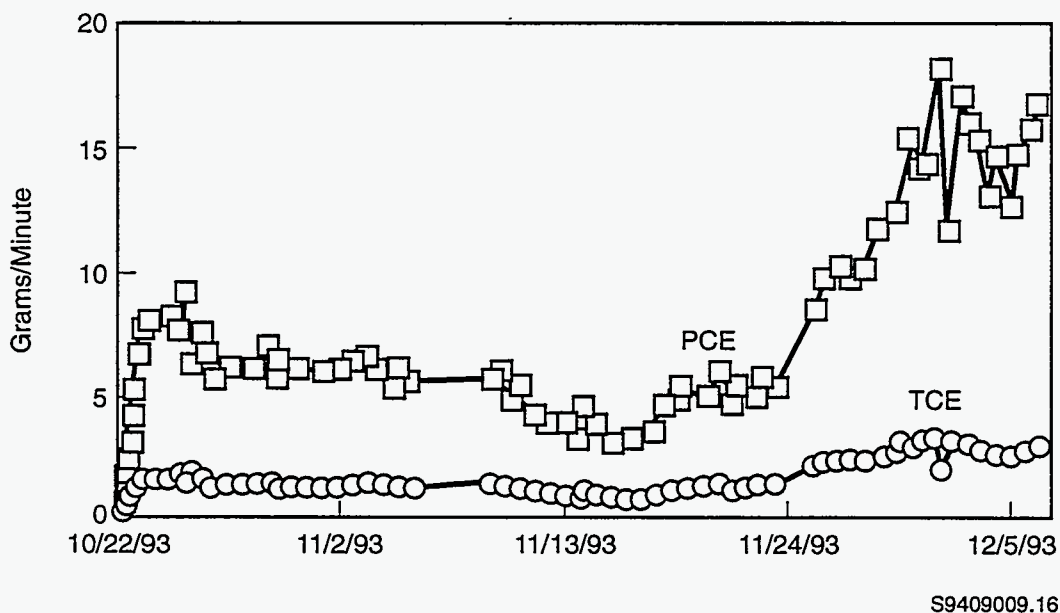


Figure 3.16. Mass Removal Rate of PCE and TCE from the Vent

1.14 m (3.75-ft) radius about three electrodes; and MHV-34 for a 1.14-m (3.75-ft) radius about the final three electrodes. The assumed uniform density results in calculated removal about 10% lower than actual, because SPSH dried the soil and reduced the soil bulk density.

The soil sample data show 180 kg of PCE and 23 kg of TCE were removed from the soil, which is less than the amount removed from the vent. This supports the view that additional contaminant was being drawn from outside the heated (and sampled) area, and the additional contaminant removed by heating was too little to be detected as a change in the off-gas concentration. Because the removal data for the wells within the electrode array are similar, the calculated mass of contaminant removed depends weakly on assumptions for appropriate areas. The exception to this is that MHV-34 had very high initial PCE contamination near the surface (4500 ppm) where the sampling interval was 5 ft; the change in PCE concentration at this location accounts for about half the calculated 180 kg of PCE removed.

3.6 SPSH Energy Usage

Energy consumption is an 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 1100 m³ 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 (see Figure 2.5). Combining this energy usage with the rough estimate of the heated volume gives an energy usage of 90 kWh/m³, or \$7/m³ at \$0.07/kWh. As with most heating methods, the energy cost to heat the soil is small when compared to the costs for the capital equipment for the electrical system, the off-gas destruction system, and the operator time.

4.0 Conclusions

Six-phase soil heating was demonstrated as an effective technology for heating and remediating low-permeability soils containing volatile organic compounds. Testing was performed as part of the Volatile Organic Compounds in Non-Arid Soils Integrated Demonstration at the Savannah River Site. The soil remediated at the integrated demonstration site was initially contaminated with perchloroethylene and trichloroethylene; the highest soil contamination occurred in clay-rich zones that are ineffectively treated by conventional soil vapor extraction because of the very low permeability of the clay. The success of the SPSH technology at the Savannah River Site has resulted in the planned use of SPSH at the Rocky Flats Plant and consideration by several potential commercial partners for use at private industrial sites.

The following conclusions can be drawn from the SPSH demonstration at the Savannah River Site.

1. The PCE removal from the clay zone was 99.7% (median) within the electrode array, based on a comparison of pre- and post-test soil samples. This removal is due to venting and soil heating by the SPSH process.
2. SPSH accelerated the removal of VOCs from the clay soil, based on the comparison of soil remediation inside (99.7%) and outside (93%) the electrode array.
3. SPSH effectively heated the clay soil at the Savannah River Site to about 100°C within 8 days, and maintained this elevated temperature as the soil was dried.
4. The efficiency of contaminant removal increased with increased soil drying due to heating.
5. 72,000 L (19,000 gal) of condensed steam was removed from the central vent, indicating substantial drying of the soil.
6. The water-drip system needed to maintain conduction at the electrodes did not overwhelm the removal of moisture from the soil. 21,000 L (5,500 gal) of water, with 500 mg/L table salt, were added at the electrodes compared to 72,000 L (19,000 gal) of condensed steam removed from the soil.
7. Automation and computer control of the SPSH system allowed unattended operation after an initial start-up period.
8. Off-gas concentrations showed little change during heating, most likely because of a more highly contaminated region within the influence of the vent but outside the heated zone.
9. Model results for heating as a result of SPSH agree with the temperature data, further validating the process simulator as a useful design tool.

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Appendix A

Soil VOC Data (Figures)

The figures in this appendix present the results of the pre- and post-test soil sampling for PCE and TCE. The first five pages give a well-by-well comparison of the PCE and TCE soil contamination before and after heating with SPSH. These concentration data are averages of the duplicate samples taken at each depth. The next two figures in this appendix give the percent contaminant remaining after treatment with SPSH for both PCE and TCE. This represents the difference between the pre- and post-test samples in adjacent wells. The curves are 3-point running averages of the calculated percent contaminant remaining. These data are discussed in Section 3.2 of this report. The remaining figures present the individual results of the duplicate samples taken at each depth (data points); also shown (lines) are the averages of the duplicate samples.

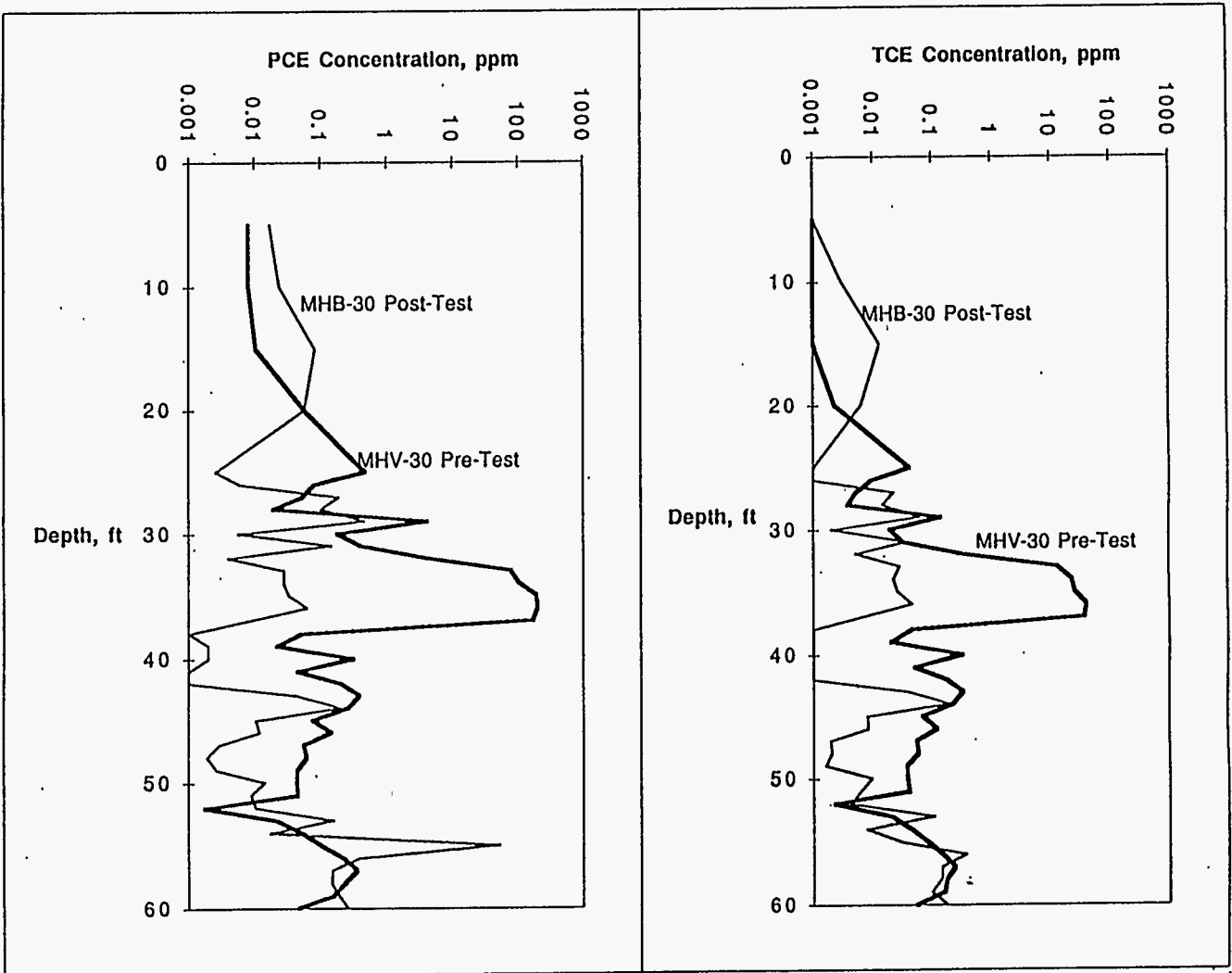


Figure A.1. PCE and TCE Concentrations for Pre-Test (MHV-30) and Post-Test (MHB-30) as a Function of Depth from Surface

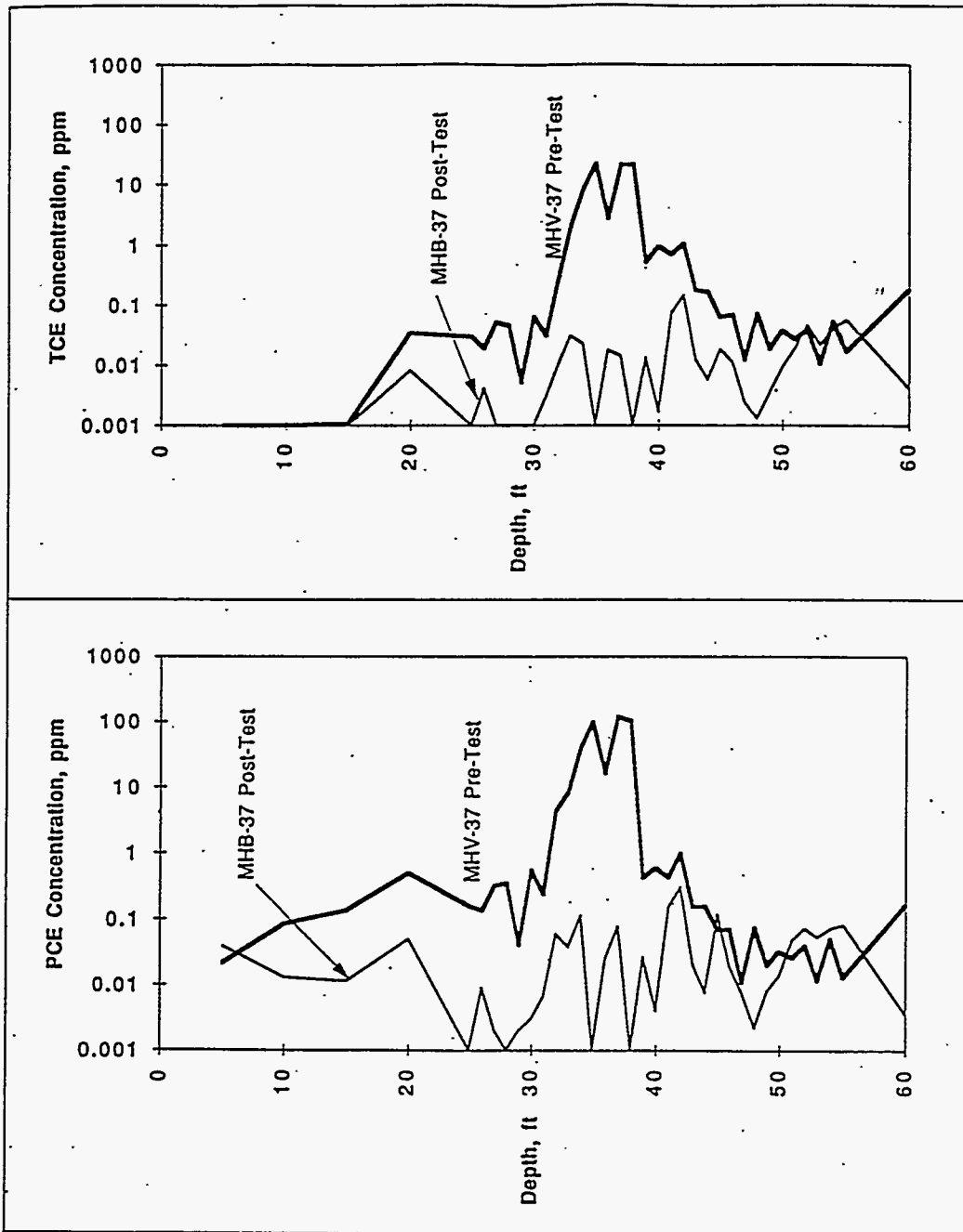


Figure A.2. PCE and TCE Concentrations for Pre-Test (MHV-37) and Post-Test (MHB-37) as a Function of Depth from Surface

