DOE/EM-0272

Six Phase Soil Heating

INNOVATIVE TECHNOLOGY SUMMARY REPORT

demonstrated at

U.S. Department of Energy
M Area Savannah River Site
and 300-Area Hanford Site
Aiken, SC and Richland, WA

prepared for

U.S. Department of Energy
Office of Environmental Management
Office of Technology Development

April 1995

U.S. Department of Energy

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TABLE OF CONTENTS

APPENDICES

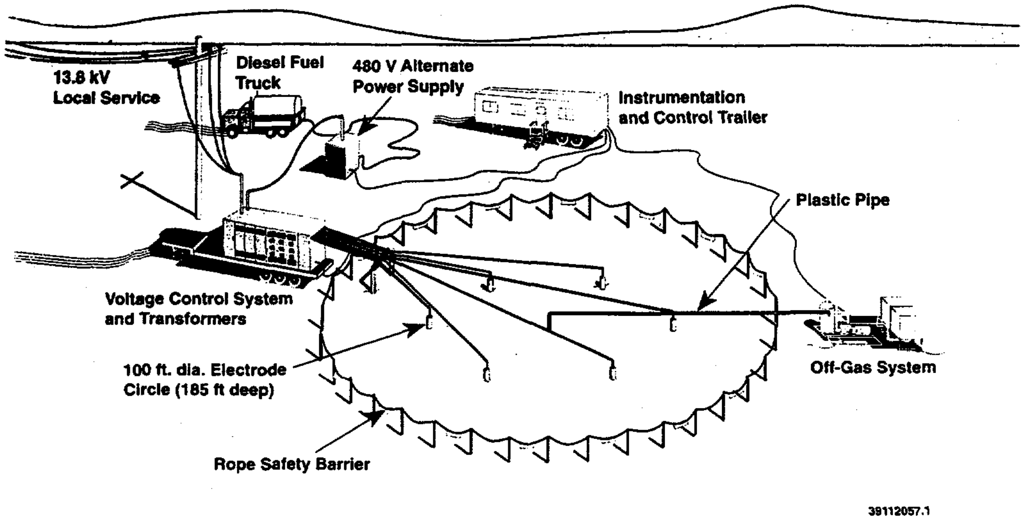
SECTION 1

SUMMARY

Technology Description

Six Phase Soil Heating (SPSH) was developed to remediate soils contaminated with volatile and semi-volatile organic compounds. SPSH is designed to enhance the removal of contaminants from the subsurface during soil vapor extraction. The innovation combines an emerging technology, that of six-phase electrical heating, with a baseline technology, soil vapor extraction, to produce a more efficient in situ remediation system for difficult soil and/or contaminant applications.

SPSH is especially suited to sites where contaminants are tightly bound to clays and are thus difficult to remove using soil vapor extraction alone. Target zones to be treated would most likely be above the water table, but a thicker treatment zone could be addressed by hydraulically lowering the water table with pumping wells.



- Electrical heating increases the temperature of the soil internally by passing standard AC current through the soil moisture.
  - Heating is largely dependent on soil moisture; soils of low permeability and high water content are preferentially heated.
  - Heating also raises the vapor pressure of volatile and semi-volatile contaminants, increasing their volatilization and concomitant removal from the soil via vapor extraction.
  - Heating dries the soil and creates steam which 1) increases the permeability of the formation (this may be quite beneficial in low permeability materials), and 2) strips contaminants that may not be removed via simple soil vapor extraction.
- SPSH splits conventional three-phase electricity into six separate electrical phases, producing an improved subsurface heat distribution. Each phase is delivered to a single electrode, each of which is placed in a hexagonal pattern. The vapor extraction well, which removes the contaminants, air, and steam from the subsurface, is located in the center of the hexagon. Alternative extraction (venting) configurations may be applied.
- SPSH delivers significantly more power to the bulk soil and less at the electrodes than other resistive heating techniques.
- SPSH uses conventional utility power transformers at a relatively low capital cost as compared to other electrical heating techniques.
- SPSH does not require permeable soils as does soil vapor extraction and as do most other heating methods.
- SPSH can accelerate remediation by
  - better removing contaminants from low permeability and heterogeneous soils,
  - enhancing removal of less volatile contaminants.

SUMMARY continued

Technology Status

Field demonstrations were conducted as part of two Department of Energy (DOE) Integrated Demonstration Programs: VOCs in Soils and Ground Water at Nonarid Sites (Savannah River) and VOCs in Soils and Ground Water at Arid Sites (Hanford):

U.S. Department of Energy
Savannah River Site
M Area Process Sewer/Integrated Demonstration Site
Aiken, South Carolina
October 1993 to January 1994

U.S. Department of Energy
Hanford Site
300 Area
Richland, Washington
1993

The demonstration site at the Savannah River Site was located at one of the source areas within the one-square mile VOC ground water plume. The contaminated target zone was a ten-foot thick clay layer at a depth of approximately 40 feet. Prior to application of SPSH, trichloroethylene (TCE) and tetrachloroethylene (PCE) concentrations in sediments ranged from 0 to 181 ug/kg and 0 to 4529 ug/kg. The site is underlain by a thick section of relatively permeable sands with thin lenses of clayey sediments. Appendix A describes the site in detail.

The demonstration site at Hanford was located in the 300 Area at an uncontaminated, undisturbed site. The objective of the demonstration was to improve the understanding of the six-phase heating process, refine design of electrodes and other system components, and address scale-up issues in the field.

Key Results of the SRS Demonstration

- 99.7% of contaminants were removed from within the electrode array. Outside the array, 93% of contaminants were removed at a distance of 8 feet from the array. This difference indicates that heating accelerates the removal of contaminants.
- Temperatures within the array were elevated to 100 degrees C after 8 days of heating and were maintained for 17 days. Eight feet outside the array, temperatures were elevated to 50 degrees C.
- Clays were heated more rapidly than the adjacent sands.
- The efficiency of contaminant removal increased with increased soil drying due to heating.
- 19,000 gallons of condensed steam were removed from the extraction well, indicating substantial drying of the soil.
- Offgas concentrations showed little change during heating, most likely because the soil vapor extraction system affected an area of influence greater than the area of heating.
- Completion of a cost-benefit analysis by Los Alamos National Laboratory (LANL) showing that SPSH could be performed for a cost of $88/cubic yd. assuming that a contaminated site of 100 feet in diameter and 20 to 120 feet deep could be remediated in five years.
- SPSH is estimated to reduce the time required to remediate such a site from 50 years for the baseline technology of SVE to five years.

SPSH is patented by Battelle Pacific Northwest Laboratory. Battelle is working closely with commercial vendors via nondisclosure agreements with the goal of licensing the technology. SPSH has been selected as the remediation technology of choice at a contaminated site at the DOE Rocky Flats Environmental Technology Site where remediation will be initiated in the spring of 1996. Licenses are available through Battelle Pacific Northwest Laboratory.

Contacts

Technical

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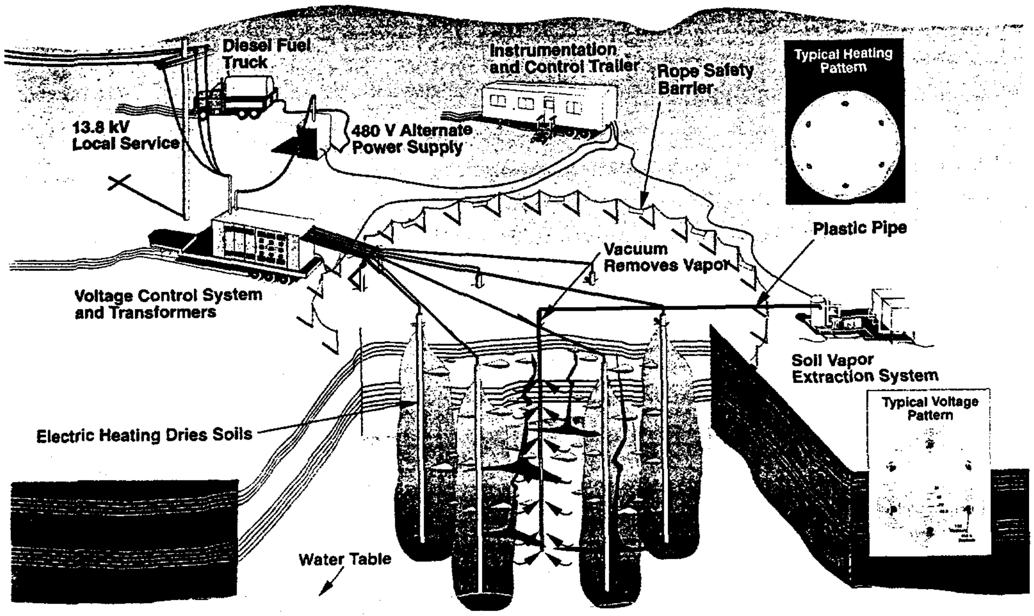
Licensing Information

