EPA 542-R-97-009
PB97-177562
July 1997

Remediation Case Studies: Soil Vapor Extraction and Other In Situ Technologies

VOLUME 6

Federal Remediation Technologies Roundtable

Prepared by the

Member Agencies of the Federal Remediation Technologies Roundtable

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Environmental Protection Agency
Department of Defense
- U.S. Air Force
- U.S. Army
- U.S. Navy

Department of Energy
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July 1997

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Compilation of this material has been funded wholly or in part by the U.S. Army Corps of Engineers and the U.S. Environmental Protection Agency under USACE Contract Number DACA45-96-D-0016 to Radian International LLC.

FOREWORD

This report is a collection of six case studies of soil vapor extraction or associated technologies and three case studies of other in situ technologies (frozen barrier containment, sonic drilling, and fracturing) prepared by federal agencies. The case studies, collected under the auspices of the Federal Remediation Technologies Roundtable, were undertaken to document the results and lessons learned from early technology applications. They will help establish benchmark data on cost and performance which should lead to greater confidence in the selection and use of cleanup technologies.

The Roundtable was created to exchange information on site remediation technologies, and to consider cooperative efforts that could lead to a greater application of innovative technologies. Roundtable member agencies, including the U.S. Environmental Protection Agency, U.S. Department of Defense, and U.S. Department of Energy, expect to complete many site remediation projects in the near future. These agencies recognize the importance of documenting the results of these efforts, and the benefits to be realized from greater coordination.

The case study reports and abstracts are organized by technology in a multi-volume set listed below. Remediation Case Studies, Volumes 1-4, and Abstracts, Volume 1, were published in March 1995, and contain 37 case studies. Remediation Case Studies, Volumes 5 and 6, and Abstracts, Volume 2, were published in July 1997, and contain 17 case studies. These 17 case studies cover recently completed full-scale remediations and large-scale field demonstrations. In the future, the set will grow through periodic supplements tracking additional progress with site remediation.

Remediation Case Studies, Volume 1:	Bioremediation, EPA-542-R-95-002; March 1995; PB95-182911
Remediation Case Studies, Volume 2:	Groundwater Treatment, EPA-542-R-95-003; March 1995; PB95-182929
Remediation Case Studies, Volume 3:	Soil Vapor Extraction, EPA-542-R-95-004; March 1995; PB95-182937
Remediation Case Studies, Volume 4:	Thermal Desorption, Soil Washing, and In Situ Vitrification, EPA-542-R-95-005, March 1995; PB95-182945
Remediation Case Studies, Volume 5:	Bioremediation and Vitrification, EPA 542-R-97-008, July 1997; PB97-177554
Remediation Case Studies, Volume 6:	Soil Vapor Extraction and Other In Situ Technologies, EPA 542-R-97-009, July 1997; PB97-177562

Abstracts of Remediation Case Studies, Volume 1:	EPA-542-R-95-001; March 1995
Abstracts of Remediation Case Studies, Volume 2:	EPA 542-R-97-010, July 1997; PB97-177570

Ordering Information

These documents are available free of charge by fax or mail from NCEPI (allow 4-6 weeks for delivery), at the following address:

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In addition, the case studies and case study abstracts are available on the internet through the Federal Remediation Technologies Roundtable (FRTR) home page at: http://www.frtr.gov. The FRTR home page provides links to individual FRTR members' home pages, and includes a search function. Case studies and abstracts prepared by EPA are also available through EPA's Cleanup Information Bulletin Board System (CLU-IN BBS). CLU-IN BBS is available through the internet at http://clu-in.com, or via modem at (301) 589-8366 (8 Data Bits, 1 Stop Bit, No Parity, VT-100 or ANSI; Voice help: (301) 589-8368). Case studies prepared by the U.S. Department of Energy (DOE) are available through the internet, on the Office of Science and Technology home page, at http://em-52.em.doe.gov/ifd/ost/pubs.htm, under Innovative Technology Summary Reports. Individual Reports prepared by DOE are available to DOE and DOE contractors from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831; or to the public through the U.S. Department of Commerce, National Technical Information Service (NTIS), Springfield, VA 22161 ((703) 487-4650).

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INTRODUCTION

Increasing the cost-effectiveness of site remediation is a national priority. The selection and use of more cost-effective remedies requires better access to data on the performance and cost of technologies used in the field. To make data more widely available, member agencies of the Federal Remediation Technologies Roundtable (FRTR) are working jointly to publish case studies of full-scale remediation and demonstration projects. In March, 1995, the FRTR published a four-volume series of case study reports. At this time, the FRTR is publishing two additional volumes of case study reports, providing case studies of site cleanup projects using bioremediation, vitrification, soil vapor extraction, and other in situ technologies.