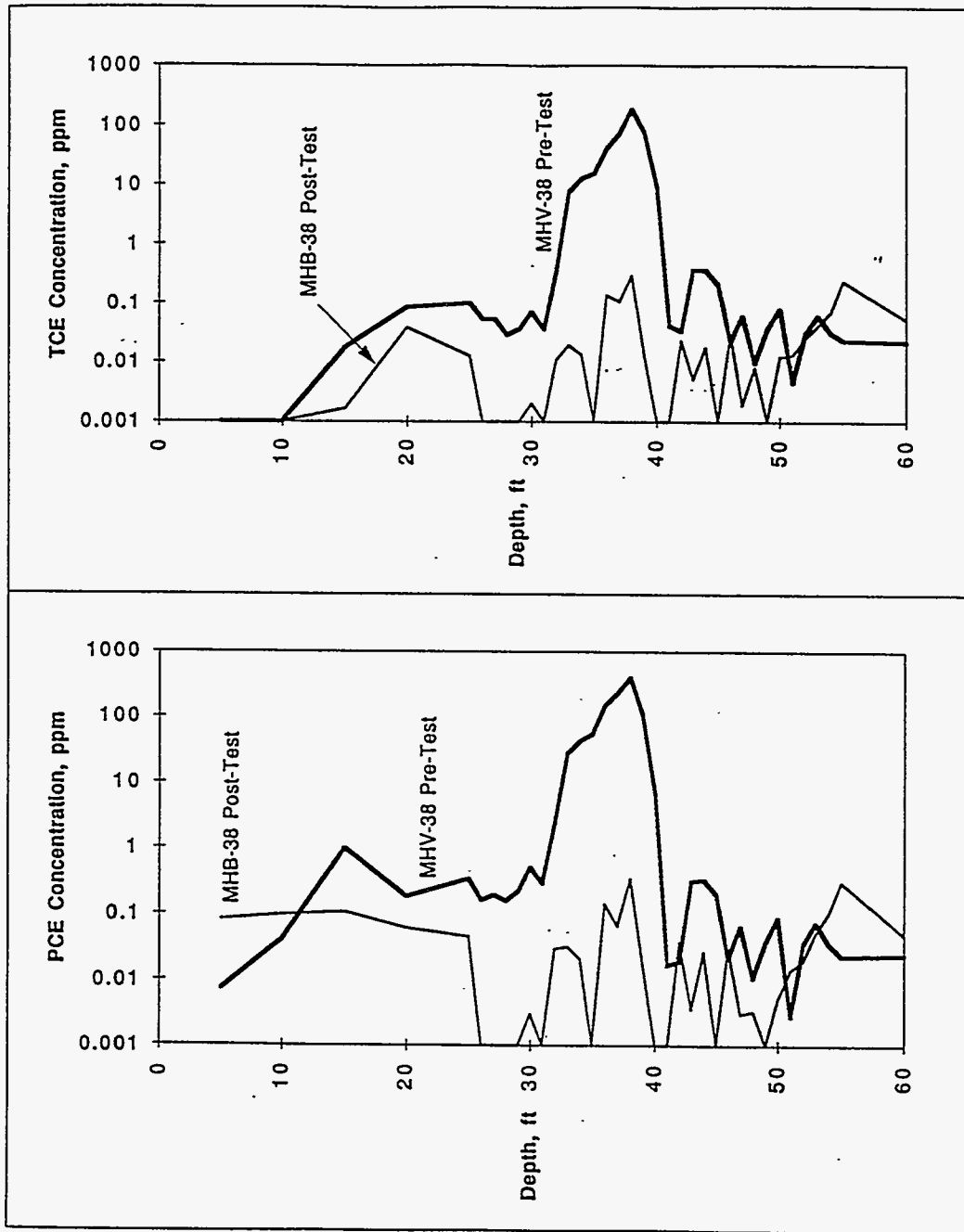


Figure A.3. PCE and TCE Concentrations for Pre-Test (MHV-38) and Post-Test (MHB-38) as a Function of Depth from Surface

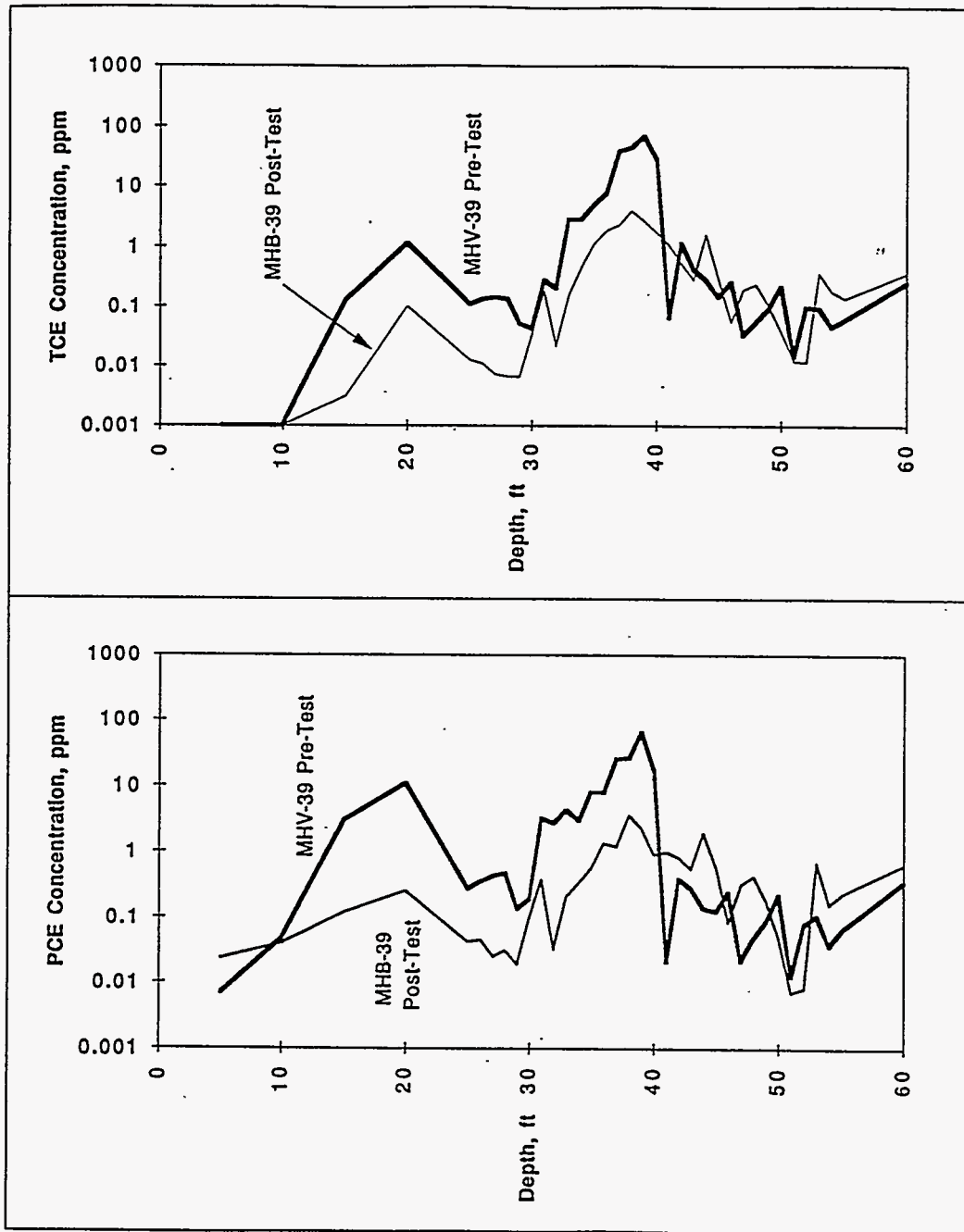


Figure A.4. PCE and TCE Concentrations for Pre-Test (MHV-39) and Post-Test (MHB-39) as a Function of Depth from Surface

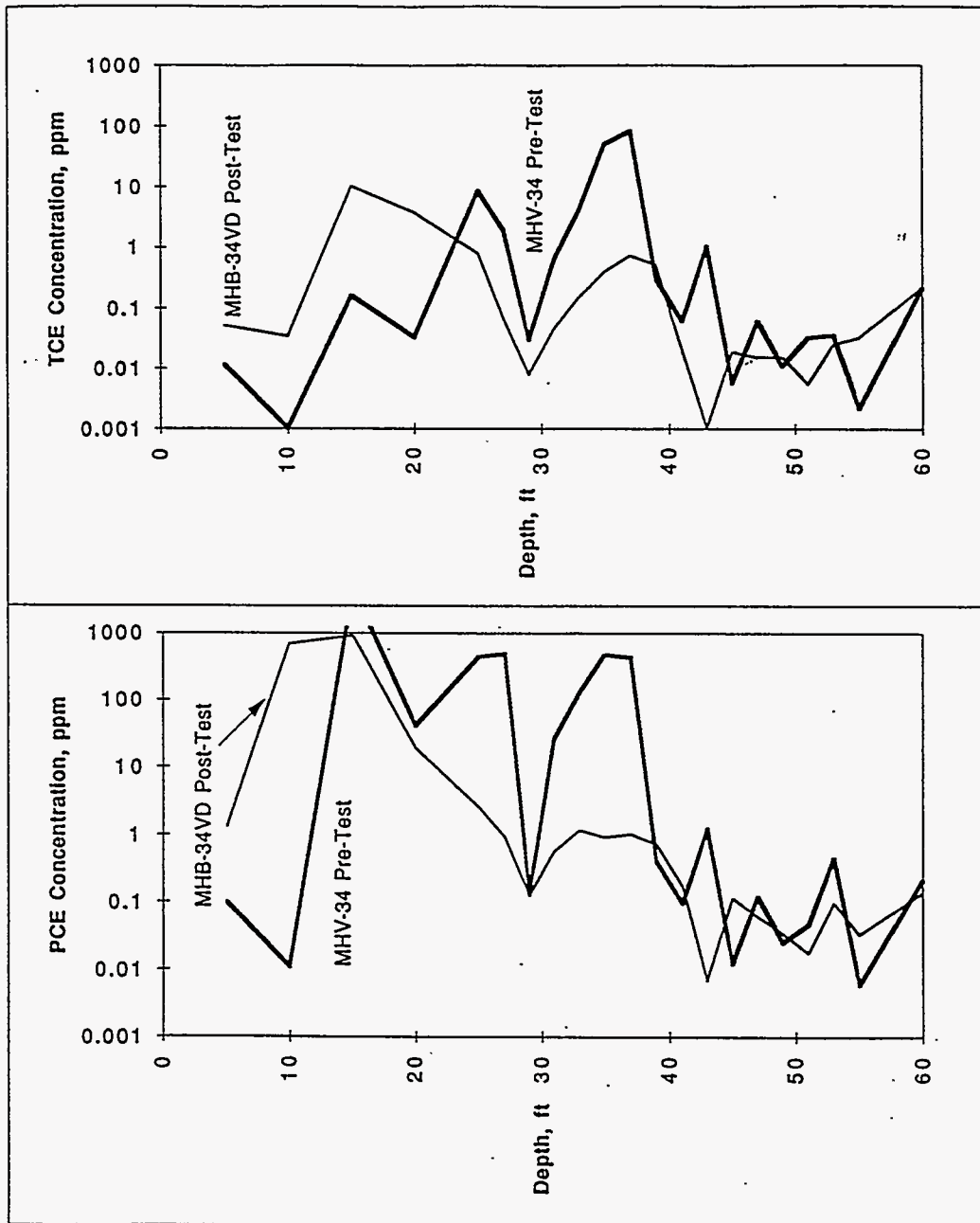


Figure A.5. PCE and TCE Concentrations for Pre-Test (MHV-34) and Post-Test (MHB-34) as a Function of Depth from Surface

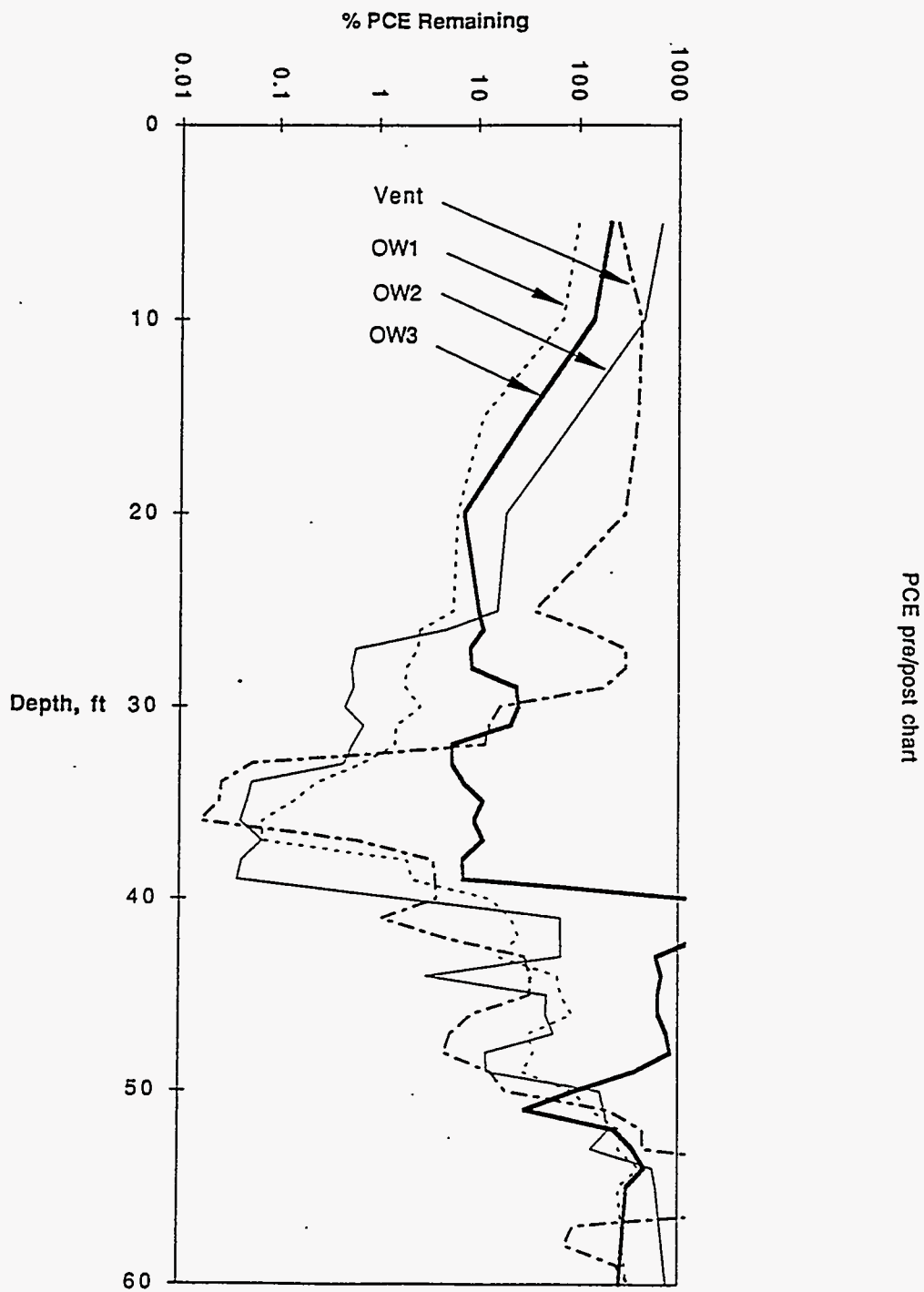


Figure A.6. Percent PCE Remaining as a Function of Depth from Surface for the Central Vent and Observation Wells OW1, OW2, and OW3