Harry Burkholder, PNL, (509) 376-1867

SECTION 2

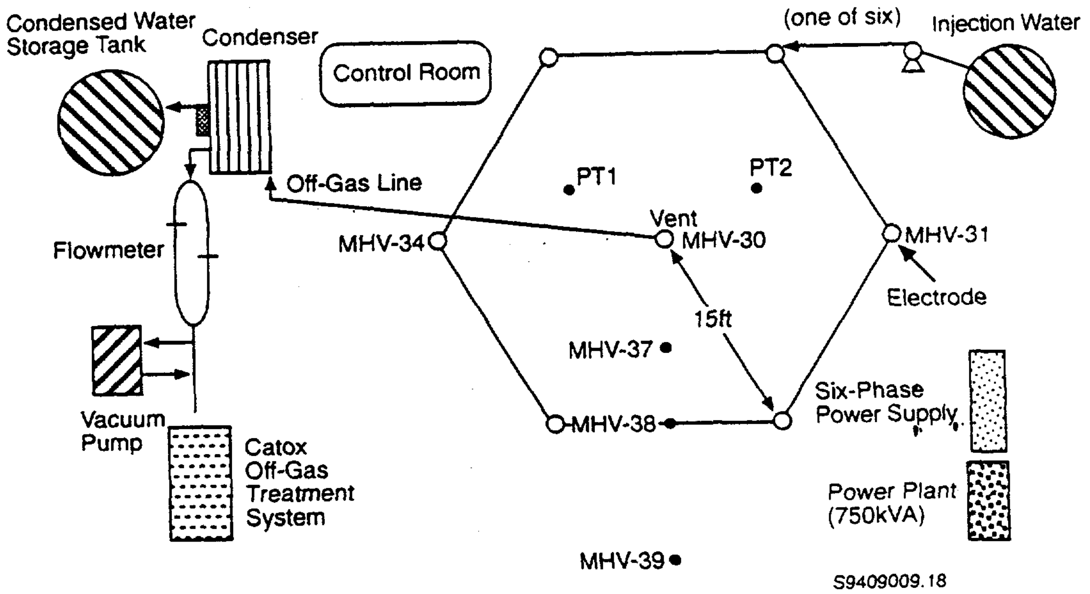
TECHNOLOGY DESCRIPTION

Overall Process Schematic



- Six electrodes, through which electrical power is applied to the subsurface, are placed in the ground in a hexagonal pattern. At SRS, the diameter of the hexagon was 30 feet. The extraction well is placed in the center of the hexagon.
- To maintain soil conduction at the electrodes, they are backfilled with graphite and small amounts of water containing an electrolyte are added to maintain moisture. At SRS 1 to 2 gallons/hour of water with 500 ppm NaCl was added at each electrode. The actual rate of water addition depends upon soil type.
- An offgas treatment system treats the contaminated vapors removed from the subsurface. At SRS, electrical catalytic oxidation was used for the demonstration, but other technologies are available.
- Electrical resistivity tomography (ERT) was used to monitor the progess of the heating of the subsurface.

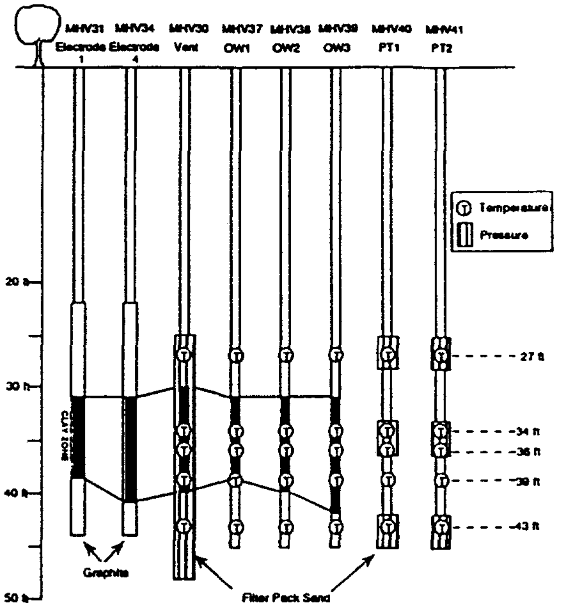
Above Ground System



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

- The 750kVA trailer-mounted power plant supplied 480 V of three-phase power to a six-phase power transformer. The six-phase transformer was rated at 950kVA. Total power applied averaged 200kW. A remote computer controlled output voltages for each electrode.
- The electrodes were connected to the transformer via insulated power cables lying on the surface.
- The soil surrounding each electrode was supplied with water through a drip system.
- The vacuum system removed contaminant vapors and air from the subsurface; the vapors were passed through a condenser to remove the steam generated by the heating.
- The water that collected in the central extraction well was removed with an air-actuated piston pump with remote speed control.
- The generated VOCs were treated by electrically heated catalytic oxidation.

Below Ground System



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.

- Vertical placement of the electrodes, the central extraction well, and monitoring wells is depicted above. The target clay zone, approximately 30 to 40 feet in depth, is indicated by the shaded region for the cored wells. The electrodes were placed between 23 and 44 feet below ground surface. The other symbols indicate the location of the temperature and pressure measurement devices (thermocouples and pressure transducers).

- ERT utilized 4 boreholes in which resistivity electrodes were installed. Data were collected so that images could be obtained from 5 vertical planes, three of which intersected the heating array, i.e the hexagon.
- Automation and computer control of the SPSH system allowed unattended operation after an initial start-up period.

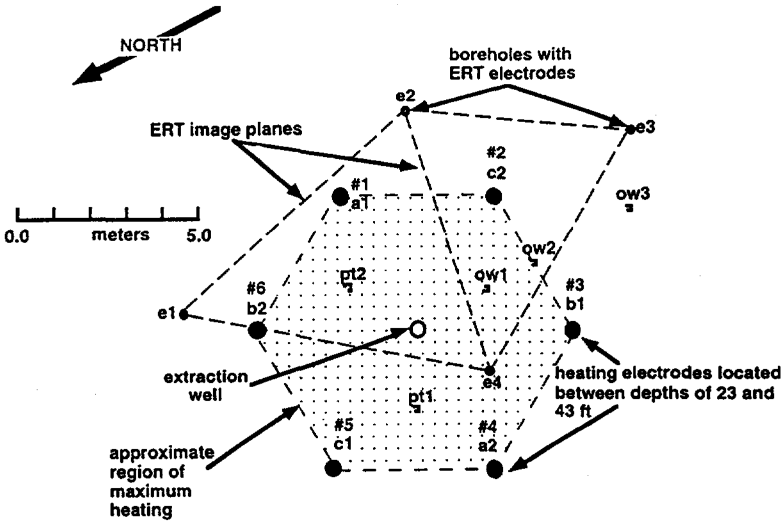


Figure 1. Plan view of the experimental site showing the location of the boreholes used for ERT (e1, e2, e3, e4), extraction well and the ohmic heating electrodes. The clay layer targeted for this demonstration is located between 9.14 to 12.5 m (30 and 41 ft) of depth

SECTION 3

PERFORMANCE

Demonstration Plan

- Performance of the technology has been assessed using information from the initial clean-site field demonstration at Hanford and the demonstration at a contaminated site at SRS.

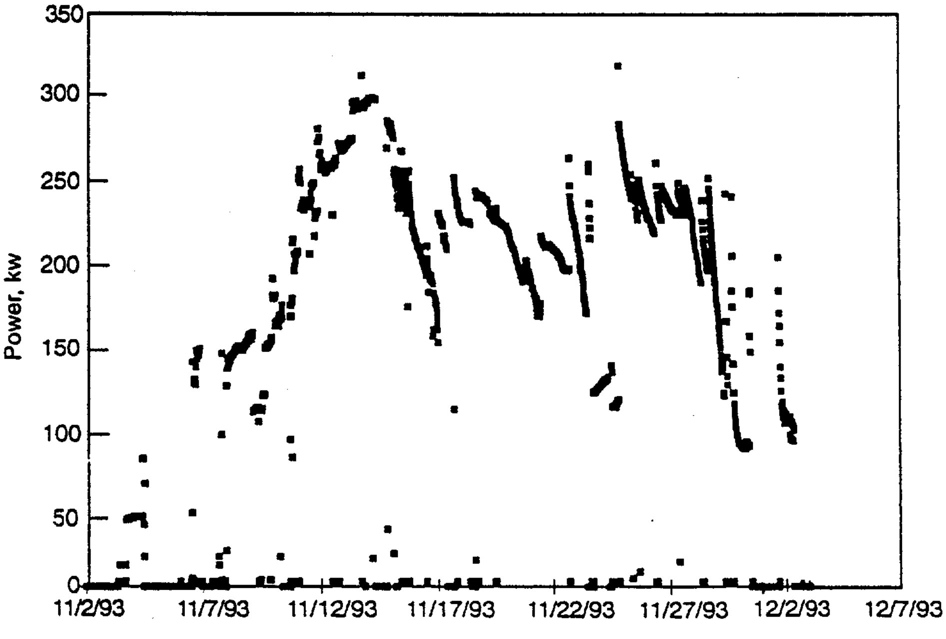
- Major objectives of the SRS demonstration included:
  - accelerated removal of TCE and PCE from clay soils at a depth of 30 to 40 feet
  - quantification of the areal and vertical distribution of heating (30-foot diameter circular array)
  - demonstration of functional electrode and extraction well designs
  - demonstration of economic feasibility of commercial application of the technology

- Major elements of the SRS demonstration included:
  - pre-test drilling and soil sampling
  - baseline SVE test without heating (12 days)
  - SPSH with venting (25 days)
  - venting after heating
  - post-test soil sampling