The case studies were developed by the U.S. Environmental Protection Agency (EPA), the U.S. Department of Defense (DoD), and the U.S. Department of Energy (DOE). The case studies were prepared based on recommended terminology and procedures from the Guide to Documenting Cost and Performance for Remediation Projects (EPA-542-B-95-002; March 1995). They present available cost and performance information for full-scale remediation efforts and several large-scale demonstration projects. The case studies are meant to serve as primary reference sources, and contain information on site background and setting, contaminants and media treated, technology, cost and performance, and points of contact for the technology application. The studies contain varying levels of detail, reflecting the differences in the availability of data and information. Because full-scale cleanup efforts are not conducted primarily for the purpose of technology evaluation, data collection on technology cost and performance is often limited.

This volume contains reports on nine projects. Three of the projects were full-scale projects using SVE - two in situ and one ex situ. Two of the projects were large-scale demonstrations of technologies used to enhance the effectiveness of SVE, and another project demonstrated an innovative technology for treating off-gasses from an SVE system. Three of the projects concerned other in situ technologies - a frozen soil barrier containment technology, an innovative approach to drilling monitoring or remediation wells, and a technology for performing hydraulic and pneumatic fracturing of subsurfaces.

Table 1 provides a summary including information on technology used, contaminants and media treated, and project duration for the nine soil vapor extraction and other in situ technology projects in this volume. This table also notes highlights of the technology applications. Table 2 summarizes cost data, including information on quantity of media treated and contaminant removed. In addition, Table 2 shows a calculated unit cost for some projects, and identifies key factors potentially affecting project cost. While a summary of project costs is useful, it is difficult to compare costs for different projects because of site-specific factors and differences in level of detail. Cost data are shown on Table 2 as reported in the case studies, and have not been adjusted for inflation to a common year basis. The dollar values shown in Table 2

should be assumed to be dollars for the time period that the project was in progress (shown on Table 1 as project duration).

The project costs shown in the second column of the table were compiled, where possible, according to an interagency Work Breakdown Structure (WBS).[1] The WBS specifies costs as 1) before-treatment costs, 2) after-treatment costs, or 3) treatment costs. (Table 2 provides some additional information on activities falling under each category.) In many cases, however, the available information was not sufficiently detailed to be broken down in this way.

The column showing the calculated treatment cost provides a dollar value per unit of soil or groundwater treated and, where available, per pound of contaminant removed. Note that when calculated costs are available on a per cubic yard or per ton basis, costs cannot be converted back-and-forth due to limited availability of soil bulk density data, and, therefore, comparisons using the information in this column may be complicated.

Key factors that potentially affect project costs include economies of scale, concentration levels in contaminated media, required cleanup levels, completion schedules, and hydrogeological conditions. It is important to note that several projects in the case study series represent early applications, and the costs of these technologies are likely to decrease in the future as firms gain experience with design and operation.

[1]Additional information on the contents of the WBS and on whom to contact for WBS and related information is presented in the Guide to Documenting Cost and Performance for Remediation Projects.

Table 1. Summary of Remediation Case Studies: Soil Vapor Extraction and Other In Situ Technologies

Site Name, State (Technology)	Contaminants Treated				Media (Quantity)	Project Duration	Highlights
	BTEX and/or TPH	Chlorinated Aliphatics	Non-chlorinated Aliphatics	Historical Activity (Principal Contaminants)			
Soil Vapor Extraction (SVE)							
Basket Creek Surface Impoundment Site, GA (SVE)	●	●	●	Illegal disposal of liquid refinery and other hazardous wastes (Toluene, MIBK)	Soil (1,600 yd^3)	9/92 - 4/93	SVE was performed after low-permeability soil was excavated (ex situ SVE).
Sacramento Army Depot Superfund Site, Burn Pits Operable Unit, CA (SVE)		●		Army support - Burn Pits (TCE, PCE, DCE)	Soil (247,900 yd^3)	5/94 - 9/95	SVE system combining injection and extraction wells in a complex subsurface.
Sand Creek Industrial Superfund Site, Operable Unit No. 1, CO (SVE)	●	●		Pesticide manufacturing, petroleum refinery (PCE, TCE)	Soil (31,440-52,920 yd^3)	9/93 - 4/94	SVE system combining injection and extraction wells.
Enhancements/Additions							
U.S. Department of Energy, Portsmouth Gaseous Diffusion Plant, OH (In Situ Enhanced Soil Mixing)		●		Waste Treatment Plant (TCE, TCA, DCE)	Soil (not provided)	6/92	Field demonstration of four technologies used to remediate fine-grained soils, including enhancing SVE performance.
U.S. Department of Energy Savannah River Site, SC (Flameless Thermal Oxidation)		●		Nuclear material production and research (TCE, PCE, TCA)	Off-Gases (not provided)	4/95 - 5/95	Field demonstration of an alternative technology for treatment of extracted vapors during an SVE application.
U.S. Department of Energy, Savannah River Site, SC, and Hanford Site, WA (Six Phase Soil Heating)		●		Nuclear material production and research (TCE, PCE)	Soil and Sediment (not provided)	10/93 - 1/94	Field demonstration of technology used to enhance removal of contaminants from clayey soil during an SVE application.
Other In Situ Technologies							
U.S. Department of Energy, Portsmouth Gaseous Diffusion Plant, OH, and Other Sites (Hydraulic and Pneumatic Fracturing)		●		Tinker AFB - Underground Storage Tank Others - not provided (VOCs, DNAPLs, product)	Soil and Groundwater (not provided)	7-91 - 8/96 (multiple demonstrations during this period)	Field demonstrations of technology used to increase hydraulic conductivity, contaminant mass recovery, and radius of influence (for example, in a SVE application).
U.S. Department of Energy, SEG Facilities, TN (Frozen Soil Barrier Technology)				Not applicable (not a contaminated site)	Soil (35,694 ft^3)	5/94 - 10/94	Field demonstration of technology used to control waste migration in soils.
U.S. Department of Energy, Multiple Sites (ResonantSonic Drilling)				Not applicable (not a contaminated site)	Soil and Sediment (not provided)	1992 - 1994	Multiple field demonstrations of alternative drilling technology that in some applications may be less costly and produce less drilling waste than cable tool or mud rotary technologies.