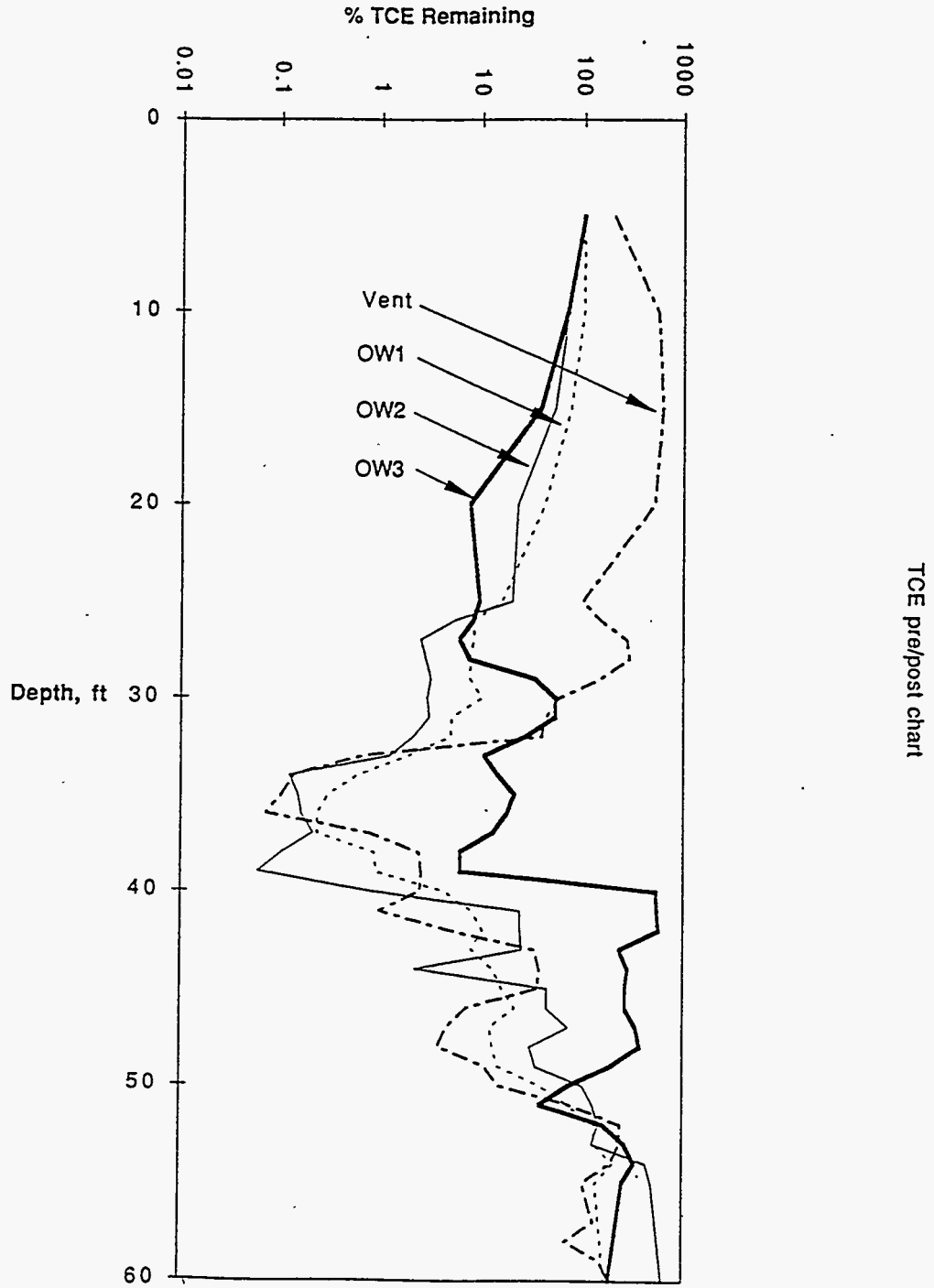
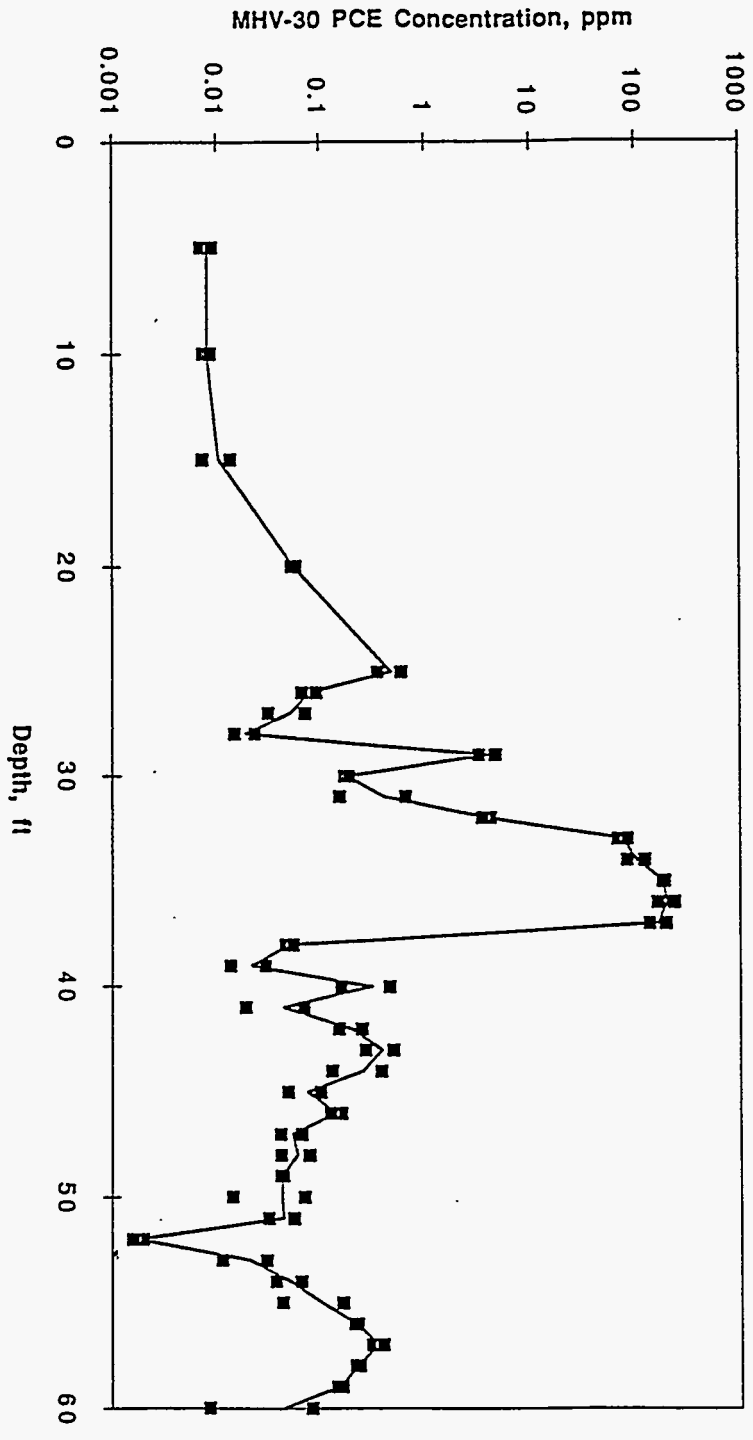
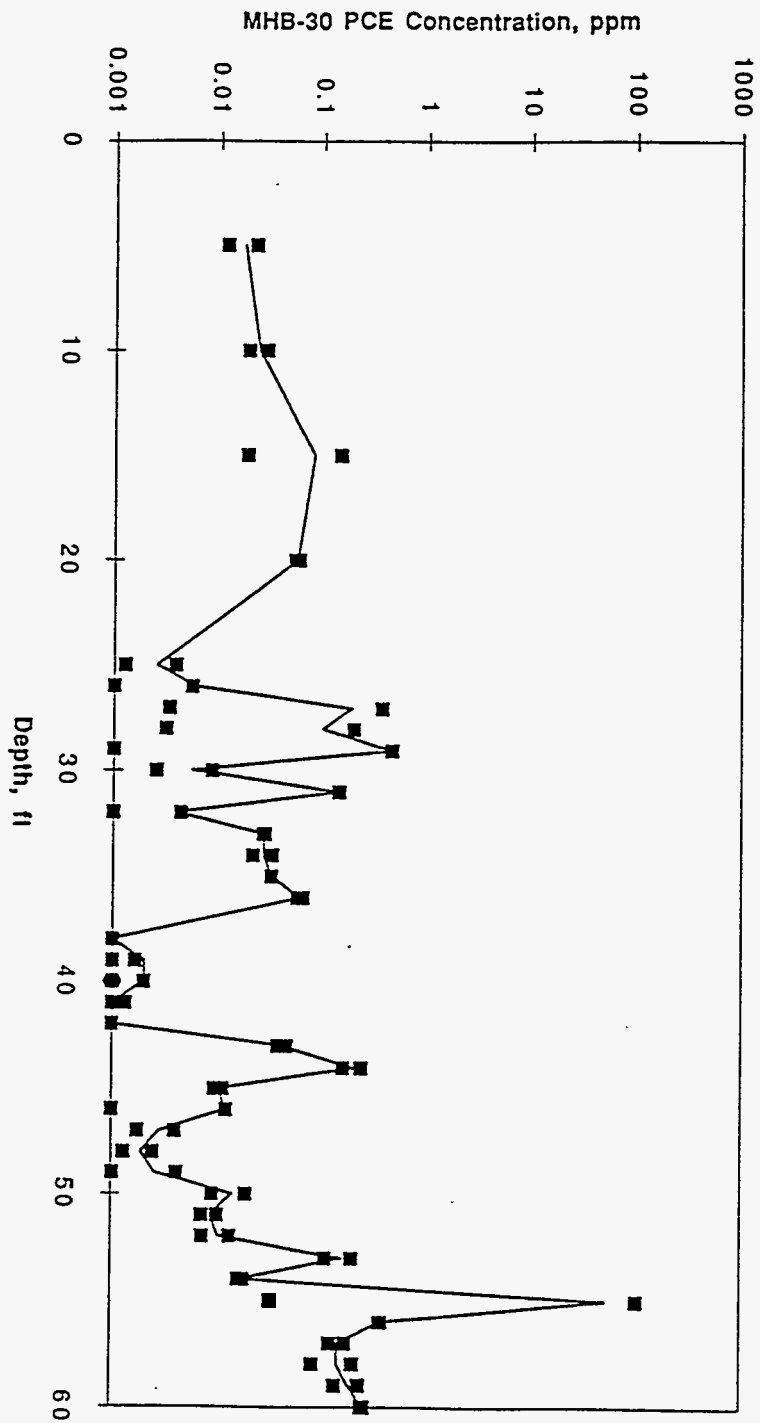


Figure A.7. Percent TCE Remaining as a Function of Depth from Surface for the Central Vent and Observation Wells OW1, OW2, and OW3



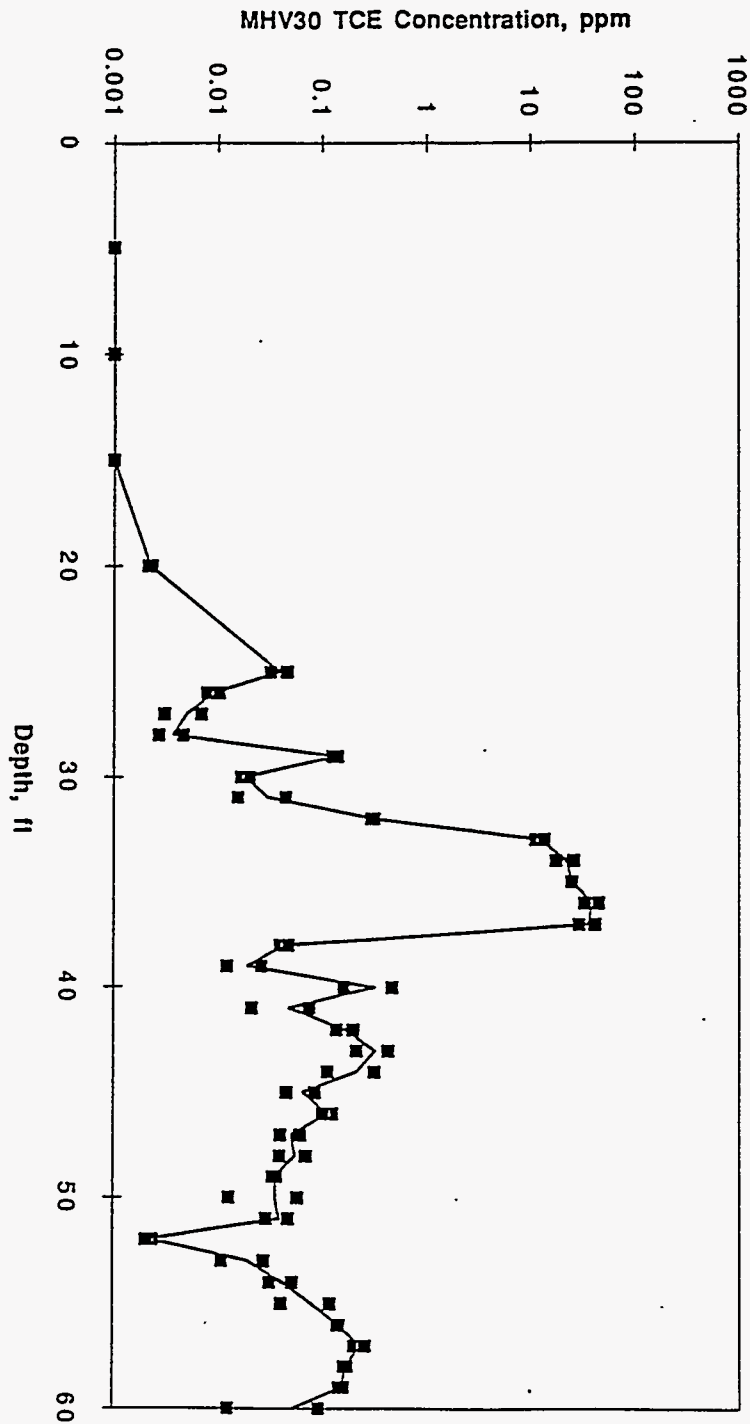
PCE30CONXLC

Figure A.8. PCE Concentration as a Function of Depth from Surface for Well MHV-30. The curve plots the average of the duplicate soil measurements at each depth.