Treatment Performance

Key System Parameters

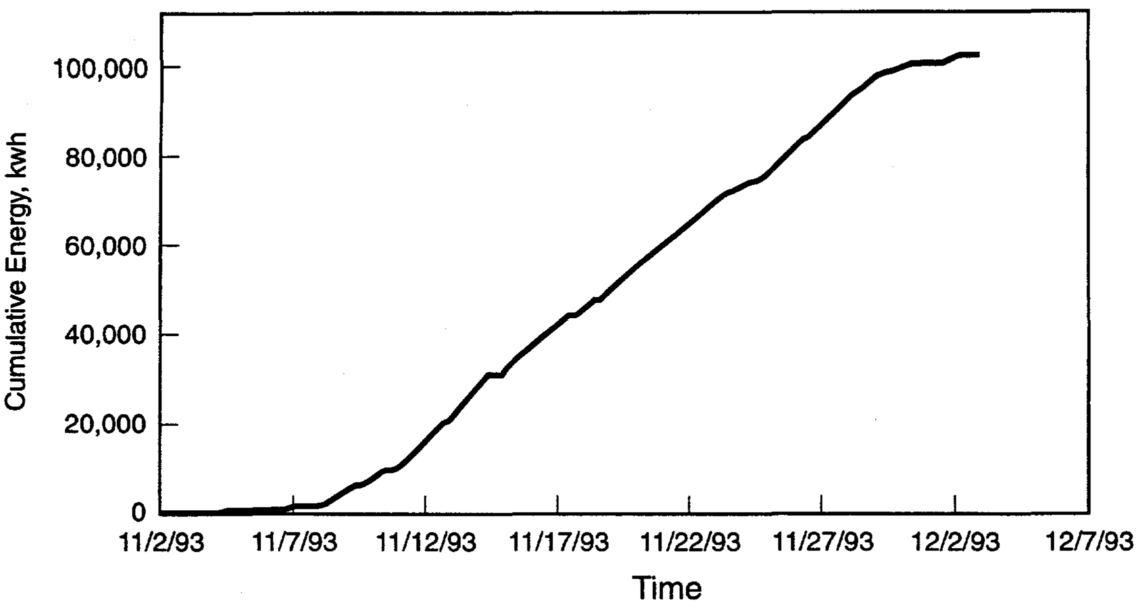
- Vacuum Applied
  - Air was extracted continuously during the demonstration.
- Power Applied
  - An average power of 200kW was applied to the electrode array. A total of 100,000kWh of energy was applied.
  - Mean voltage was 1000V. At the end of the heating period, voltage was increased to 2400V to maintain power input levels.



Power Applied to SPSH Array

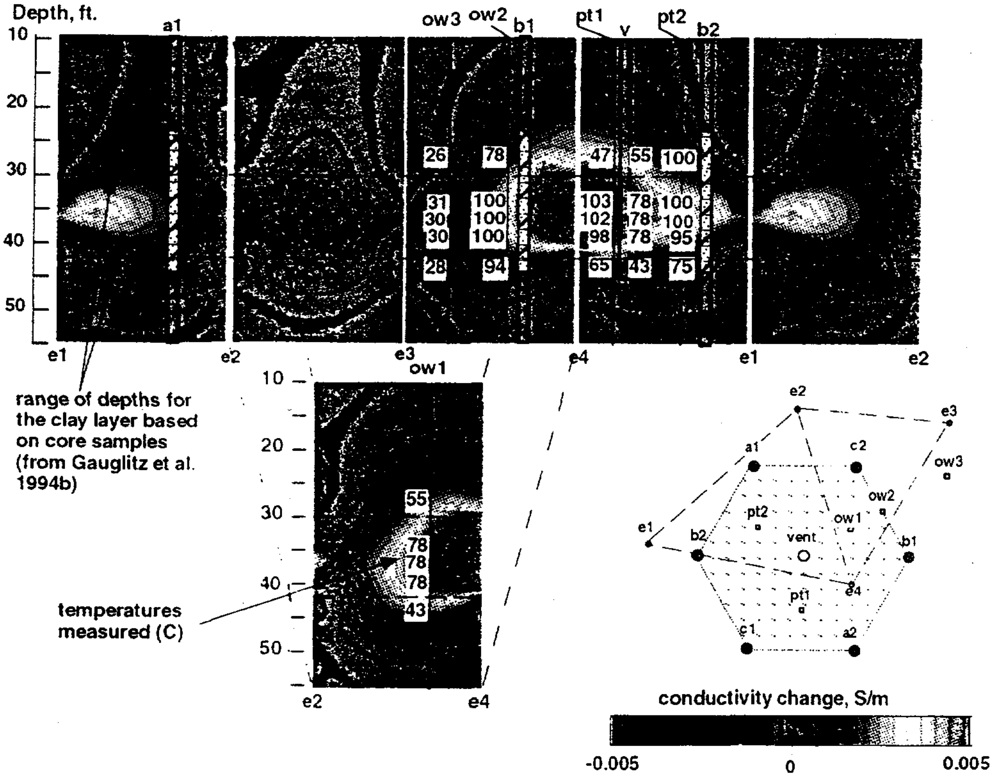
*Periods when power is zero, indicate times when the system was shutdown for maintenance or data gathering

Cumulative Energy Applied to the Soil



Zones of Influence

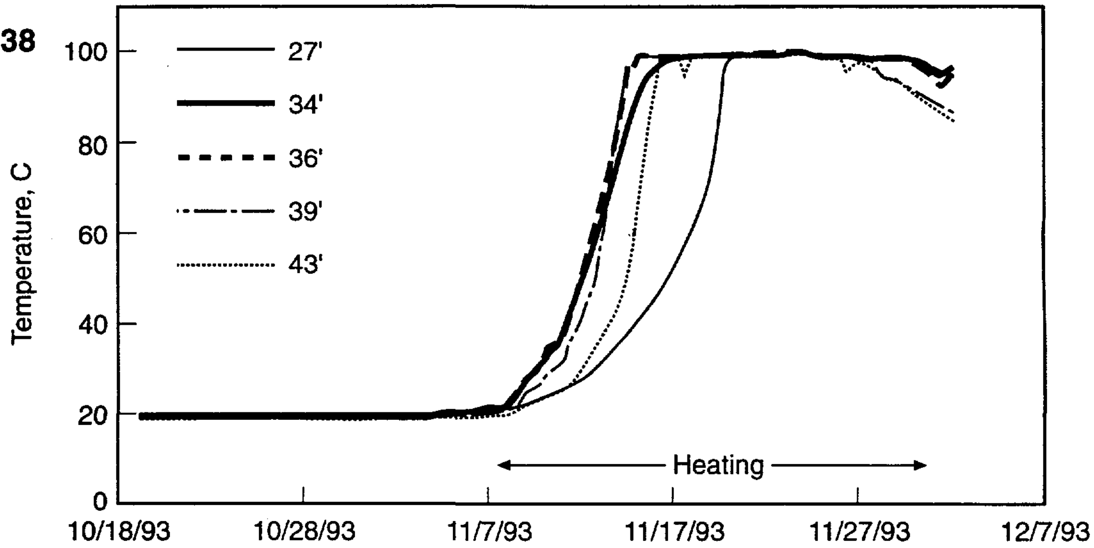
- Electrical resistance tomography (ERT) was used to map the zone of influence and effects of heating and drying on the soil.
  - A difference image representing the changes in electrical conductivity observed after two weeks of heating is shown below. The difference tomograph shows the combined effects of moisture redistribution and heating caused by six-phase heating and vapor extraction.
  - The tomograph shows that most of the clay layer increased in electrical conductivity (up to twice initial values) during the first three weeks.
  - After that time, conductivity decreased to as low as 40% of the pre-test value, as a result of the drying of the soil. At that time, clay saturation was estimated to be as low as 10%.



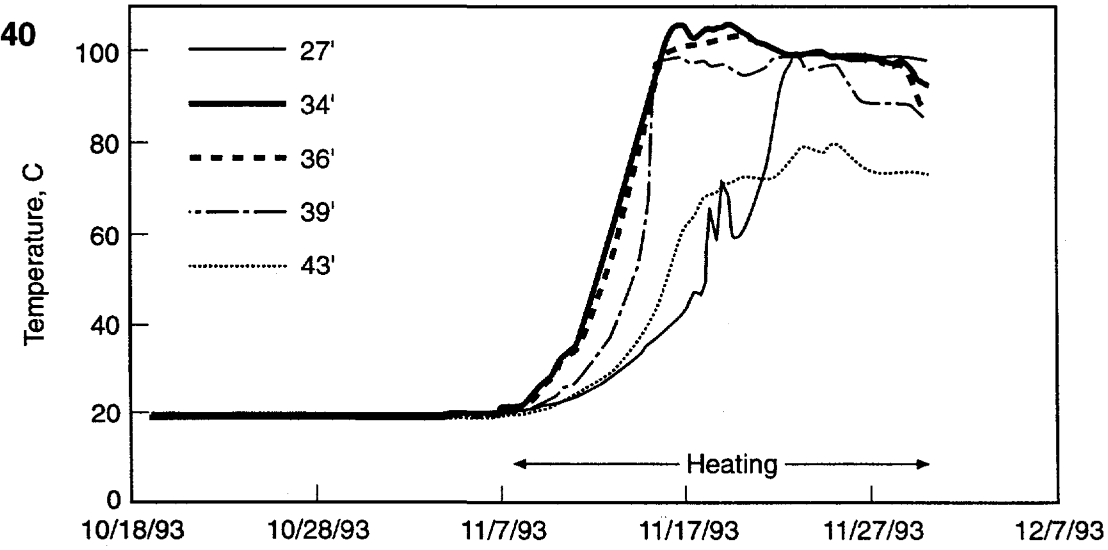
Thermal Performance

- Temperature in the clay zone was increased to 100 degrees C within eight days and was maintained at 100 to 110 degrees C for the 25-day heating campaign. Within the adjacent sands, temperatures increased to 100 degrees C within 10 to 15 days.