Key:
MIBK - Methyl Isobutyl Ketone
TCE - Trichloroethene
PCE - Tetrachloroethene
DCE - 1,2-Dichloroethene
TCA - 1,1,1-Trichloroethane

Table 2. Remediation Case Studies - Summary of Cost Data

Site Name, State (Technology)	Project Cost ($)*	Quantity Treated	Quantity of Contaminant Removed	Calculated Cost for Treatment**	Key Factors Potentially Affecting Project/Technology Costs***
Soil Vapor Extraction					
Basket Creek Surface Impoundment Site, GA (SVE)	T - 660,000 B - 1,300,000 A - 220,000	1,600 yd^3	72,084 lbs	$413/$yd^3$ ($275/ton) $9.20/lb VOC	This project addressed treatment of a relatively small quantity of highly-contaminated soil.
Sacramento Army Depot Superfund Site, Burn Pits Operable Unit, CA (SVE)	T - 670,500 B - 195,000	247,900 yd^3	138 lbs	$2.70/$yd^3$ $4,858/lb VOC	This project addressed treatment of a relatively large quantity of less-contaminated soil.
Sand Creek Industrial Superfund Site, Operable Unit No. 1, CO (SVE)	T - 2,058,564 B - 81,231	31,440-52,920 yd^3	176,500 lbs	$39-65/$yd^3$ $11.70/lb VOC	The calculated unit costs varied depending on how soil quantity treated was estimated (larger estimates of soil quantity treated lead to lower unit costs).
Enhancements/Additions					
U.S. Department of Energy, Portsmouth Gaseous Diffusion Plant, OH (In Situ Enhanced Soil Mixing)	C - 1,956,000 O - 20,000/day	Not provided	Not provided	$150-200/$yd^3$ (projected)	Demonstration project: Technology costs vary based on required materials and equipment.
U.S. Department of Energy Savannah River Site, SC (Flameless Thermal Oxidation)	C - 50,000	Not provided	Not provided	$0.72/lb VOC destroyed (projected)	Demonstration project: Heating content of off-gas and economies-of-scale are key factors affecting cost.
U.S. Department of Energy, Savannah River Site, SC, and Hanford Site, WA (Six Phase Soil Heating)	Not provided	Not provided	Not provided	$86/$yd^3$ (projected)	Demonstration project: Diameter and depth of plume, energy demand, and type of contaminants are key factors affecting cost.

Project Cost*
T = Costs for treatment activities, including preprocessing, capital equipment, operation, and maintenance
B = Costs for before-treatment activities, including site preparation, excavation, and sampling and analysis
A = Costs for after-treatment activities, including disposal of residuals and site restoration
C = Capital costs
O = Annual operating costs

Calculated Cost for Treatment**
**Calculated based on costs for treatment activities (T): excludes costs for before- (B) and after- (A)treatment activities. Calculated costs shown as "Not Calculated" if an estimate of treatment costs unavailable.

***For full-scale remediation projects, this identifies factors affecting actual project costs. For demonstration-scale projects, this identifies generic factors which would affect project costs for a future application using this technology.