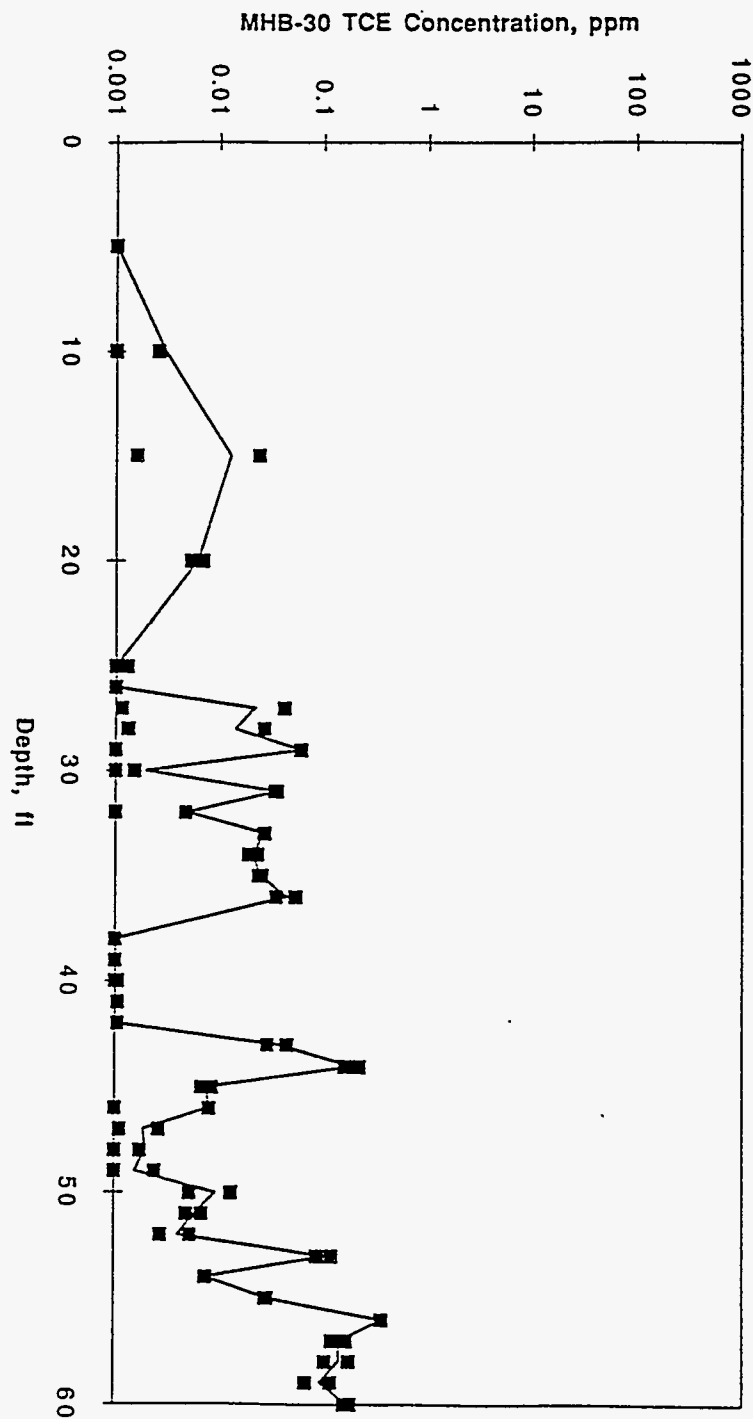
PCE30VCO.XLC

Figure A.9. PCE Concentration as a Function of Depth from Surface for Well MHB-30. The curve plots the average of the duplicate soil measurements at each depth.



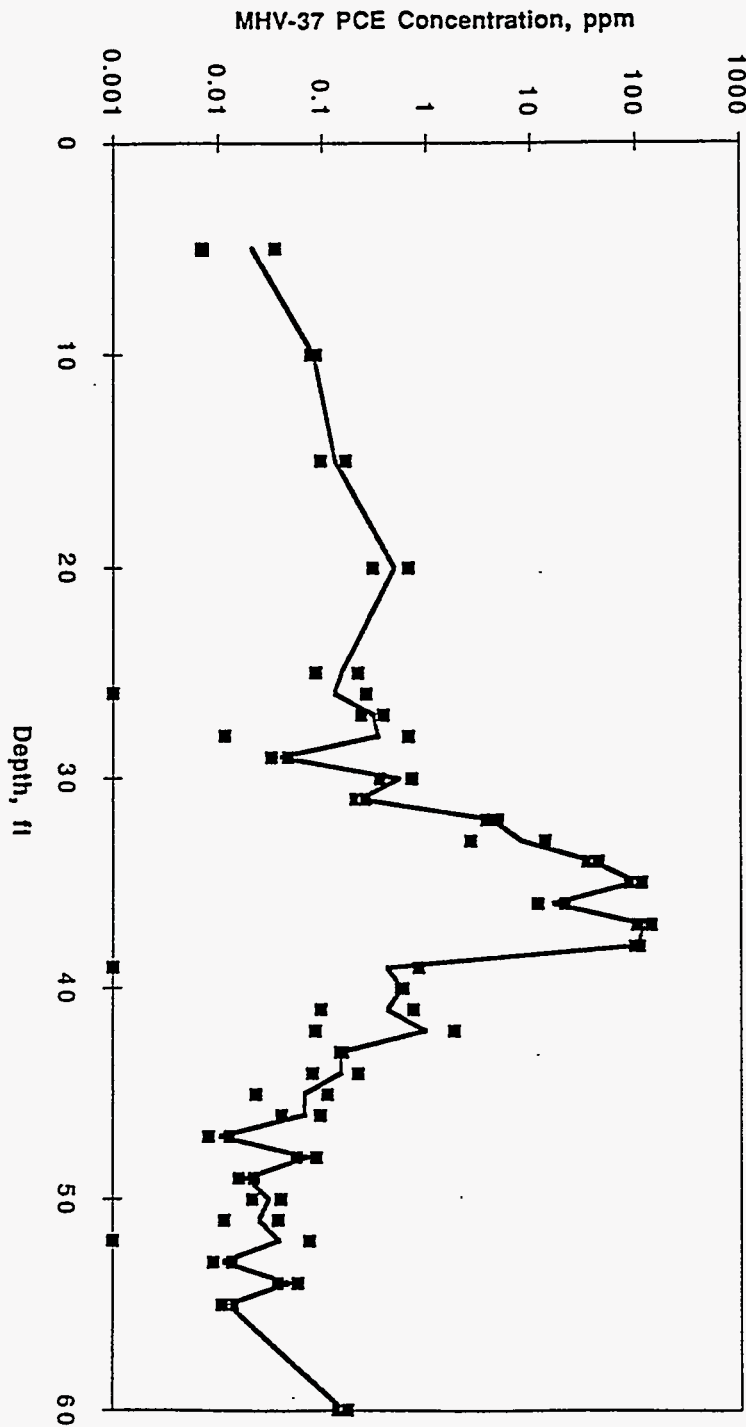
TCE30CON.XLC

Figure A.10. TCE Concentration as a Function of Depth from Surface for Well MHV-30. The curve plots the average of the duplicate soil measurements at each depth.



TCE30VCO.XLC

Figure A.11. TCE Concentration as a Function of Depth from Surface for Well MHB-30. The curve plots the average of the duplicate soil measurements at each depth.



PCE37CON.XLC

Figure A.12. PCE Concentration as a Function of Depth from Surface for Well MHV-37. The curve plots the average of the duplicate soil measurements at each depth.

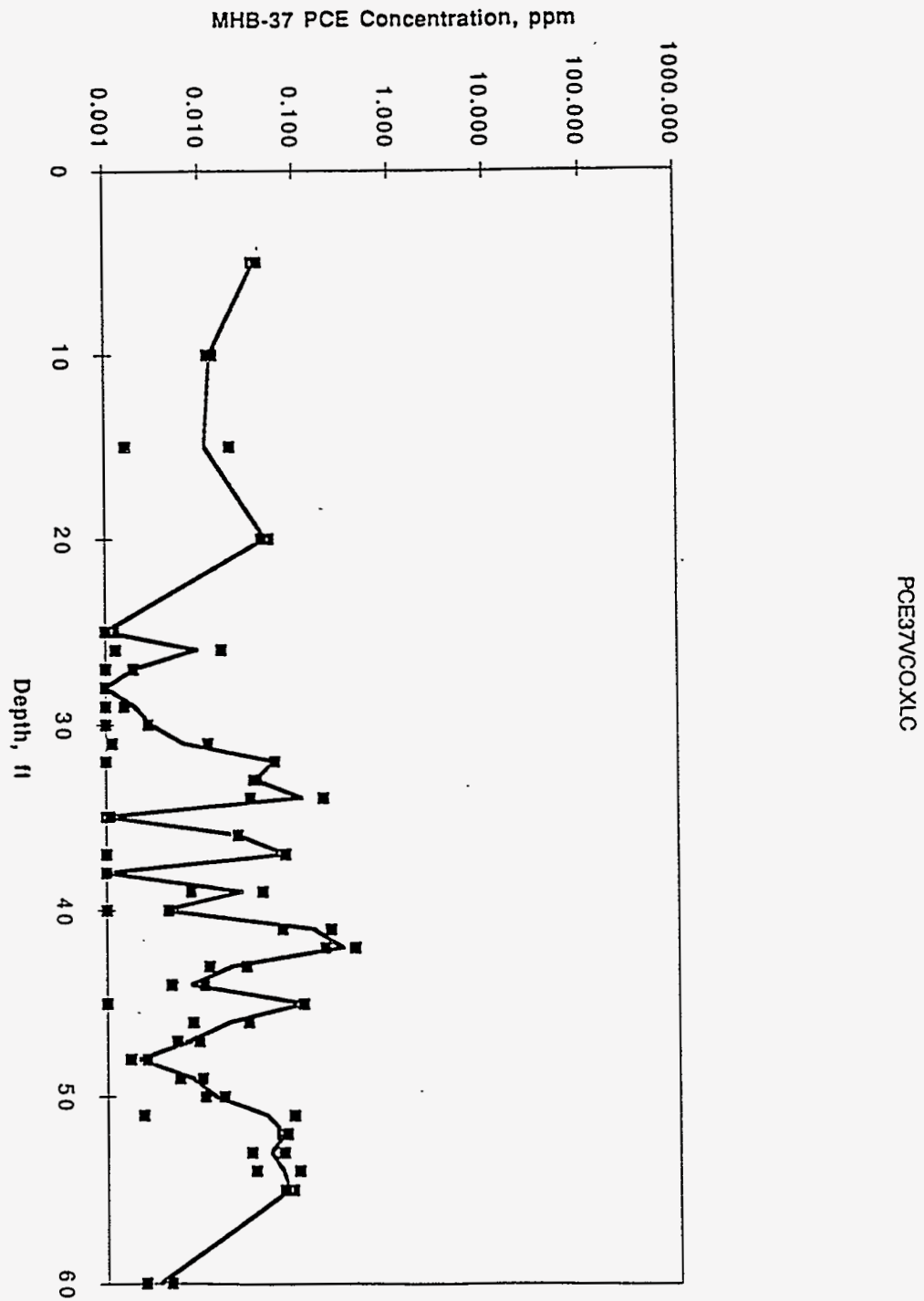


Figure A.13. PCE Concentration as a Function of Depth from Surface for Well MHB-37. The curve plots the average of the duplicate soil measurements at each depth.