Well MHV-38



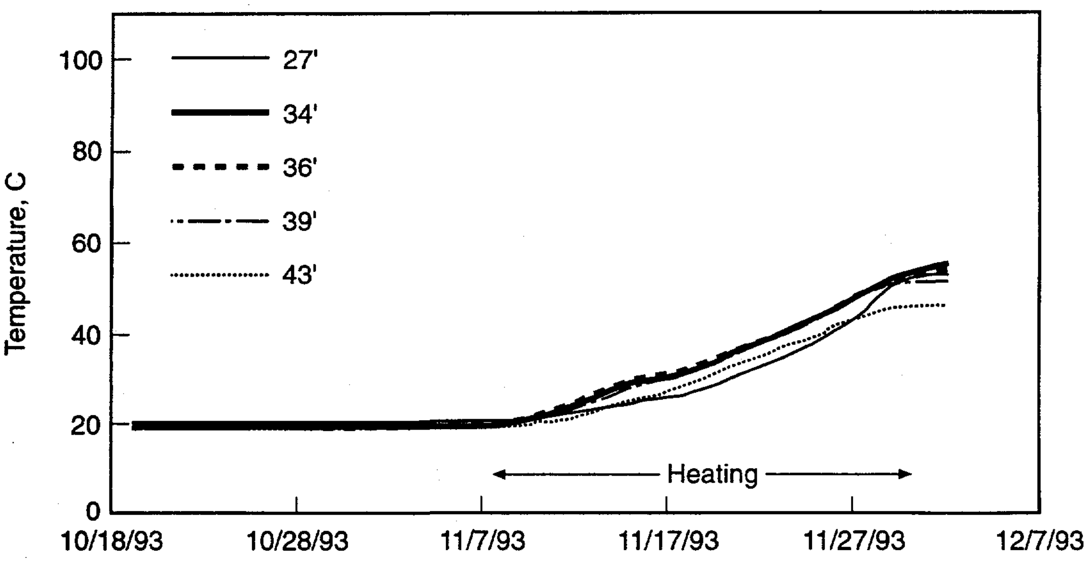
Well MHV-40



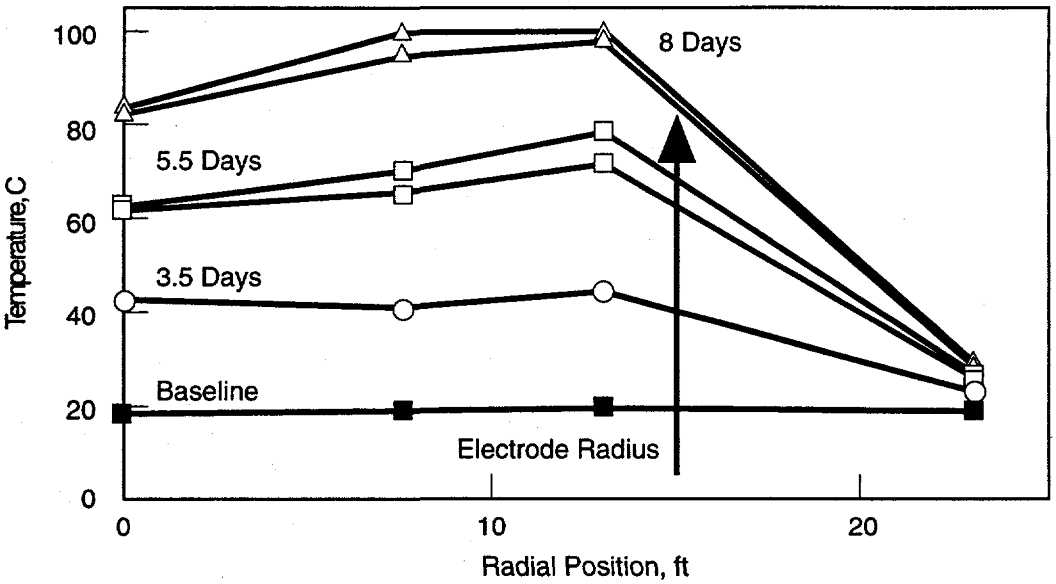
Note: MHV-38 was located midway between two electrodes.
Thermocouples at 27 and 43 feet represent sands above and below the target clay
Thermocouples at 34 and 36 feet are within the target clay, at 39 feet in the sand immediately adjacent to the clay.

- Ouside the electrode array, 23 feet from the central extraction well, temperatures were increased to 50 degrees C.

Well MHV-39 (outside the array)

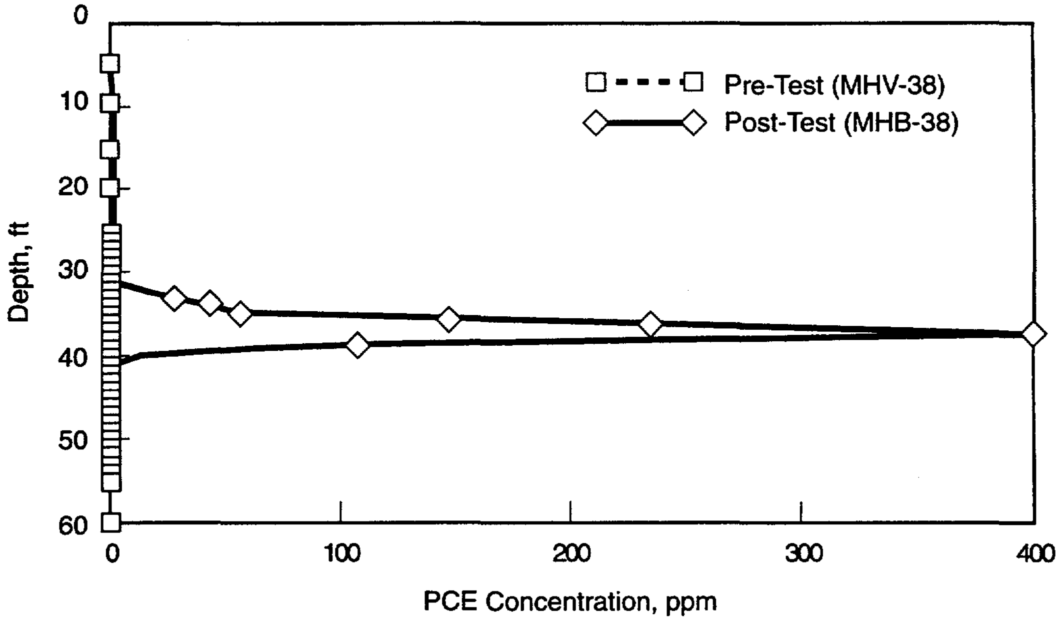


- Temperatures in the clay zone were quite uniform from the central extraction well to the electrodes and beyond (see below). Of course, temperatures outside the array are lower (see above).

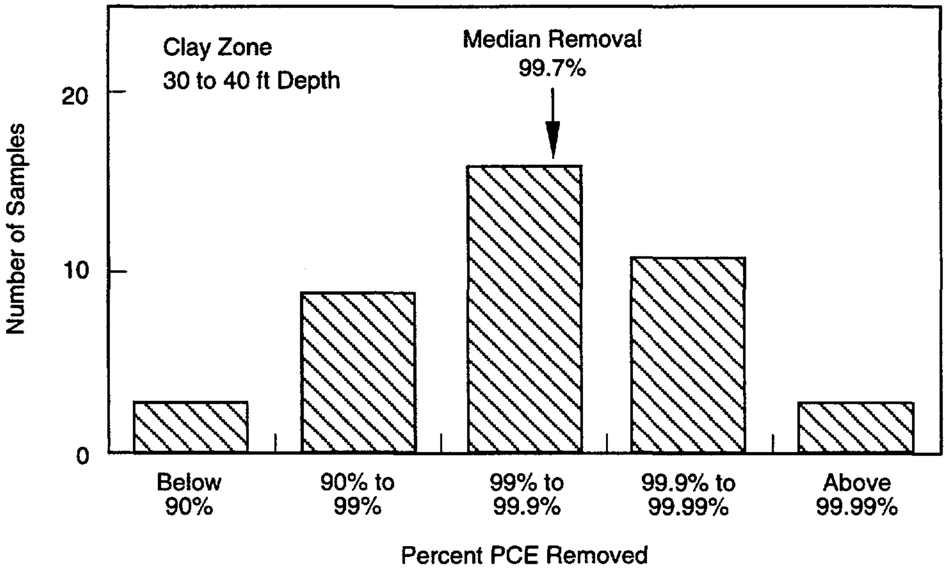


- Heating of the clays dried the soil and increased air permeability. However, core samples showed no evidence of fracturing. Permeabilities of the clays were still much less than the adjacent sands.
- As heating was initiated, the electrical resistance of the soil decreased as expected. However, as the soil actually dried out, the electrical resistance increased.
- 19,000 gallons of water were removed from the soil as steam. Approximately 5,000 gallons of water were added to maintain conductivity of the soil at the electrodes.