Table 2. Remediation Case Studies - Summary of Cost Data (Continued)

Site Name, State (Technology)	Project Cost ($)*	Quantity Treated	Quantity of Contaminant Removed	Calculated Cost for Treatment**	Key Factors Potentially Affecting Project/Technology Costs***
Other In Situ Technologies					
U.S. Department of Energy, Portsmouth Gaseous Diffusion Plant, OH, and Other Sites (Hydraulic and Pneumatic Fracturing)	Not provided	Not provided	Not provided	$8-17/yd^3 soil treated $140/lb TCE removed	Demonstration project: Labor, capital equipment, site preparation, and residuals disposed are key factors affecting cost.
U.S. Department of Energy, SEG Facilities, TN (Frozen Soil Barrier Technology)	C - 481,427	35,694 ft^3	Not provided	$4-14/ft^3 ice formed (projected)	Demonstration project: Quantity of refrigeration and barrier thickness needed are key factors affecting cost.
U.S. Department of Energy, Multiple Sites (ResonantSonic Drilling)	Not provided	Not provided	Not provided	$208-270/ft well drilled (projected)	Demonstration project: Drilling difficulty and type of site (e.g., uncontaminated, hazardous waste, mixed waste) are key factors affecting cost.

Project Cost*
T = Costs for treatment activities, including preprocessing, capital equipment, operation, and maintenance
B = Costs for before-treatment activities, including site preparation, excavation, and sampling and analysis
A = Costs for after-treatment activities, including disposal of residuals and site restoration
C = Capital costs
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Calculated Cost for Treatment**
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***For full-scale remediation projects, this identifies factors affecting actual project costs. For demonstration-scale projects, this identifies generic factors which would affect project costs for a future application using this technology.

SOIL VAPOR EXTRACTION CASE STUDIES

Soil Vapor Extraction at the Basket Creek Surface Impoundment Site, Douglasville, Georgia

Case Study Abstract

Soil Vapor Extraction at the Basket Creek Surface Impoundment Site, Douglasville, Georgia

Site Name:
Basket Creek Surface Impoundment Site

Location:
Douglasville, Georgia

Contaminants:
Organic Compounds (Volatiles - Halogenated: trichloroethene (TCE); and Volatiles - Nonhalogenated: toluene, methyl isobutyl ketone (MIBK), and methyl ethyl ketone (MEK)) and Inorganic Compounds (Heavy Metals: lead and mercury)
- Toluene: BDL-220,000 mg/kg
- MIBK: BDL-66,000 mg/kg
- MEK: BDL-23,000 mg/kg

Period of Operation:
November 1992 to April 1993

Cleanup Type:
Full-scale cleanup

Vendor:
Mark Rigatti
OHM Remediation Services Corp.
5335 Triangle Parkway, Suite 450
Norcross, GA 30092
(770) 453-7630

SIC Code:
4953 W (Refuse Systems - waste processing facility, miscellaneous)

Technology:
Soil Vapor Extraction (ex situ)
- In situ SVE was not used because of low soil permeability
- Soil was excavated on a grid basis
- 48 grids were excavated, each 10x10 ft square
- Treatment was conducted in metal building 60 ft wide by 120 ft long by 26 ft tall
- System included shaker (power) screen, 17 horizontal vapor extraction wells, 3 vacuum pumps, a baghouse, and a thermal oxidizer

Cleanup Authority:
CERCLA
- Action Memorandum Date 4/11/91
- Fund Lead

Point of Contact:
R. Donald Rigger
USEPA Region 4
345 Courtland Street, N.E.
Atlanta, GA 30365
(404) 347-3931

Waste Source:
Surface Impoundment/Lagoon

Purpose/Significance of Application:
Ex situ SVE application on low-permeability soil contaminated with organic and inorganic constituents.

Type/Quantity of Media Treated:
Soil
- 1,600 cubic yards (2,400 tons)
- Particle size distribution: clay - 16.4%; silt - 34.4%; sand - 40.8%; and gravel - 8.4%
- Air permeability: 1.5×10^{-7} cm/sec

Regulatory Requirements/Cleanup Goals:
- Soil treatment targets identified for 4 VOCs, lead, mercury, and total HOCs
- Targets for VOCs and metals set at TC regulatory levels

Results:
- Soil treatment targets met for all 14 sampling grids after 6 months of treatment
- TCLP results were as follows: TCE - <0.1 mg/L; PCE - < 0. 3 mg/L; benzene - <0.03 mg/L; MEK - < 2.0 mg/L; lead < 2.0 mg/L; and mercury - all ND
- 72,000 lbs of total VOCs recovered in this application

Soil Vapor Extraction at the Basket Creek Surface Impoundment Site, Douglasville, Georgia (Continued)

Cost Factors:

- Actual costs of $2,200,000 were expended, including $1,300,000 for before-treatment activities, $660,000 for activities directly attributed to treatment, and $220,000 for after-treatment activities
- The unit cost for activities directly attributed to treatment was $413/yd^3 of soil treated ($275/ton), and $9.20/lb of VOC removed