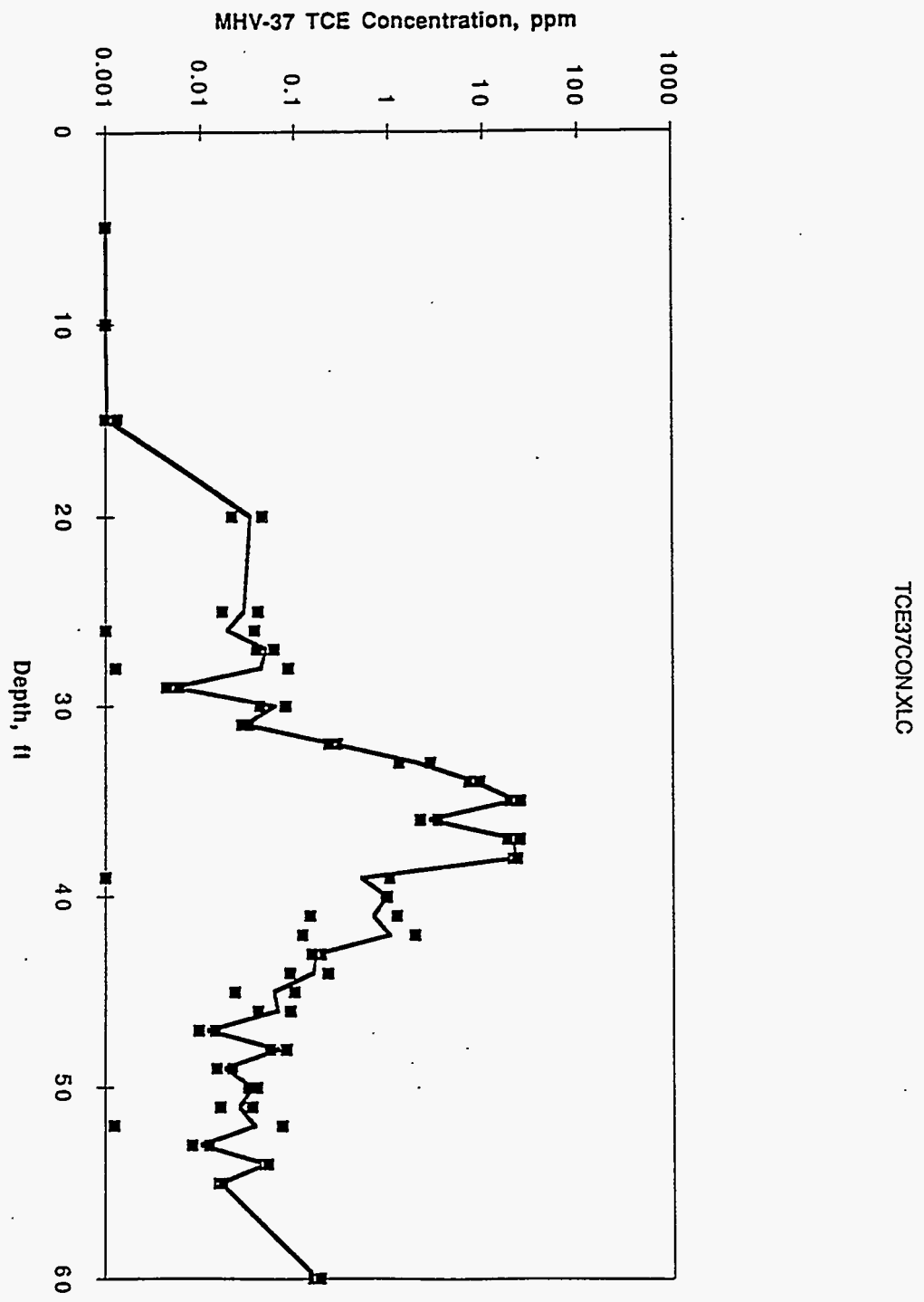
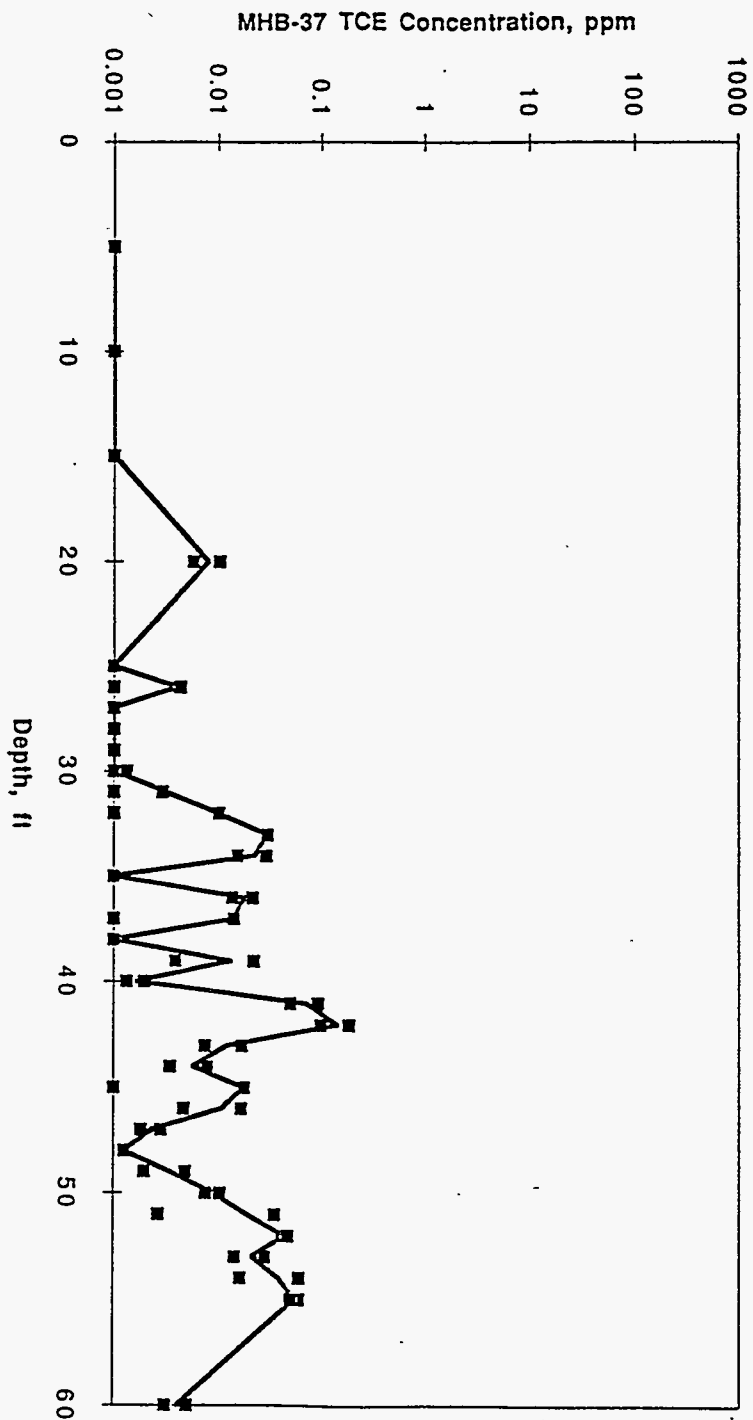
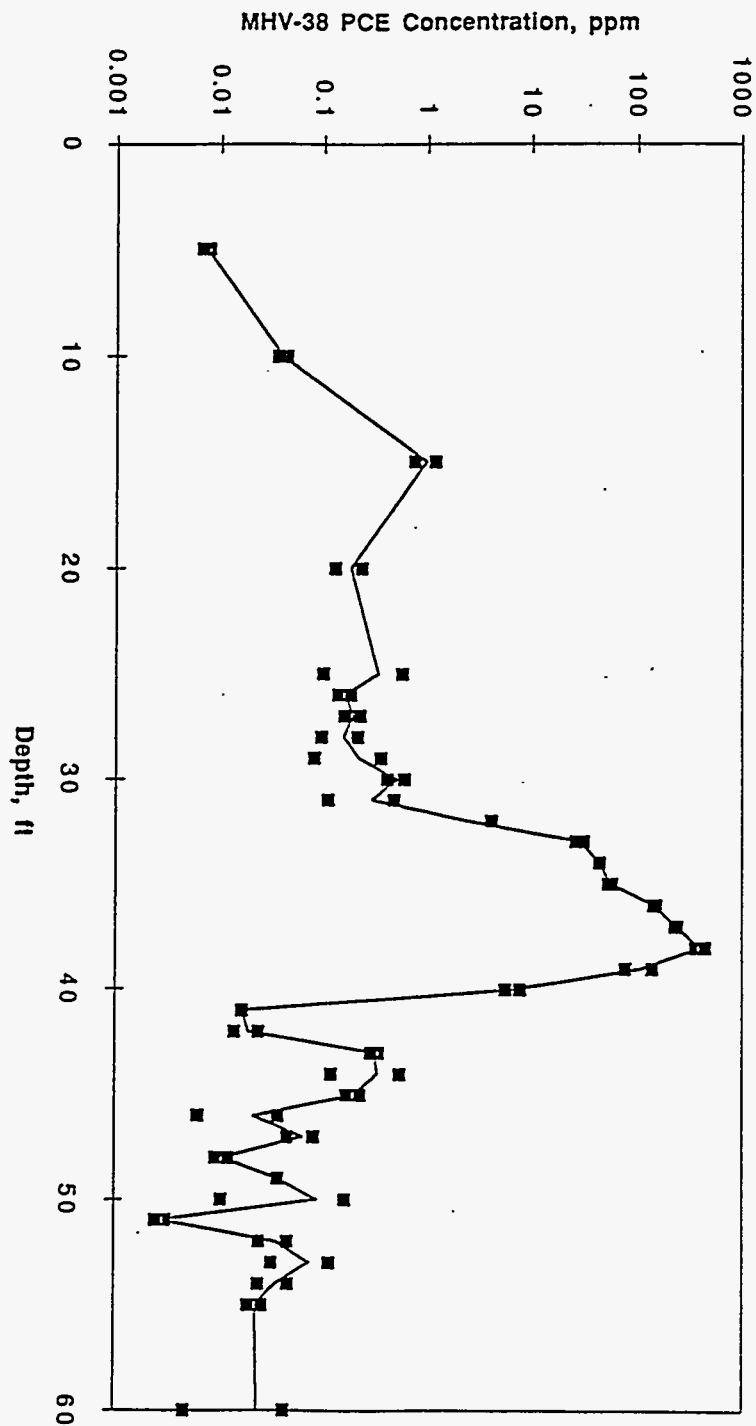


Figure A.14. TCE Concentration as a Function of Depth from Surface for Well MHV-37. The curve plots the average of the duplicate soil measurements at each depth.



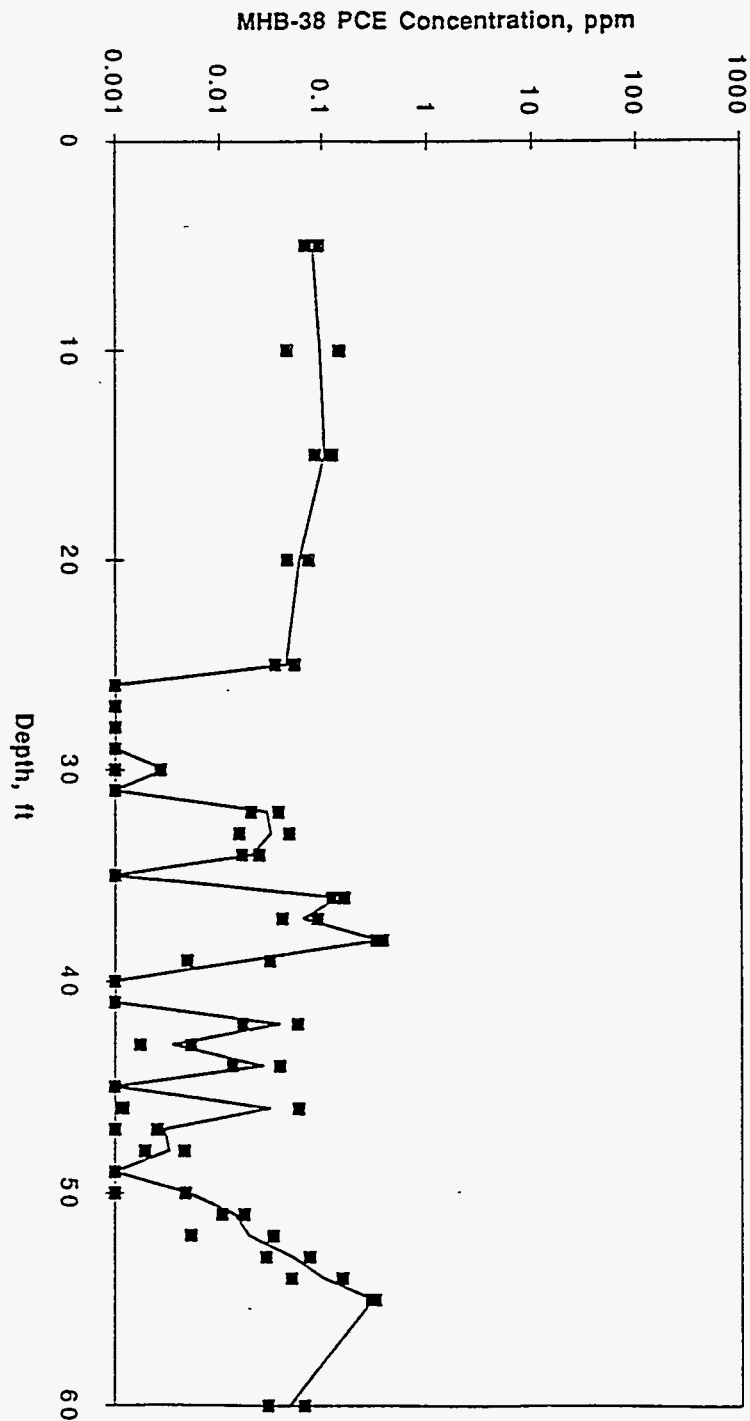
TCE37VCO.XLC

Figure A.15. TCE Concentration as a Function of Depth from Surface for Well MHB-37. The curve plots the average of the duplicate soil measurements at each depth.



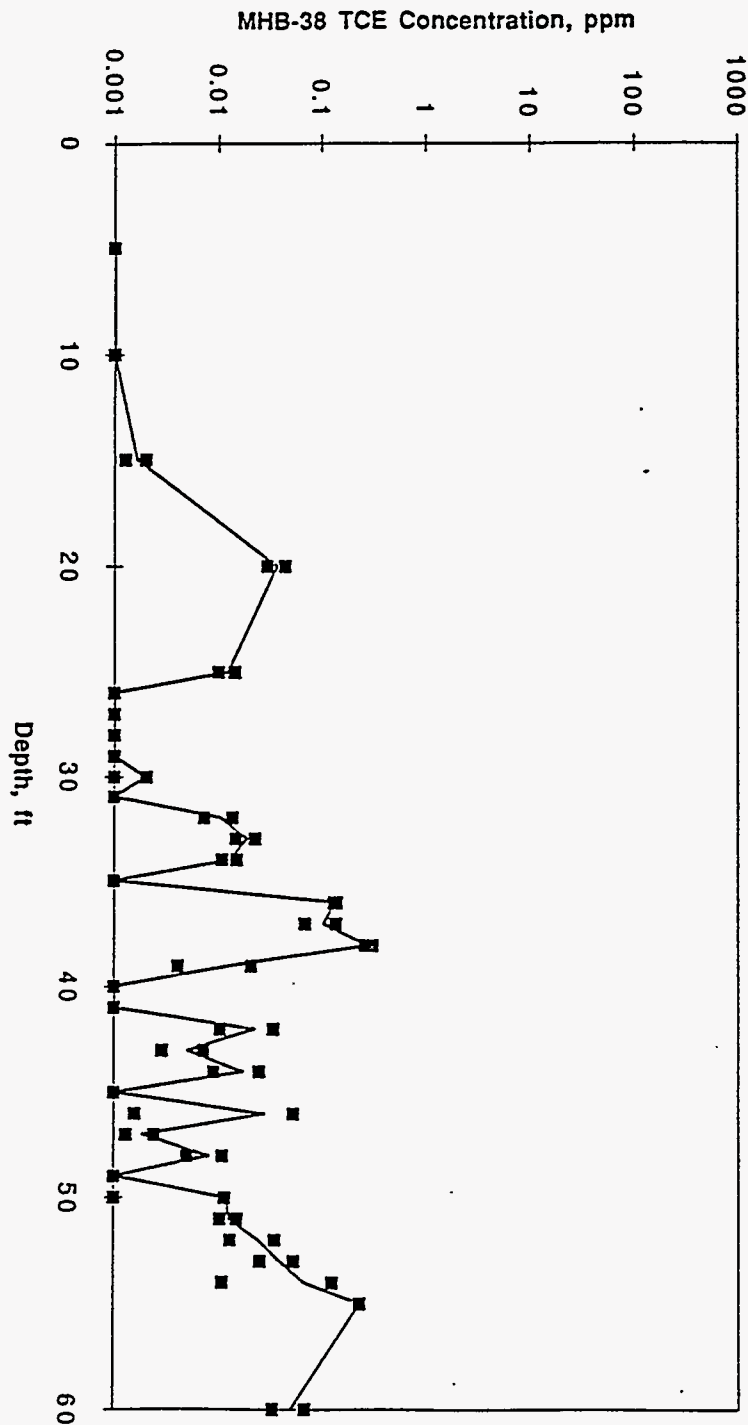
PCE38CONXLC

Figure A.16. PCE Concentration as a Function of Depth from Surface for Well MHV-38. The curve plots the average of the duplicate soil measurements at each depth.



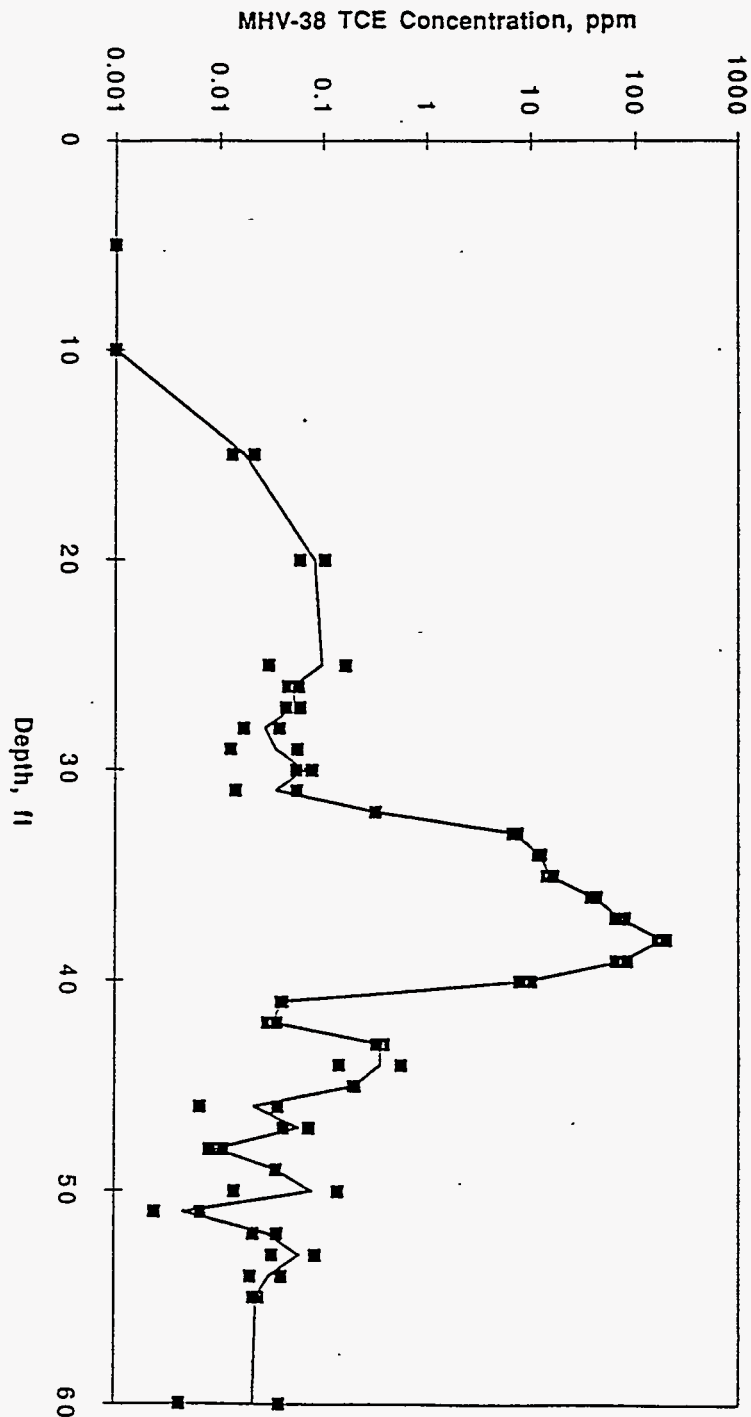
PCE38VCO.XLC

Figure A.17. PCE Concentration as a Function of Depth from Surface for Well MHB-38. The curve plots the average of the duplicate soil measurements at each depth.