Treatment Performance

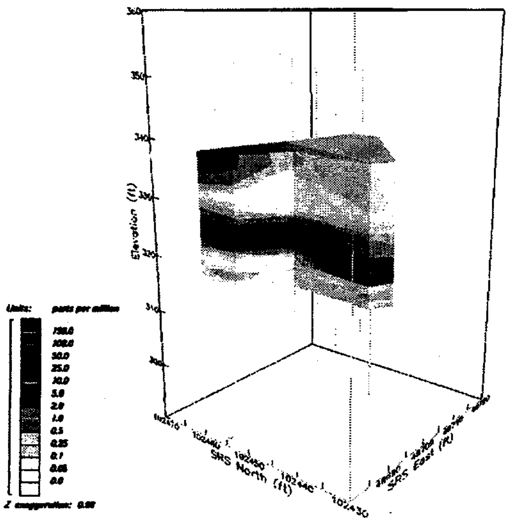


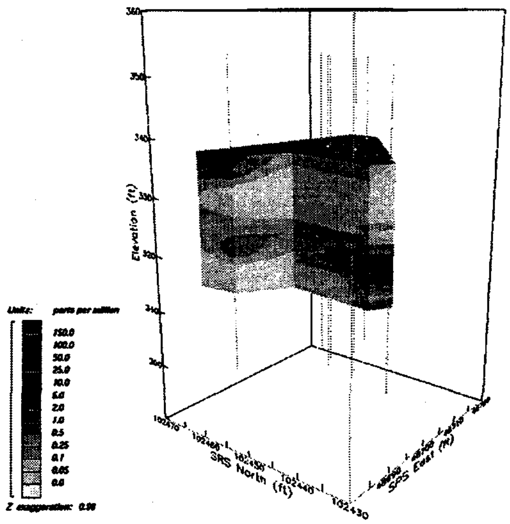
- Pre- and post-test soil samples show a tremendous difference in concentrations of PCE. Samples were collected from the same depth in adjacent boreholes. Samples collected from the borehole for monitoring well MHV-38 are shown above.



- Median removal of PCE from samples in the clay zone was 99.7%. The figure above shows the percentage of PCE removed in all samples in the clay zone within the electrode array. The wide variation is due to the heterogeneity in soil type.

The figures below show a three-dimensional image of the distribution of TCE before and after the heating demonstration.

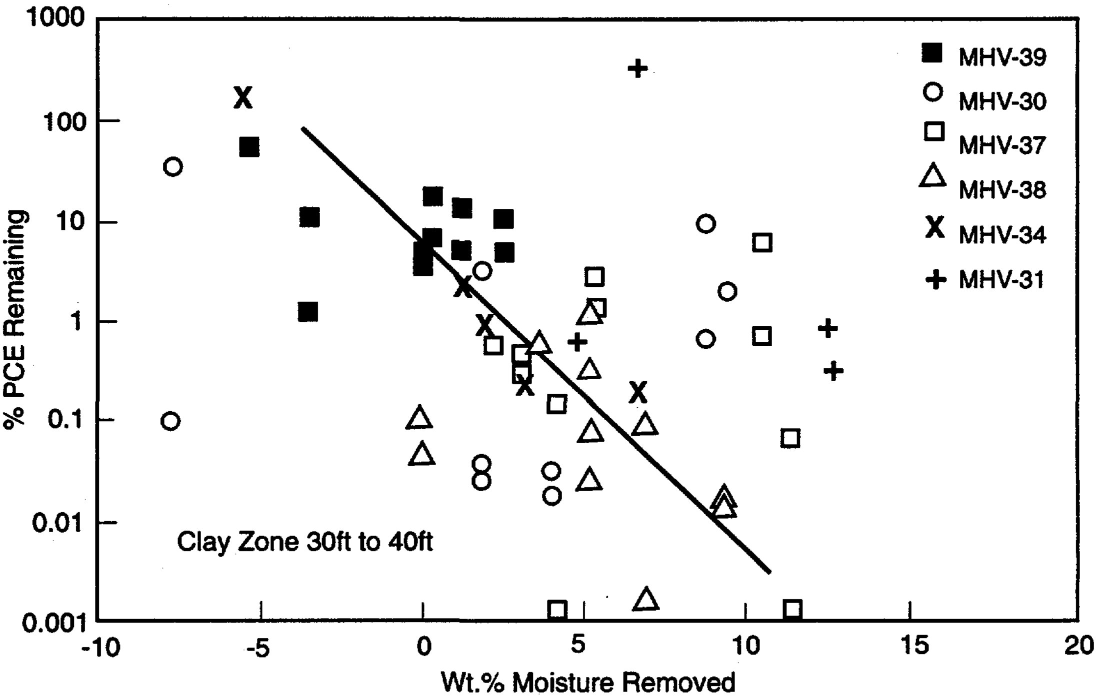




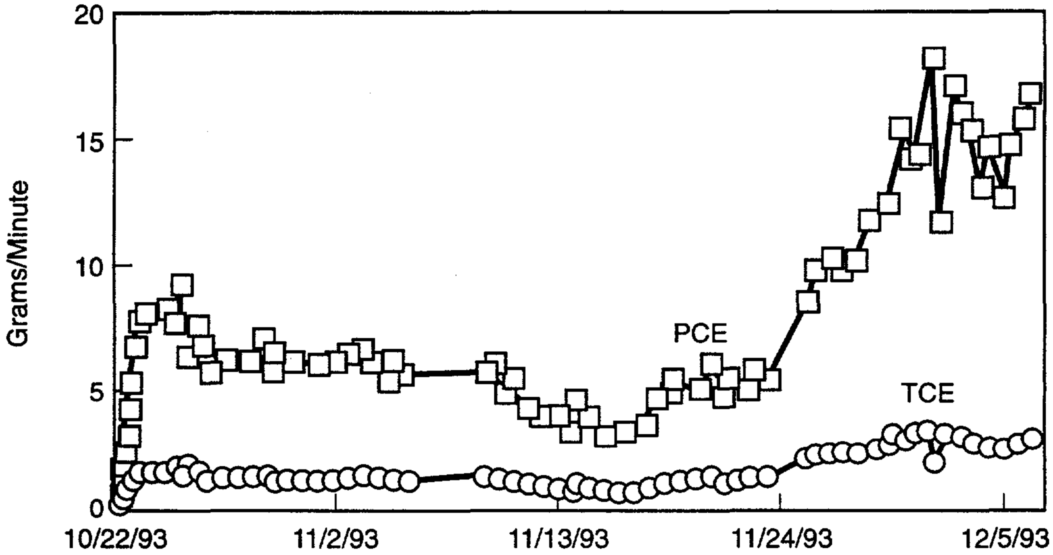
Post-test models show almost complete removal of VOCs from the heated zone.

- Median removal of PCE from the clay eight feet outside the electrode array was 93%.
- Results for TCE removal both inside and outside the electrode array were equivalent.

- Removal of volatile contaminants from low-permeability soil is accelerated by steam creation within the soil. The effect of moisture removal from the soil, i.e drying of the soil, on the percentage of PCE remaining is shown below.



- Mass removal rates increased as the soil dried out and thus increased permeability within the clay zone. This is a better measure of the acceleration of the remediation than simple measurement of the offgas concentrations.
- Offgas concentrations were not affected by the heating. One reason for this may be that the actual area of influence affected by the soil vapor extraction system was greater than the zone of heating. Mass removal from the extraction well is shown below.



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- Pre- and post-test soil samples indicate that 180 kg of PCE and 23 kg of TCE were removed from the soil. These amounts are less than that extracted from the central extraction well (475 kg PCE and 107 kg TCE). This also supports the view that the soil vapor extraction system was effective beyond the 15 foot radius of the heated zone.

Related Testing and Demonstration

- A field demonstration was conducted at a clean site in the 300 Area at Hanford to verify the predictions for heating the soil and to refine the engineering design of the system. A single 20-ft. diameter hexagonal array was installed for the demonstration. Six electrodes, six-inches in diameter, were installed to a depth of 10 feet. Data collected during the demonstration included in situ soil temperatures, voltage profiles, and moisture profiles (using a neutron-probe technique).
- A bench-scale test combining SPSH and In Situ Corona removed greater than 99.999% benzene and greater than 99.994% naphthalene fom a tight Hanford silt.
- A bench-scale test combining SPSH and the High Energy Corona offgas system demonstrated TCE removal from soil.
- A bench-scale test to accelerate biodegradation rates in soils was conducted by heating the soil to 30 to 35 degrees C.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- SPSH has been demonstrated to enhance remediation of clay-rich soils contaminated with VOCs in the unsaturated zone. Bench-scale tests demonstrated that SPSH is effective on lower volatility compounds and can be used to accelerate biodegradation rates in soils.
- SPSH is well suited for sites with highly stratified soils containing low permeability layers.
- SPSH has demonstrated that it can remove 99.7% of the volatile contaminants in clay-rich soils within a very short *time period* (less than one month), thus accelerating the remediation process over the accepted baseline technology.

Competing Technologies

- SPSH competes with a) the baseline technologies of 1) soil vapor extraction and 2) removal and treatment or disposal, b) other innovative thermal enhanced vapor extraction technologies and c) other innovative technologies such as bioventing and deep soil mixing.
- The effectiveness of SPSH was compared with performance data from soil vapor extraction alone, both before and after heating occurred. A cost analysis performed by Los Alamos National Laboratory (LANL), desribed in section 5, compares SPSH to the baseline soil vapor extraction, to the baseline of excavation and removal, to three-phase electrical heating, and to dynamic underground stripping.
- A variety of in situ thermal treatment technologies have been either demonstrated or developed through DOE, DOD, and EPA programs. The aggregate experience with these programs enhances confidence in the fundamentals of thermal enhancement technologies. Full-scale demonstrations of in situ thermal technologies included those shown in the table on p. 15.