Description:

Basket Creek was used in the 1960s for illegal disposal of liquid refinery and other hazardous wastes. In 1991, soil at the site was identified as a RCRA hazardous waste exhibiting the Toxicity Characteristic (TC) for lead, MEK, and TCE. Soil samples collected in March 1990, May 1991, and January 1992 showed the following concentrations in a total waste analysis: TCE - below detection limit (BDL) to 8,600 mg/kg; PCE - BDL to 2,700 mg/kg; toluene - BDL to 220,000 mg/kg; xylenes - BDL to 7,300 mg/kg; MEK - BDL to 23,000 mg/kg; and MIBK - BDL to 66,000 mg/kg.

An action memorandum for Basket Creek was signed on April 11, 1991 and specified soil treatment targets for TCE, PCE, benzene, MEK, lead, mercury, and total halogenated organic compounds (HOCs). An ex situ SVE system was used at Basket Creek, consisting of a 7,200 ft^2 containment building, a shaker (power) screen, 17 vapor extraction wells, vacuum pumps, a baghouse, an induced draft blower, and a thermal oxidizer. Excavation, screening, and vapor extraction all took place inside the containment building. The system was run from November 1992 to February 1993, and again from March to April 1993, for a total of 6 months of operation.

Analytical data indicated that the soil treatment targets were met for all contaminants after the six month treatment period. Total VOCs in the treated soil ranged from 0.142 to 1570.7 mg/kg, and approximately 72,000 lbs of total VOCs were recovered from the soil. Toluene was the largest quantity VOC recovered, accounting for approximately 80% of the total VOCs recovered, and MIBK was the second largest quantity, accounting for 11%. Ex situ SVE was selected for this application after in situ SVE was ruled out because of the low permeability of the contaminated soil. Excavation of soil was performed within an enclosure to control emissions. Because of space constraints, this resulted in the excavation taking a much longer time (3 months) than would have been required were the excavation to have been done outside (a few days).

COST AND PERFORMANCE REPORT

EXECUTIVE SUMMARY

This report presents cost and performance data for a soil vapor extraction (SVE) system at the Basket Creek Surface Impoundment site in Douglasville Georgia. The SVE system was used at Basket Creek to treat soil contaminated with halogenated volatile organic compounds (VOCs), including trichloroethene (TCE) and tetrachloroethene (PCE), and nonhalogenated VOCs including toluene, xylenes, methyl isobutyl ketone (MIBK), and methyl ethyl ketone (MEK).

Basket Creek was used in the 1960s for illegal disposal of liquid refinery and other hazardous wastes; however information on the quantity and specific types of waste disposed in the impoundment is not available. In 1991, soil at the site was identified as a RCRA hazardous waste exhibiting the Toxicity Characteristic (TC) for lead, MEK, and TCE. Soil samples collected in March 1990, May 1991, and January 1992 showed the following concentrations in a total waste analysis: TCE - below detection limit (BDL) to 8,600 mg/kg; PCE - BDL to 2,700 mg/kg; toluene - BDL to 220,000 mg/kg; xylenes - BDL to 7,300 mg/kg; MEK - BDL to 23,000 mg/kg; and MIBK - BDL to 66,000 mg/kg.

An action memorandum for Basket Creek was signed on April 11, 1991 and specified soil treatment targets for TCE, PCE, benzene, MEK, lead, mercury, and total halogenated organic compounds (HOCs). The cleanup levels ranged from 0.2 to 200 mg/L (measured using a TCLP) for all contaminants except total HOCs. The target for total HOCs was 1,000 mg/kg, based on the land disposal restrictions for California List wastes. In addition, EPA and the State of Georgia required that the thermal oxidizer maintain a minimum destruction efficiency of 95%.

The SVE system used at Basket Creek was an ex situ application, consisting of a 7,200 ft^2 containment building, a shaker (power) screen, 17 vapor extraction wells, vacuum pumps, a baghouse, an induced draft blower, and a thermal oxidizer. Excavation, screening, and vapor extraction all took place inside the containment building. EPA had originally considered using in situ SVE, but ruled it out because of the relatively low permeability of soil (excavation and power screening helped to increase the permeability of the soils in the ex situ process). The system was run from November 1992 to February 1993, and again from March to April 1993, for a total of 6 months of operation.

Analytical data indicated that the soil treatment targets were met for all contaminants after the six month treatment period. Total VOCs in the treated soil ranged from 0.142 to 1570.7 mg/kg, and approximately 72,000 lbs of total VOCs were recovered from the soil. Toluene was the largest quantity VOC recovered, accounting for approximately 80% of the total VOCs recovered, and MIBK was the second largest quantity, accounting for 11%. The thermal oxidizer achieved a destruction efficiency of at least 95% during system operation, and for three months of at least 98%.