TCES8VCO.XLC

Figure A.18. TCE Concentration as a Function of Depth from Surface for Well MHB-38. The curve plots the average of the duplicate soil measurements at each depth.



TCE38CONX1C

Figure A.19. TCE Concentration as a Function of Depth from Surface for Well MHV-38. The curve plots the average of the duplicate soil measurements at each depth.

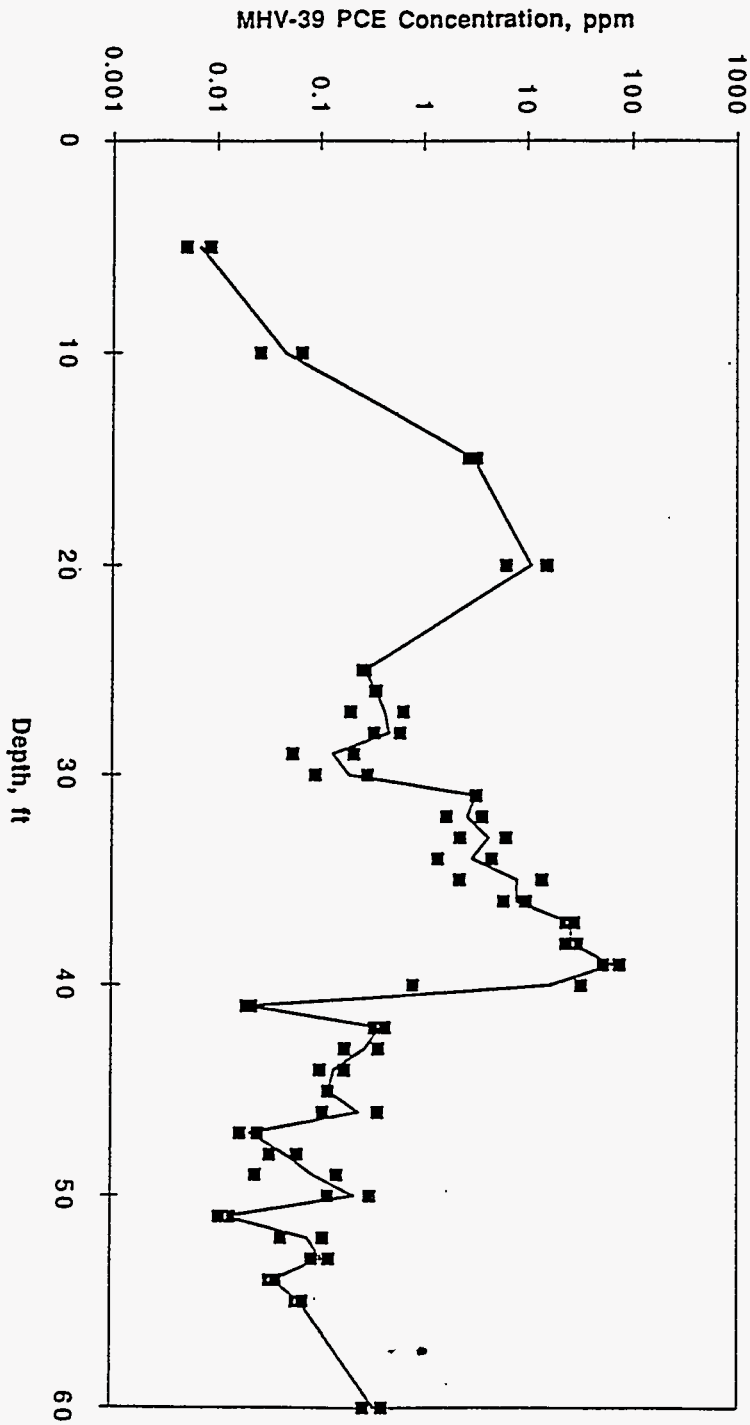
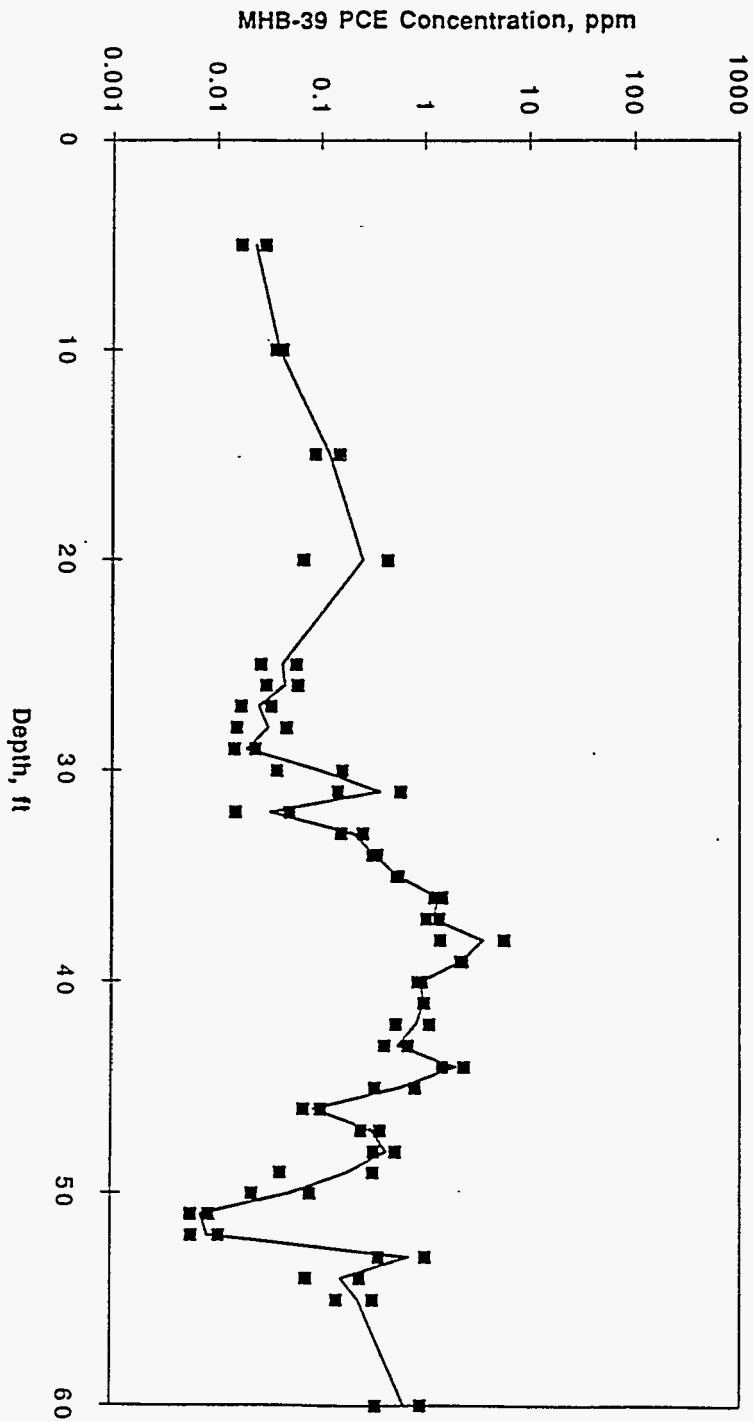
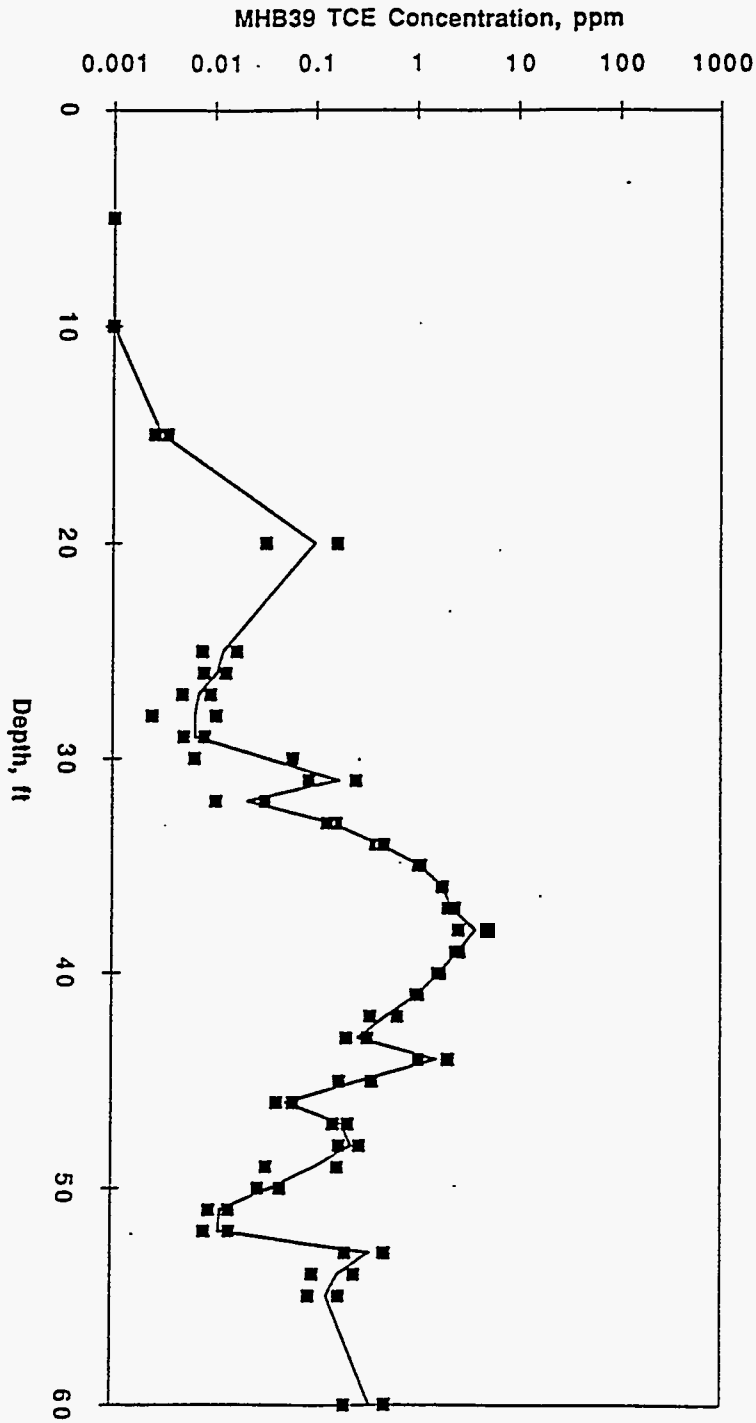


Figure A.20. PCE Concentration as a Function of Depth from Surface for Well MHV-39. The curve plots the average of the duplicate soil measurements at each depth.



POE39VCOX1C

Figure A.21. PCE Concentration as a Function of Depth from Surface for Well MHB-39. The curve plots the average of the duplicate soil measurements at each depth.



TCE39VCO.XLC

Figure A.22. TCE Concentration as a Function of Depth from Surface for Well MHB-39. The curve plots the average of the duplicate soil measurements at each depth.