Competing Technologies (continued)

Technology	Developer	Basic Principle	Status/Comments
DOE			
1 Dynamic Underground Stripping	Lawrence Livermore National Laboratory (LLNL)	Combines electrical heating , steam injection, and soil vapor extraction; uses electrical resistance tomography to monitor process	Full-scale demonstration at DOE Lawrence Livermore National Laboratory at gasoline spill site in 1993; /licensing discussions ongoing
2 Thermal Enhanced Vapor Extraction (TEVES)	Sandia National Laboratories (SNL)	Combines soil vapor extraction with powerline frequency (ohmic/electrical) and radio-frequency soil heating	Full-scale demonstration initated in 1995 at SNL chemical waste landfill in part of the Mixed Waste Landfill Integrated Demonstration; builds upon previous demonstrations at Volk Field, WI, Rocky Mountain Arsenal, CO, and Kelly AFB, TX (see EPA projects)
3 Radio Frequency Heating	KAI Technologies, Inc.	Radio frequency heating of soils combined with soil vapor extraction	Field demonstrated on VOC contaminated soils using a horizontal well at the DOE Savannah River Site as part of the VOC in Non-Arid Soils and Ground Water Integrated Demonstrationin 1993
EPA/DOD			
1 Contained Recovery of Oily Wastes (CROW ™)	Western Research Institute	Steam or hot water displacement guides contamination to extraction wells	EPA SITE field demonstration underway at the Pennsylvania Power & Light Brodhead Creek Superfund site, PA; pilot-scale demonstrations completed at a wood treatment site in Minnesota
2 HRUBOUT^R Process	Hrubetz Environmental Services, Inc.	Hot air injection combined with a surface exhaust collection system	EPA SITE field demonstration on JP-4 contaminated soils completed at Kelly AFB, TX, in 1993
3 In Situ Steam and Air Stripping	Novaterra, Inc. (formerly Toxic Treatments USA, Inc.)	Portable steam and air injection device (Detoxifier ™) used in soils	EPA SITE field demonstration conducted on VOC and SVOC contaminated soils at the Annex Terminal, San Pedro, CA, in 1989
4 In Situ Steam Enhanced Extraction Process	Praxis Environmental Technologies, Inc.	Steam injection/vacuum extraction (same as 5 and 7)	Field demonstrations underway at Hill AFB, UT, and McClellan AFB, CA
5 In Situ Steam Enhanced Extraction Process	Udell Technologies, Inc.	Steam injection/vacuum extraction (same as 4 and 7)	Field demonstrations underway at Naval Air Stations Lemoore and Alameda in California; Udell technologies no longer in existence
6 Radio Frequency Heating	Illinois Institute of Technology Research Institute/Halliburton NUS	Radio frequency heating of soils combined with soil vapor extraction	EPA SITE field demonstration completed at Kelly AFB, TX, in 1993; earlier demonstrations occurred at Rocky Mountain Arsenal, CO, and Volk Field, WI; demonstration cofunded by DOE
7 Steam Enhanced Recovery System	Hughes Environmental Systems, Inc.	Steam injection/vacuum extraction (same as 4 and 5)	EPA SITE field demonstration completed at the Rainbow Disposal Site in Huntington Beach, CA, from 1991 to 1993; Hughes no longer offering technology

Further information on these full-scale applications is available in references 16 (DOE programs) and 5 (DOD/EPA programs). In addition EPA's Vendor Information System for Innovative Treatment Technologies (VISITT) electronic database lists additional suppliers of equipment and services related to in situ thermally enhanced recovery of contaminants. These include:

- Bio-Electrics, Inc., Kansas City, MO
- EM&C Engineering Associates, Costa Mesa, CA
- SIVE Services, Dixon, CA
- Thermatrix, Inc., San Jose, CA

Patents/Commercialization/Sponsor

- The primary sponsor is the U.S. Department of Energy, Office of Environmental Management, Office of Technology Development.
- The technology is currently available for licensing. A commercialization plan has been written. Battelle is currently working with commercial partners to deploy the technology.
- Three patents have been granted and one patent has been applied for:
  -Patent 5,330,291 "Heating of Solid Earthen Material, Measuring Moisture and Resistivity," W.O. Heath, R.L. Richardson, and S.C. Goheen assignors to Battelle Memorial Institute.
  -Patent 5,347,070 "Treating of Solid Earthen Material and A Method for Measuring Moisture Content and Resistivity of Solid Earthen Material," W.O. Heath, R.L. Richardson, and S.C. Goheen assignors to Battelle Memorial Institute.
  -Patent 4,957,393 "In Situ Heating to Detoxify Organic-Contaminated Soils," J. L. Buelt and K. H. Oma, assignors to Battelle Memorial Institute.

SECTION 5

COST

Introduction

- Information in this section was prepared from data provided by Battelle Pacific Northwest Laboratory to the Los Alamos National Laboratory, tasked by the DOE Office of Technology Development to perform an independent cost analysis of the technology under demonstration.
- The conventional technology of soil vapor extraction (SVE) was used as the baseline technology, against which SPSH was compared.
- The LANL cost comparison for the thermally enhanced VOCs extraction technology was not meant to involve comprehensive cost estimation of these thermal systems. Thus, the final cost per cubic foot may not match actual remediation numbers exactly.1
- In order to compare the innovative and the baseline technology, a number of assumptions were made:
  - The preliminary cost information is based on clean up of a plume described as:
    - 100 ft diameter
    - Begins at a depth of 20 ft and ends at 120 ft
    - Typical energy demand is between 200 kW-hr ($5 to $15) per cubic yards (or 1.05 and 7.407 kW-hr per cubic feet) or 450 kW per array from line power.
    - Target contaminants - VOCs and semi-VOCs
  - Volatilized contaminants are sent to a catalytic oxidation system for destruction.
    - Capital equipment costs are amortized over the useful life of the equipment, which is assumed to be 10 years, not over the length of time required to remediate a site.
- Energy consumption is an important factor in considering the economic feasibility of SPSH technology. During the SRS demonstration:
  - 100,000 kWh of energy was applied to an estimated 1100 cubic meters of soil (heated to above 70 degrees C). The calculated energy consumption is $7/cubic meter at $0.07/kWh.
  - The energy cost to heat the soil is small when compared to capital equipment costs and operator time.

Capital Costs

Cost Category	Cost Description	Total ($)
Direct Cost	Mobilization	9,000
	Power Source	286,000
	Water Source	24,400
	AC Applications Well	53,700
	Site Characterization/Well Installation	53,100
	SVE Pilot Testing	13,000
	Permitting	16,300
	Vacuum System	174,500
	Treatment System	50,800
	Dismantlement/De-Mobilization	22,500
	Start up and First Month of Operation	21,400
Construction Management		72,500
Engineering, Design, and Inspection		181,200
Project Management		43,500
Contingency		255,400
Project Total		1,277,300

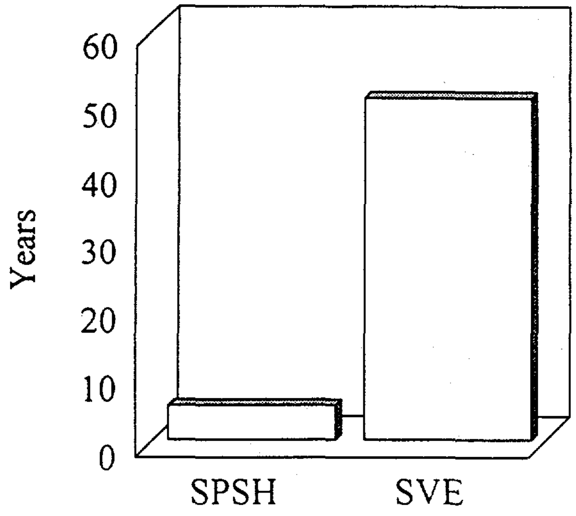
Operating Costs

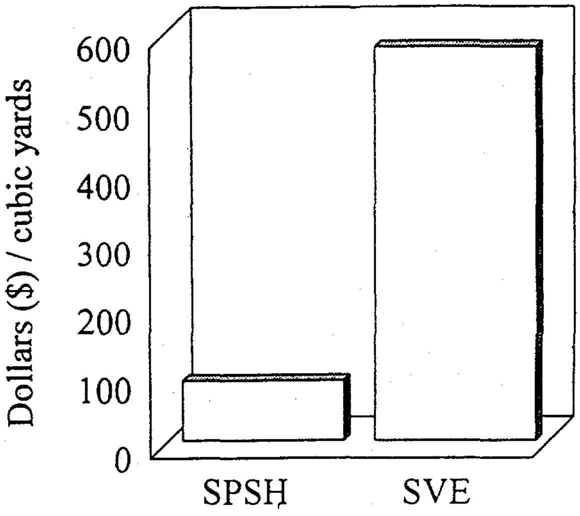
Cost Category	Description	Total ($/month)
Direct Cost	Field Monitoring	6,300
	Monitoring and Reporting	4,800
	System Operation and Maintenance	5,800
	Total O & M Costs	16,900

Cost Comparison for Thermally Enhanced VOC Extraction Technologies[2]

The costs to clean up a cubic yard of soil for the duration of remediation activities using SPSH and SVE are presented in the following table.