Approximately $2.2 million were expended in this application, including $1.3 million for before-treatment activities, $660,000 for activities directly attributed to treatment, and $220,000 for after-treatment activities, including off-site disposal of treated soil. Approximately $650,000 of the before-

EXECUTIVE SUMMARY (CONT.)

treatment costs were for the building (enclosure), air handling system, and treatment of building vapors in the incinerator.

The $660,000 in costs directly attributed to treatment activities corresponds to $413 per cubic yard treated (1,600 cubic yards), $275 per ton of soil treated (2,400 tons), and $9.20 per pound of VOC removed (approximately 72,000 pounds VOC removed). These unit costs reflect treatment of a relatively small quantity of soil that contained a relatively high concentration of contaminants.

According to the OSC, excavation within an enclosure takes longer than outside due to the space constraints. Normally, the excavation at Basket Creek would have been completed in a few days, instead of the three months actually taken.

SITE INFORMATION

Identifying Information:

Basket Creek Surface Impoundment site
Douglasville, Georgia
CERCLIS # GAD980843833
Action Memorandum Date: 4/11/91

Treatment Application:

Type of Action: Removal
Treatability Study Associated with Application? Yes
(see discussion under Remedy Selection)
EPA SITE Program Test Associated with Application? No
Period of Operation: 11/92 - 4/93
Quantity of Material Treated During Application: Approximately 1,600 cubic yards (2,400 tons) of soil [2]

Background

Historical Activity that Contributed to Contamination at the Site: Waste Disposal

Corresponding SIC Code: 4953 W (Refuse Systems - waste processing facility, miscellaneous)

Waste Management Practice that Contributed to Contamination: surface impoundment/lagoon

Site History: The Basket Creek Surface Impoundment site (Basket Creek) is located in Douglasville, Georgia, as shown in Figure 1. The site was contaminated during the 1960s when it was used for the illegal disposal of hazardous wastes. At that time, an intermittent stream bed was dammed with soil to form a small impoundment. The impoundment area measured 35 feet north to south and 50 feet east to west, and ranged in depth from 6 to 12 feet. [1, 2]

Liquid refinery and other hazardous wastes were reportedly disposed in the impoundment over a number of years. However, information on the quantity and specific types of waste disposed was not available. The impoundment was accidentally ignited in July of 1970 and burned for several days. Subsequent to the fire, local officials required the landowner to discontinue waste disposal and cover the impoundment with soil. [1,2]

In November 1989, EPA performed a Hazard Ranking System evaluation for Basket Creek. The evaluation was limited to a review of existing file material, completion of a target survey, and a site walk-through. Based on that evaluation, the site did not qualify for the National Priorities List (NPL). [3]

SITE INFORMATION (CONT.)

Background (cont.)

Regulatory Context: EPA signed an Action Memorandum for Basket Creek on April 11, 1991. Initial activities included sampling to characterize the nature and extent of contamination at the site. The soil was found to be a RCRA hazardous waste by exhibiting the Toxicity Characteristic (TC) for lead (Waste Code D008), methyl ethyl ketone (Waste Code D035), and trichloroethene (Waste Code D039). Additionally, the soil was found to be a California List Waste under the RCRA Land Disposal Restrictions program because total halogenated organic compounds were greater than 1,000 parts per million (ppm) and, therefore, waste from the site was prohibited from land disposal. As described under the Contamination Characterization section of this report, elevated levels of mercury were also found in the soil; however, the soil was not identified as exhibiting the TC for mercury. [3]