TCE39CON.XLC

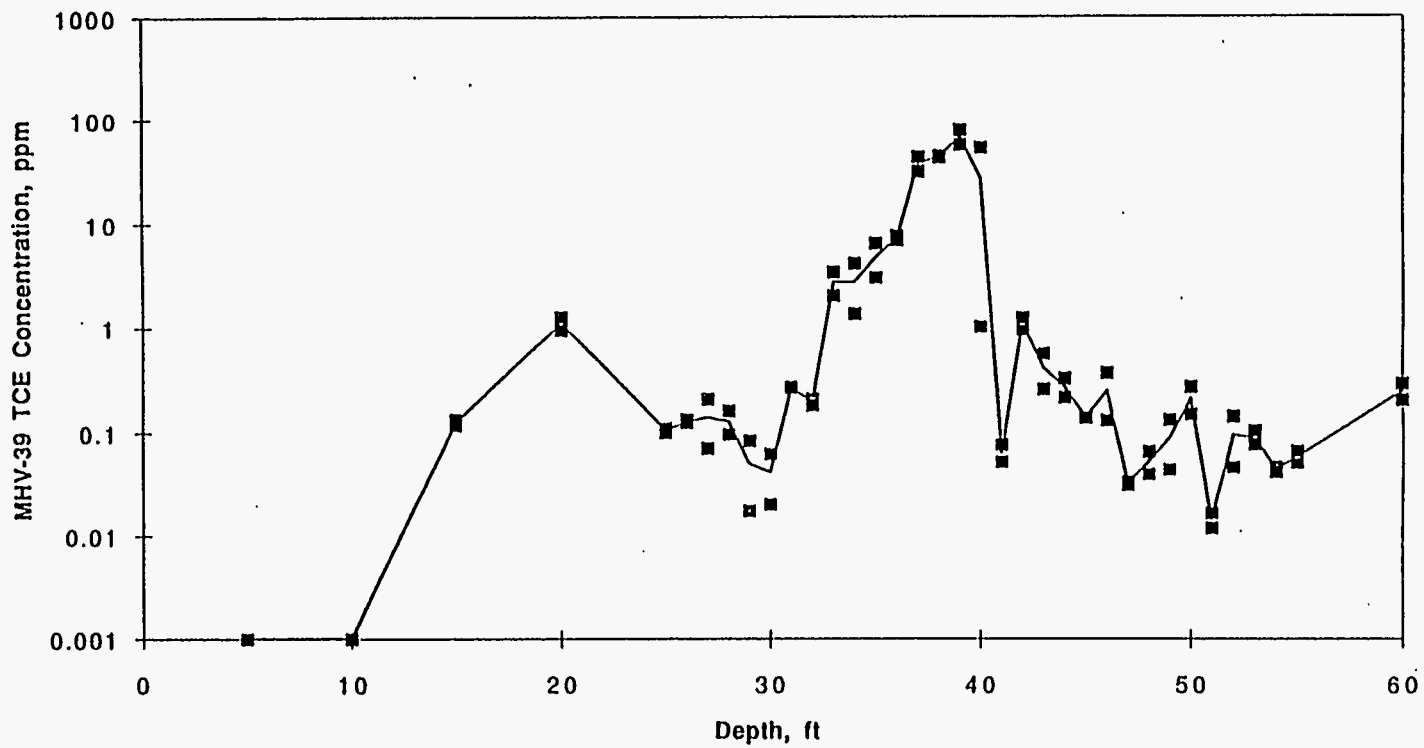
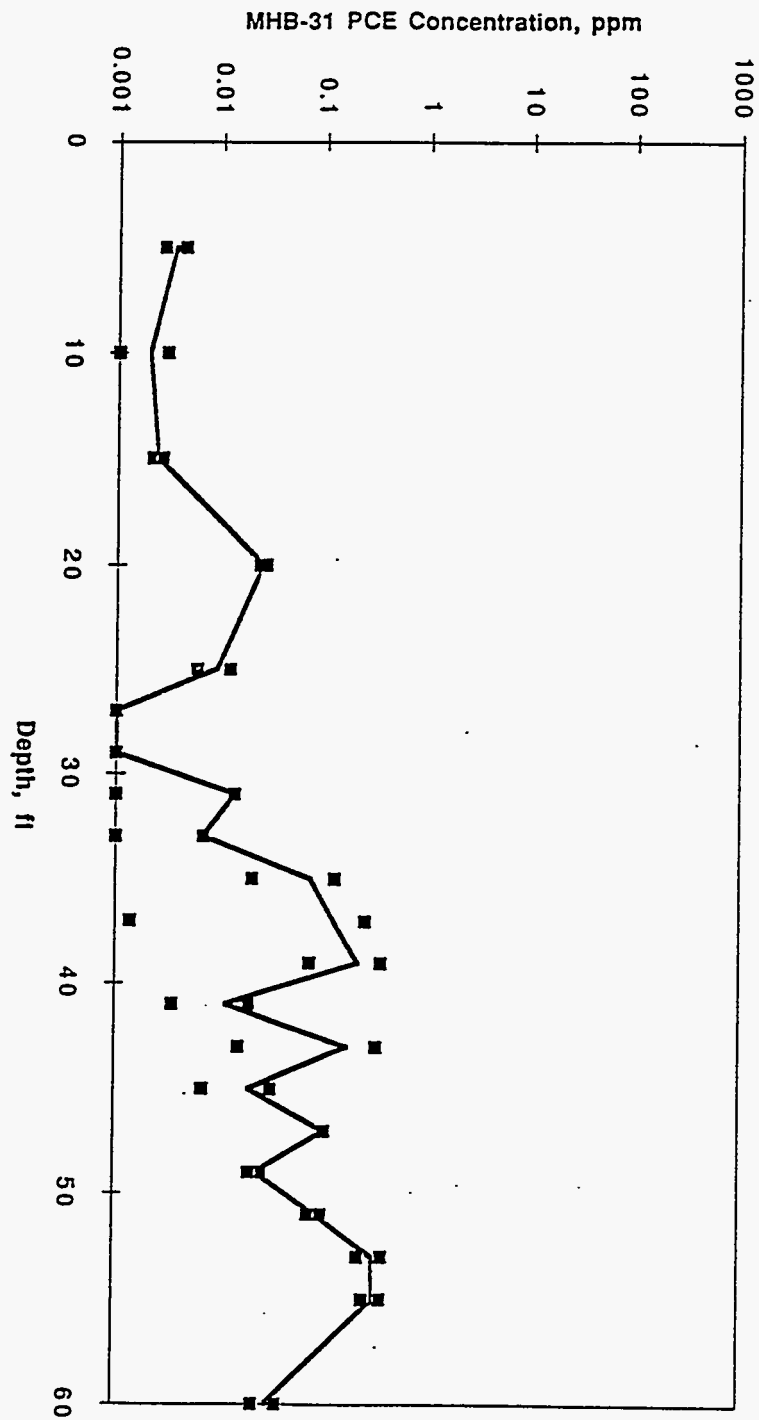
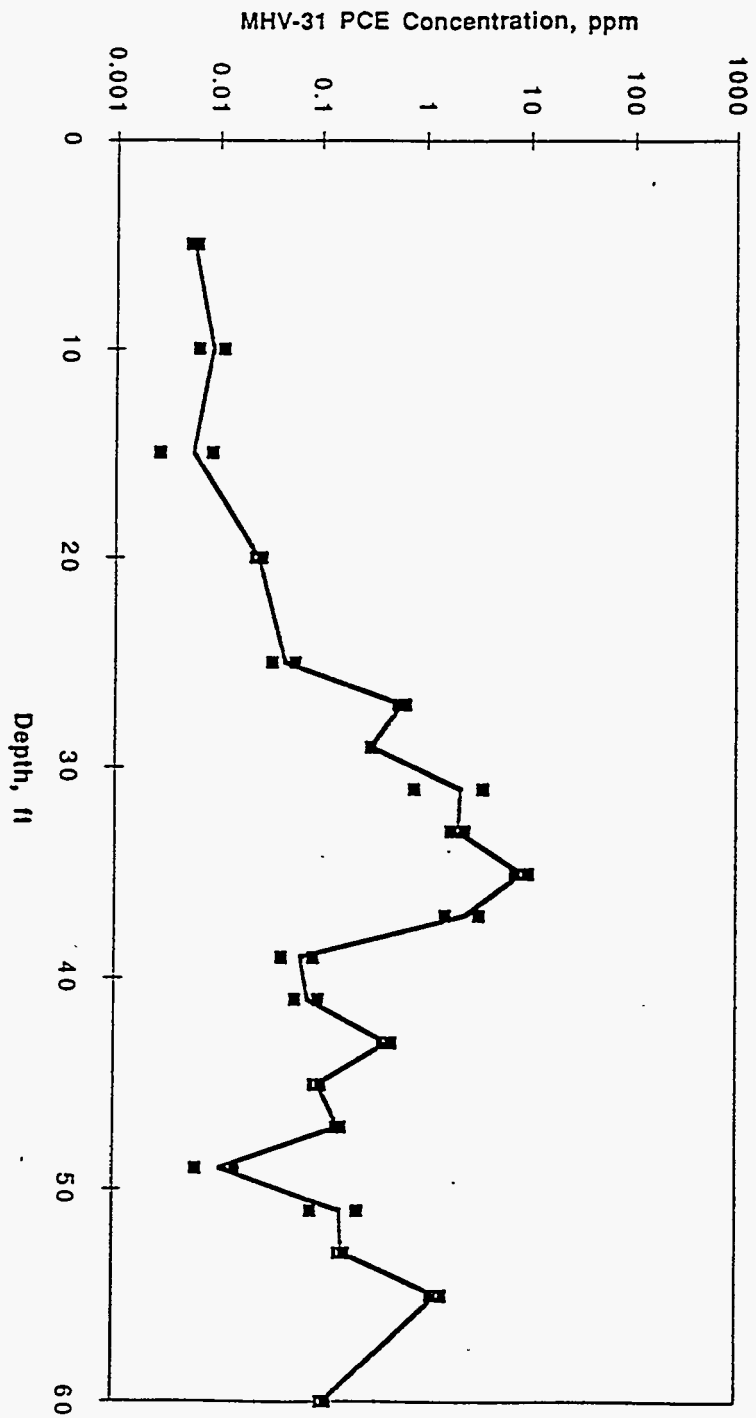


Figure A.23. TCE Concentration as a Function of Depth from Surface for Well MHV-39. The curve plots the average of the duplicate soil measurements at each depth.



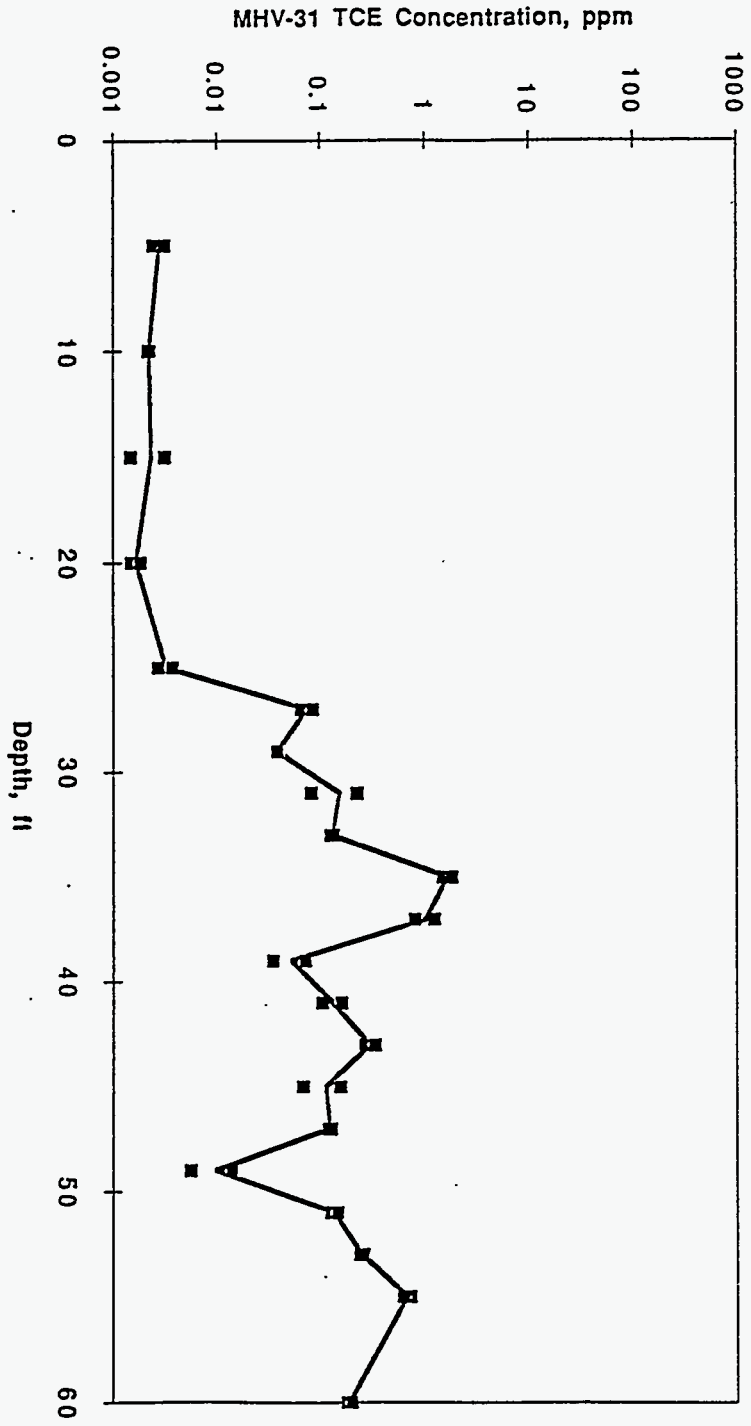
PCE31VCOX1C

Figure A.24. PCE Concentration as a Function of Depth from Surface for Well MHB-31. The curve plots the average of the duplicate soil measurements at each depth.



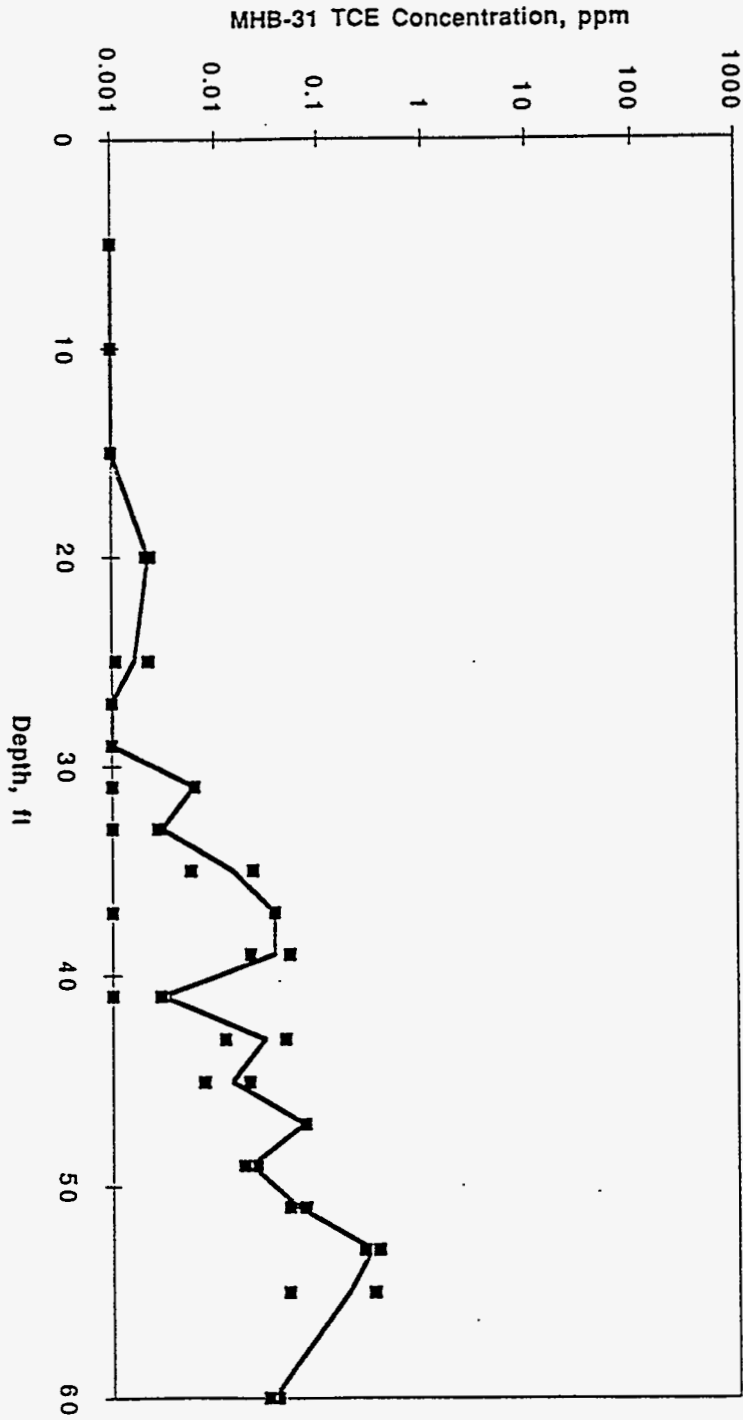
PCE31CON.X1C

Figure A.25. PCE Concentration as a Function of Depth from Surface for Well MHV-31. The curve plots the average of the duplicate soil measurements at each depth.



TCE31CONX1C

Figure A.26. TCE Concentration as a Function of Depth from Surface for Well MHV-31. The curve plots the average of the duplicate soil measurements at each depth.



TCE31VCO.XLC

Figure A.27. TCE Concentration as a Function of Depth from Surface for Well MHB-31. The curve plots the average of the duplicate soil measurements at each depth.