Technology	Cleanup Duration (year)	Amortized Total Cost ($M)[3]	Total Volume Remediated (cubic yards)	Total Cost ($)/ Cubic Yards
SPSH	5	2.724	785,000	86
SVE	50	33.358	785,000	576





1 Memo from S. Booth to D. Kaback dated March 22, 1995 (Re: Thermally Enhanced VOC Extraction Cost Data)
2 Letter from P.A. Gauglitz, Battelle PNL to J. Bremser, LANL, dated 1/25/95
3 Total cost (capital and O&M) is amortized with a discount rate of 2.5%.

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- Permit requirements for the demonstration were controlled by the South Carolina Department of Health and Environmental Control (SCDHEC) and included 1) an Air Quality Permit and 2) an Underground Injection Permit (because of the addition of NaCl-bearing water to retain moisture at the electrodes). A NEPA checklist was also prepared; a categorical exclusion was granted.
- Permit requirements for future applications of SPSH are expected to include:
  - On-site air quality monitoring and air permit for ground-extracted and discharged vapor streams would be required. Permits would require compliance with the Clean Air Act.
  - A special permit may be required to treat, contain, and dispose of the secondary waste stream, which contains liquid contaminants condensed from soil off-gas.
  - Depending on whether the site is being cleaned up under CERCLA or RCRA or both, other requirements may apply.
    - For example at SRS, the M-Area HWMF RCRA Part B Permit must be reviewed to determine if a permit modification is necessary.
  - Groundwater Protection Standards (GWPS) have been established as a part of a RCRA permit. The GWPs are based on EPA Maximum Contaminant Levels (MCLs). Specific goals for contaminants of greater concern for the M-Area at SRS are:

compound	concentration [ppb]
TCE	5
PCE	5
TCA	200

  - A special safety permit may be required for handling high voltage power suppliers..
  - Federal sites would require NEPA review.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- This technology will be set up with engineered barriers to prevent worker exposure to high voltages.
- The presence of buried metal objects presents a safety hazard. Technologies such as ground penetrating radar must be utilized to map the subsurface before the heating system is installed.
- A potential explosion hazard exists. If concentrated fumes are released from the vacuum unit, the conditions may create a potential explosion.
- Other health and safety issues for the installation and operation of SPSH are essentially equivalent to those for conventional technologies of pump-and-treat or soil vapor extraction.
- Level D personnel protection was used during installation and operation of the system.

Community Safety

- SPSH with offgas treatment should not produce any routine release of contaminants at a significant level to affect the public.
- No unusual or significant safety concerns are associated with the transport of equipment, samples, waste, or other materials associated with SPSH.
- The transportation and packing of the equipment should meet DOT requirements (on trailers no larger than 8 ft wide by 10 ft by 40 ft long).
- Barriers enclose the treated area to prevent direct access to the site.

Environmental Impacts

- Treated soil, left in place, will be dry. Soil moisture can be restored with further or no follow-up treatment.
- The treated area will need to be defoliated and evened with a bulldozer.

Socioeconomic Impacts and Community Perception

- SPSH has a minimal economic or labor force impact.
- The general public has limited familiarity with SPSH; however, the technology received positive support on public visitation days at Savannah River. It has also been explained to the public at Hanford and received positive input.

SECTION 7

LESSONS LEARNED

Design Issues

- The success of the SPSH process is dependent upon boiling the subsurface environment, drying the soil and thus increasing permeability of tight formations.
- The extraction well should be screened both above and below the clay target zone to ensure sufficient vacuum pressure to allow for removal of steam generated in the subsurface. This extraction well design also ensures total capture of contaminants released as a result of the heating.
- The offgas treatment system must be sized to handle anticipated peak extraction rates and the expected distribution of VOCs in extracted vapor and liquid streams.
- The vacuum pump must be sized to accomodate removal of the subsurface steam that is generated.
- Concern about buried metal objects and the issue of worker saftey must be addressed and considered when designing a field application.

Implementation Considerations

- Operational difficulties encountered included drying out of the electrodes and shorting of the thermocouples. The field experience allowed for improving the design of the system to overcome these difficulties.

Technology Limitations/Needs for Future Development

- Longer-term performance data are required to assess the need for design improvements and system optimization. This information can then be used to better quantify life-cycle costs.
- Optimization of electrode design and design of the water injection system should be addressed in future applications.
- Questions still remain as to how power should be applied to the subsurface with an emphasis on how quickly the soil should be heated. A better understanding of the affects of site specific conditions will also be gained after additional applications/demonstrations are completed.

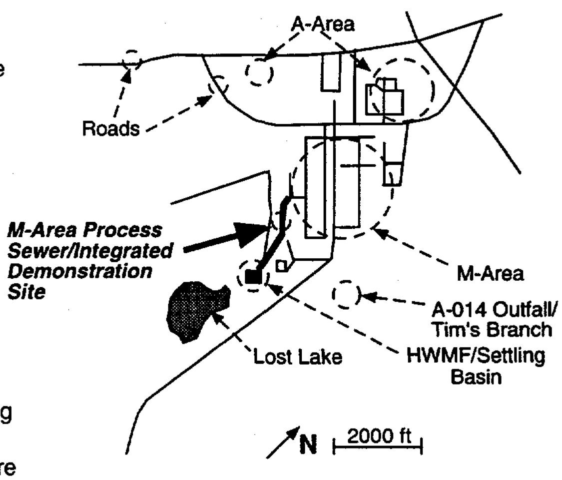
APPENDIX A

DEMONSTRATION SITE CHARACTERISTICS

Site History/Background

- The Savannah River Site's historical mission has been to support national defense efforts through the production of nuclear materials. Production and associated research activities have resulted in the generation of hazardous waste by-products now managed as 266 waste management units located throughout the 300 mile² facility.
- The A and M Areas at Savannah River have been the site of administrative buildings and manufacturing operations, respectively. The A/M-Area is approximately one mile inward from the northeast boundary of the 300 mile² Savannah River Site. Adjacent to the site boundary are rural and farming communities. Specific manufacturing operations within the M-Area included aluminum forming and metal finishing.
- The M-Area operations resulted in the release of process wastewater containing an estimated 3.5 million lbs. of solvents. From 1958 to 1985, 2.2 million lbs. were sent to an unlined settling basin, which is the main feature of the M-Area Hazardous Waste Management Facility (HWMF). The remaining 1.3 million lbs. were discharged from Outfall A-014 to Tim's Branch, a nearby stream, primarily during the years 1954 to 1982.

Site Layout



- Discovery of contamination adjacent to the settling basin in 1981 initiated a site assessment effort eventually involving approximately 250 monitoring wells over a broad area. A pilot ground water remediation system began operation in February 1983. Full-scale ground water treatment began in September 1985.
- High levels of residual solvent are found in the soil and ground water near the original discharge locations. Technologies to augment the pump-and-treat efforts, for example soil vapor extraction, ISAS, and bioremediation, have been tested and are being added to the permitted corrective action.

Contaminants of Concern

Contaminants of greatest concern are:

1,1,2-trichloroethylene (TCE)
tetrachloroethylene (PCE)
1,1,1-trichloroethane (TCA)

Property at STP*	Units	TCE	PCE	TCA
Empirical Formula	-	$ClCH{=}CCl_2$	$Cl_2C{=}CCl_2$	CH_3CCl_3
Density	g/cm^3	1.46	1.62	1.31
Vapor Pressure	mmHg	73	19	124
Henry's Law Constant	atm*m^3/mole	9.9E-3	2.9E-3	1.6E-2
Water Solubility	mg/L	1000-1470	150-485	300-1334
Octanol-Water Partition Coefficient; K_{ow}	-	195	126	148

**STP = Standard Temperature and Pressure; 1 atm, 25 °C*

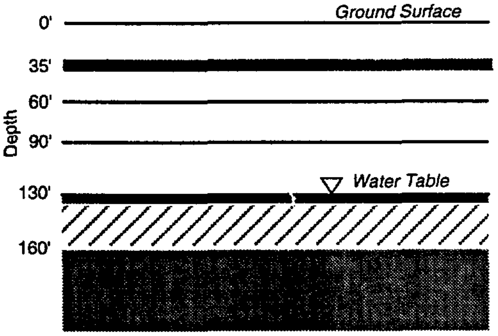
Nature and Extent of Contamination

- Approximately 71% of the total mass of VOCs released to both the settling basin and Tim's Branch was PCE, 28% was TCE, and 1% was TCA.
- The estimated amount of dissolved organic solvents in ground water in concentrations greater than 10 ppb is between 260,000 and 450,000 lbs and is estimated to be 75% TCE. This estimate does not include contaminants sorbed to solids in the saturated zone or in the vadose zone. The area of VOC-contaminated ground water has an approximate thickness of 150 feet, covers about 1200 acres, and contains contaminant concentrations greater than 50,000 ug/L.
- DNAPLs found in 1991 present challenges for long-term remediation efforts.
- Vadose zone contamination is mainly limited to a linear zone associated with the leaking process sewer line, solvent storage tank area, settling basin, and the A-014 outfall at Tim's Branch.

Contaminant Locations and Hydrogeologic Profiles

Simplified schematic diagrams show general hydrologic features of the A/M Area at SRS.