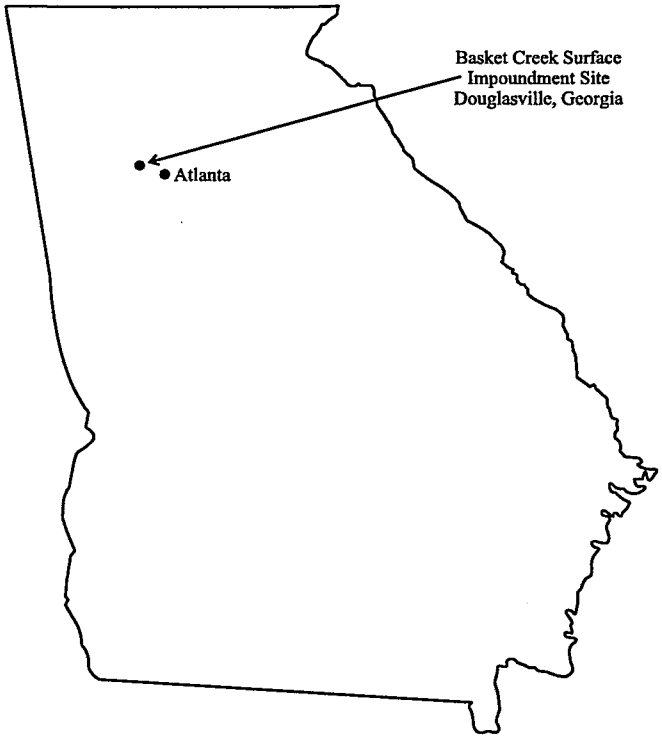

Figure 1. Site Location

The action memorandum identified treatment targets for soil, including TC regulatory levels for selected volatile organic compounds (VOCs) and metals, and the California List regulatory level of 1,000 ppm for total HOCs. [3]

Remedy Selection: EPA evaluated several potential remedies for this site. The first remedy evaluated, off-site incineration, was not selected because of cost. Bids for off-site incineration of soil from Basket Creek ranged from $2,500 to $2,800 per ton. [3] According to the OSC, the incineration bids were high because of the elevated mercury levels. [13]

Two on-site treatment technologies, in situ soil vapor extraction and low temperature thermal desorption, were also considered, and treatability studies were conducted for each technology. In situ soil vapor extraction was ruled out because of the low permeability of the contaminated soil. During the low temperature thermal desorption treatability study, the soil sample ignited. This indicated that the soil was too highly contaminated with VOCs to treat safely with low temperature thermal desorption and EPA did not select this technology. [1]

SITE INFORMATION (CONT.)

Background (cont.)

The remedy selected by EPA for this site was ex situ soil vapor extraction (SVE). The remedy included excavating the soil from the impoundment, processing the soil through a power screen, stockpiling the soil on site, and treating the stockpiled soil with an ex situ SVE system. According to the OSC, the SVE system was installed primarily to control VOC emissions from the stockpile. [3, 13] According to the vendor, bench-scale testing was performed for this application; however, no details of the study or results were provided. [14]

Calculations were made to estimate the quantity of VOCs that would be released to the atmosphere from the excavation, screening, and stockpiling operations. The maximum quantity of VOCs released from the operations as fugitive emissions was estimated at 1,800 pounds per day. Depending on weather conditions, these emissions posed potential health risks for local residents and a threat to general air quality. EPA decided to include the following engineering controls to minimize fugitive emissions [3]:

- Construction of an enclosure large enough to cover the impoundment area and stockpile area;
- Development of an air handling system capable of exhausting a sufficient quantity of contaminated air to maintain a safe working environment in the building; and
- Installation of a thermal oxidizer (fume incinerator) to thermally destroy the VOCs in the air stream exhausted from the building.

Site Logistics/Contacts

Site Management: Fund-Lead
Oversight: EPA

On-Scene Coordinator:
R. Donald Rigger
U.S. EPA Region 4
345 Courtland Street, N.E.
Atlanta, Georgia 30365
(404) 347-3931

Treatment Vendor:
Mark Rigatti
OHM Remediation Services Corp.
5335 Triangle Parkway, Suite 450
Norcross, GA 30092
(770) 453-7630

MATRIX DESCRIPTION

Matrix Identification

Type of Matrix Processed Through the Treatment System: soil (ex situ)

Contaminant Characterization

Primary Contaminant Groups: Organic Compounds (Volatiles - Halogenated: trichloroethene; and Volatiles - Nonhalogenated: toluene, methyl isobutyl ketone, and methyl ethyl ketone) and Inorganic Compounds (Heavy Metals: lead and mercury)

Soil samples were collected by EPA in the surface impoundment in March 1990, May 1991, and January 1992, and analyzed for organics and metals. The results of these investigations for reported constituents are shown in Table 1.

The composite sample collected in May 1991 consisted of nine grab samples from various depths in the former impoundment. As shown in Table 1, the May 1991 sample was characterized by total waste analysis and Toxicity Characteristic Leaching Procedure (TCLP). The sample collected in January 1992 was collected as a "worst-case" sample (i.e., the most highly contaminated part of the site) for treatability testing. [2, 4, 9, 13]

Table 1. Results of Soil Sampling for Reported Constituents in Surface Impoundment

Constituent	Samples Collected March 1990 - Total Waste Analysis [9] (mg/kg)	Samples Collected May 1991 [4]		Sample Collected January 1992 - Total Waste Analysis* [2] (mg/kg)
		Composite Sample Total Waste Analysis (mg/kg)	Composite Sample TCLP (mg/L)	
Volatile Organics				
Trichloroethene	BDL (90)	BDL (90.0)	BDL (11.0)	8,600
Tetrachloroethene	BDL (120) - 720	230	BDL	2,700
Toluene	9,300 - 11,000	11,000	BDL	220,000
Ethylbenzene	BDL (220)	BDL (240)	BDL	1,600
Xylenes (total)	1,300 - 1,500	1,280	BDL	7,300
2-Butanone (Methyl Ethyl Ketone)	890	BDL	280.0	23,000
4-Methyl-2-Pentanone (Methyl Isobutyl Ketone)	1,400	4,700	BDL	66,000

MATRIX DESCRIPTION (CONT.)