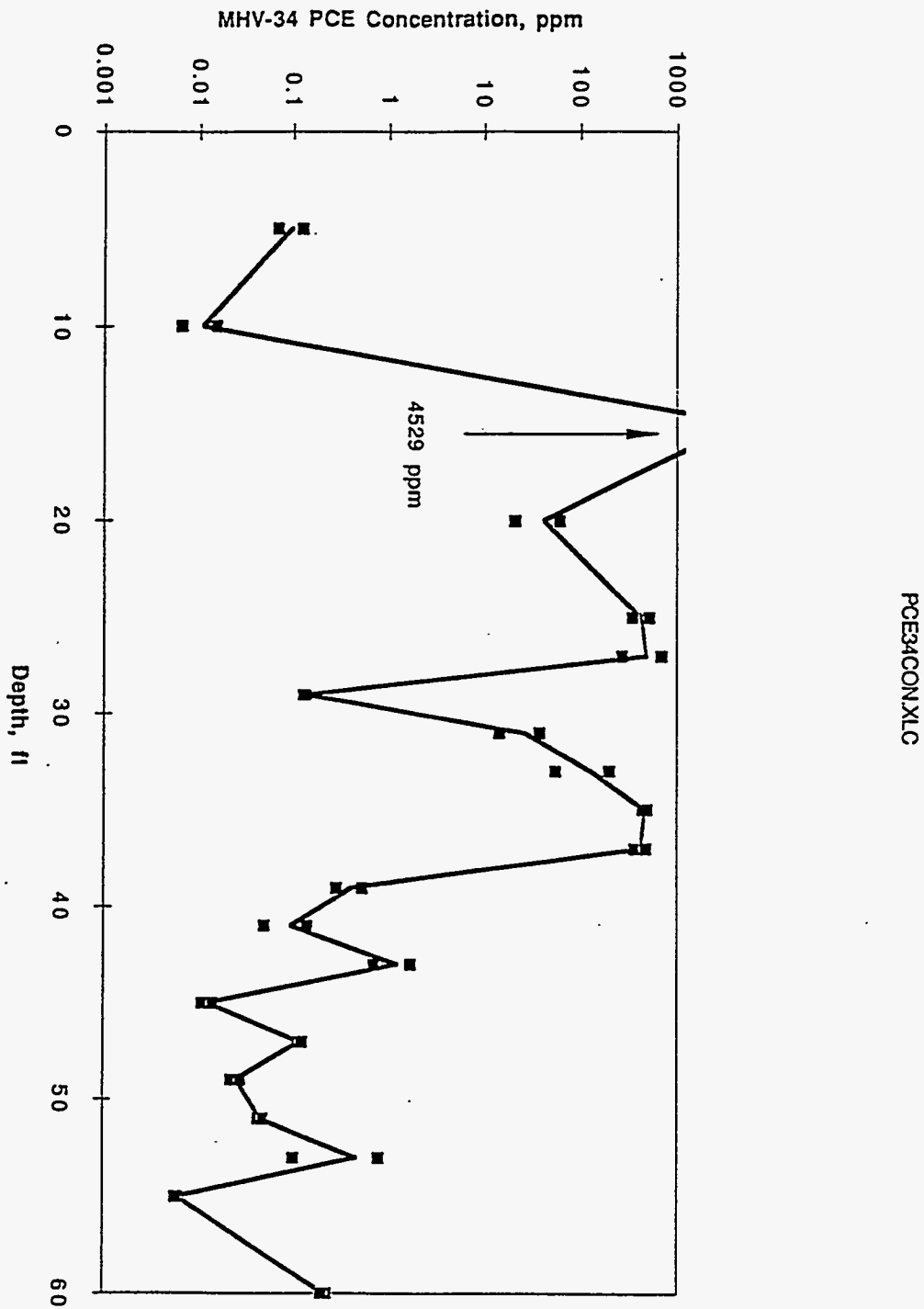


Figure A.28. PCE Concentration as a Function of Depth from Surface for Well MHV-34. The curve plots the average of the duplicate soil measurements at each depth.

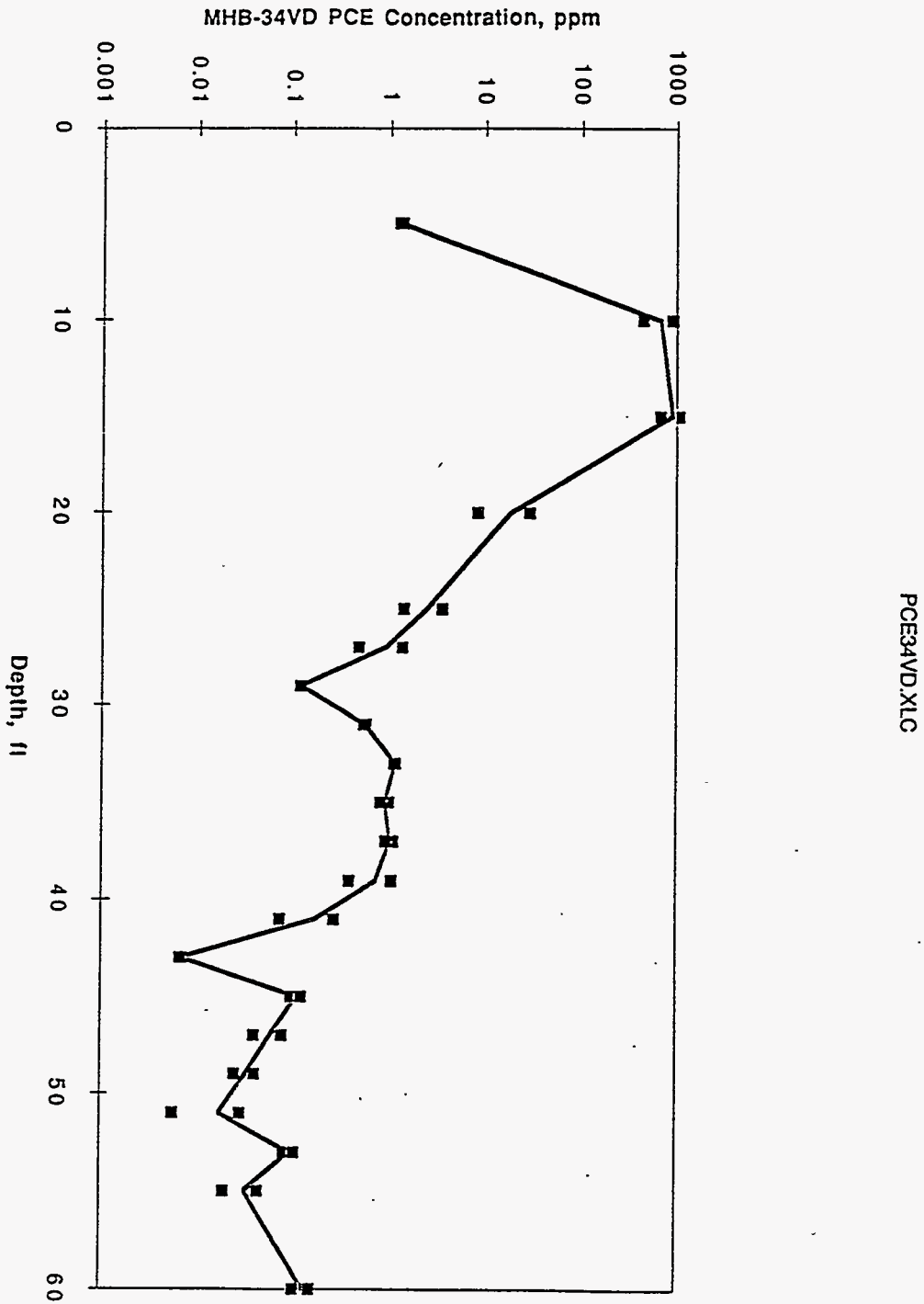


Figure A.29. PCE Concentration as a Function of Depth from Surface for Well MHB-34VD. The curve plots the average of the duplicate soil measurements at each depth.

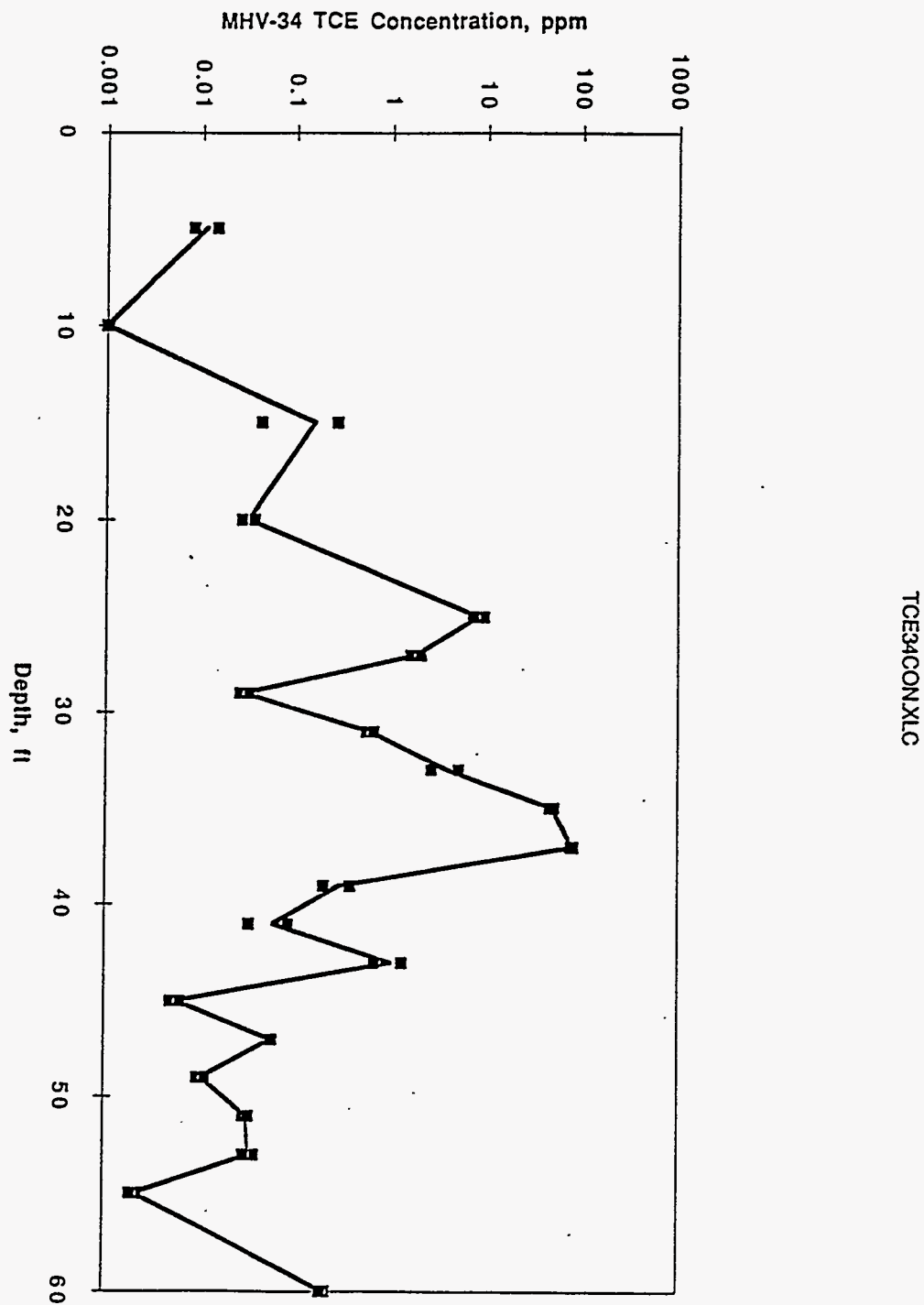
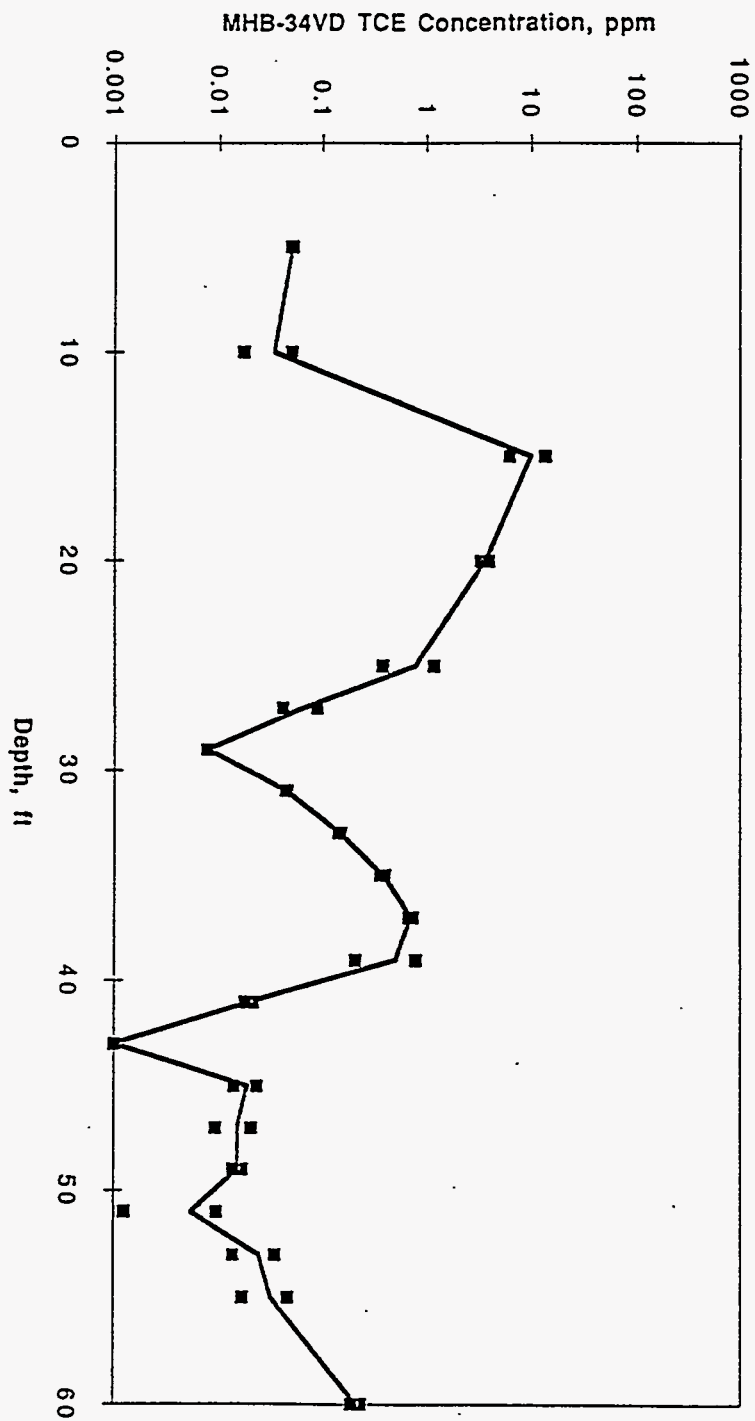


Figure A.30. TCE Concentration as a Function of Depth from Surface for Well MHV-34. The curve plots the average of the duplicate soil measurements at each depth.



TCE34VD.XLC

Figure A.31. TCE Concentration as a Function of Depth from Surface for Well MHB-34VD. The curve plots the average of the duplicate soil measurements at each depth.

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