Vadose Zone and Upper Aquifer Characteristics



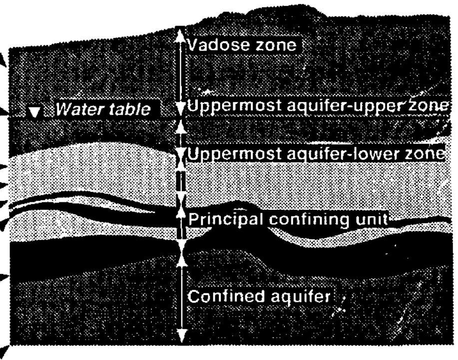
(figure modified from Reference 12)

Legend
■ Water Table ▨ Semiconfined Aquifer
☐ Unsaturated Zone ■ Confined Aquifer

- Sediments are composed of sand, clay and gravel.
- Clay layers are relatively thin and discontinuous, with the exception of the clay layers at 160-foot depth and a thicker zone of interbedded clay and sand found at 90-foot depth. A clay layer at 30 to 40 feet in depth is the target for this demonstration. This clay is discontinuous on the scale of the entire A/M Area, but not across the site of this demonstration.
- The water table is approximately 135 feet below grade.
- A moderate downward gradient appears to exist beneath the M-Area. Vertical flow rates have been estimated to be 2 to 8 ft/year.
- Radial flow outward from a ground water plateau under most of the A/M-Area exists. Flow is approximately 15 to 100 ft/year.

Hydrogeologic Units

Aquifer Unit	Description	Thickness
Vadose Zone	Poorly sorted mix of sand, cobbles, silt and clay	~57 ft
	Moderate to well-sorted, fine to medium sand containing some pebbles; 13% silt and clay	0-97 ft
	Moderately to well-sorted medium sand; 18% silt and clay	30-55 ft
Water Table Unit	Moderate to well-sorted fine sand with some calcaneous zones; 25% silt and clay; 14% silt and clay beds	16-34 ft
Upper	Well-sorted fine to medium sand; 16% silt and clay; 7% silt and clay beds.	14-60 ft
Lost Lake Aquifer	*Discontinuous clay beds containing 70% silt & clay*	
Lower	Moderate to well-sorted medium sand; 17% silt and clay; 7% silt and clay beds	4-44 ft
Crouch Branch Confining Unit	Clay, clayey silt, and poorly sorted fine to coarse, clayey sand; 62% silt and clay; contains 2 major clay layers the lower of which is 10-56 ft thick and is the principal confining unit for lower aquifer zones	32-95 ft
Crouch Branch Aquifer	Very poorly to well-sorted, medium to coarse sands; 5% sand and clay beds; an important production zone for water supply wells in the M-Area	152-180 ft

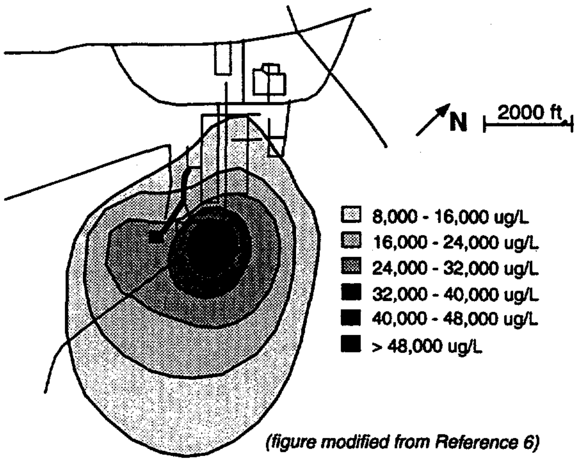


Contaminant Locations and Hydrogeologic Profiles (continued)

Metal-degreasing solvent wastes were sent to the A-014 outfall and, via the process sewer, to the M-Area settling basin. Data from hundreds of soil borings, ground water monitoring wells, and a variety of other investigative techniques have established a well-documented VOC plume in both the vadose and saturated zones.

TCE Ground Water Plume (Top View)

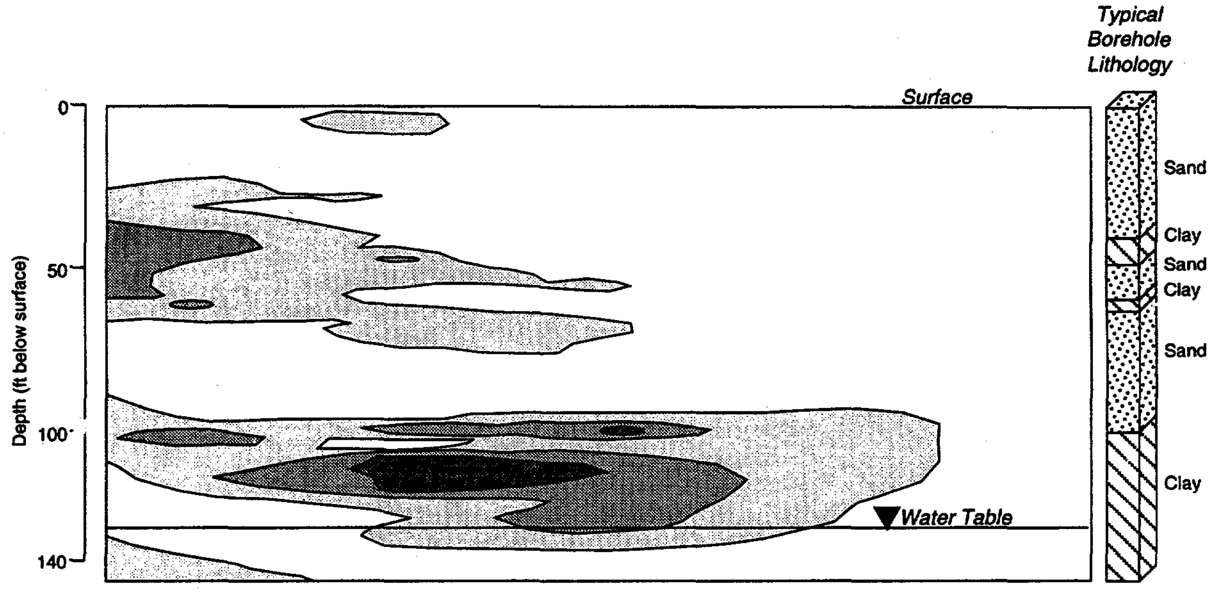
Data from 15 feet below water table in the third quarter of 1990.



(figure modified from Reference 6)

TCE Concentrations in Soil (West-East Cross-Section)

Concentration and lithology data from 1991 along an approximately 200-ft cross-section across the integrated demonstration site. Concentration contours of TCE in sediments are based on analysis of over 1000 sediment samples. Highest concentrations of TCE and PCE occur in clay zones. The clay layer at a depth of 30 to 40 feet shows high concentrations of TCE and PCE at the left end of the cross section.



(figure modified from Reference 6)

Legend

soil concentrations in ug/kg

░ 100 to 1,000 ug/kg	■ 5,000 to 10,000 units ug/kg
▨ 1,000 to 5,000 ug/kg	■ >10,000 ug/kg

APPENDIX B

PERFORMANCE DETAIL

Operational Performance

Maintainability and Reliability

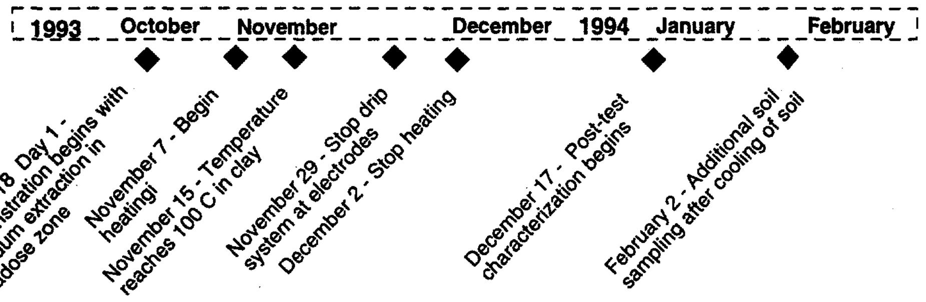
- No functional problems encountered during demonstration; system was operational approximately 90% of all available time.
- Operational performance over long periods (years) not yet available.

Operational Simplicity

- An automated system that is computer controlled allows unattended operation. It can bemaintained in the field typically by 1/6 full-time equivalent technician.

Demonstration Schedule

Major Milestones of the Demonstration Program



Sampling, Monitoring, Analysis, and QA/QC Issues

Objectives

- Gather baseline information and fully characterize site before and after the demonstration
- Evaluate removal efficiencies with time
- Identify and evaluate zones of influence

Baseline Characterization

- Baseline characterization was performed before the demonstration to gather information on the geology and geochemistry of the site. These data were compared with data on soil collected after the demonstration to evaluate the effectiveness of SPSH.
- Geologic cross-sections were prepared using core logs.
- Continuous cores were collected from 2 electrode boreholes, 3 observation wells, and the extraction well. Sediments for VOC analysis were collected at 1-ft intervals for chemical and moisture content determinations.

Analytical Methods and Equipment

- Vapor grab samples were analyzed in the field using both a Photo Vac field gas chromatograph (GC) and a GC fitted with flame ionization and electron capture detectors. Analysis was performed immediately after collection.
- VOC analysis of sediment samples was performed daily using an improved quantitative headspace method developed by Westinghouse Savannah River Company. Analyses were performed on an HP-5890 GC fitted with an electron capture detector and headspace sampler.

QA/QC Issues

- Vapor samples were analyzed immediately after collection and GC analysis of soil and water samples were completed less than 3 weeks after collection.
- GC calibration checks were run daily using samples spiked with standard solutions.

APPENDIX C

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