Contaminant Characterization (cont.)

Table 1. (Continued)

Constituent	Samples Collected March 1990 - Total Waste Analysis [9] (mg/kg)	Samples Collected May 1991 [4]		Sample Collected January 1992 - Total Waste Analysis* [2] (mg/kg)
		Composite Sample Total Waste Analysis (mg/kg)	Composite Sample TCLP (mg/L)	
Metals				
Barium	58.15 - 103.14	63.0	BDL (0.326)	N/A
Cadmium	6.33 - 17.57	2.1	BDL (0.045)	N/A
Chromium	312.90 - 192.97	180.0	BDL (0.02)	N/A
Lead	667.88 - 2,579.67	4,400.0	32.6	940
Mercury	38.20 - 3553.68	190.0	0.1	390

*This sample was collected as a "worst-case" sample for treatability purposes.
BDL - below detection limit (detection limit shown in parentheses, where available).
N/A - not analyzed.

Matrix Characteristics Affecting Treatment Cost or Performance

The major matrix characteristics affecting cost or performance for this technology and the values measured for each are shown in Table 2.

Table 2. Matrix Characteristics [4]

Parameter	Value	Measurement Method
Soil Classification	Not provided	Not provided
Clay Content and/or Particle Size Distribution	% Clay - 16.4 % Silt - 34.4 % Sand - 40.8 % Gravel - 8.4	Grain size analysis
Moisture Content	16.9%	N/A
Air Permeability	1.5×10^{-7} cm/sec	Not provided
Porosity	0.316	N/A
Total Organic Carbon	Not provided	N/A
Bulk Density	112.5 lbs/ft^3	N/A
pH	5.46	N/A

N/A - Measurement method not reported for this parameter because resulting value not expected to vary among measurement procedures.

TREATMENT SYSTEM DESCRIPTION

Primary Treatment Technology Type: Soil Vapor Extraction (ex situ)

Supplemental Treatment Technology Type:
Pretreatment: power screening,
Post-treatment (air): baghouse, thermal oxidizer

Soil Vapor Extraction System Description and Operation

System Design [1, 2, 11]

The SVE system used at Basket Creek included the following equipment: a metal building measuring 60 feet wide by 120 feet long by 26 feet tall; a shaker (power) screen; 17 horizontal vapor extraction wells; and three vacuum pumps for the vapor extraction system (with filters and silencers). In addition, the system included a baghouse (dust collector), an induced draft blower for exhausting the building air, and a thermal oxidizer to treat the contaminated air and vapor streams.

Figure 2 shows the layout for the treatment system used at Basket Creek. As shown in Figure 2, the vapors extracted from the soil stockpile were combined with the vapors extracted from the building air prior to treatment in the thermal oxidizer.

The building was designed to totally enclose the impoundment and also have sufficient room for treatment of the stockpiled soil. Inside the building, soil was excavated, processed through a power screen, and stockpiled. The soil was excavated using a track mounted excavator and placed directly into a power screen. The power screen was used to shred soil clumps and break up the soil to increase the soil permeability. The power screened soil was transported to the stockpile area using a 25-foot long covered stacking conveyor. According to the OSC, analytical data for vapors extracted from the building and soil stockpile showed that 20% to 25% of the VOCs recovered during this application came from the excavation and screening operations.

The soil vapor extraction system consisted of seventeen 4-inch diameter slotted well screen strings lying horizontally through the soil stockpile. The well screens were placed in three rows, six near ground level, five at 4 feet above ground level, and six more at 7 feet above ground level. Chemical resistant sleeves were placed over the well screen sections to prevent soil from clogging the slots. As the stockpile was built, additional well screen sections were screwed onto the previous section and covered with excavated soil. The vacuum for each well screen row was supplied by a 1,240-cubic feet per minute (cfm) vacuum pump. Each vacuum pump was equipped with a filter canister and a silencer to reduce the high pitched noise of the pump. Vapors were drawn out of the stockpile and routed to the thermal oxidizer through PVC piping.

In addition, vapors were collected using a movable fume hood at two locations inside the building: at the excavation; and at the power screen. The vacuum for the excavation and power screen was supplied by an 8,000-cfm, 50 horse power (hp) induced draft blower located outside the operations building. A baghouse was used to remove all particulates from the air stream. The baghouse consisted of a metal structure housing 96 filter bags designed to remove particles

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

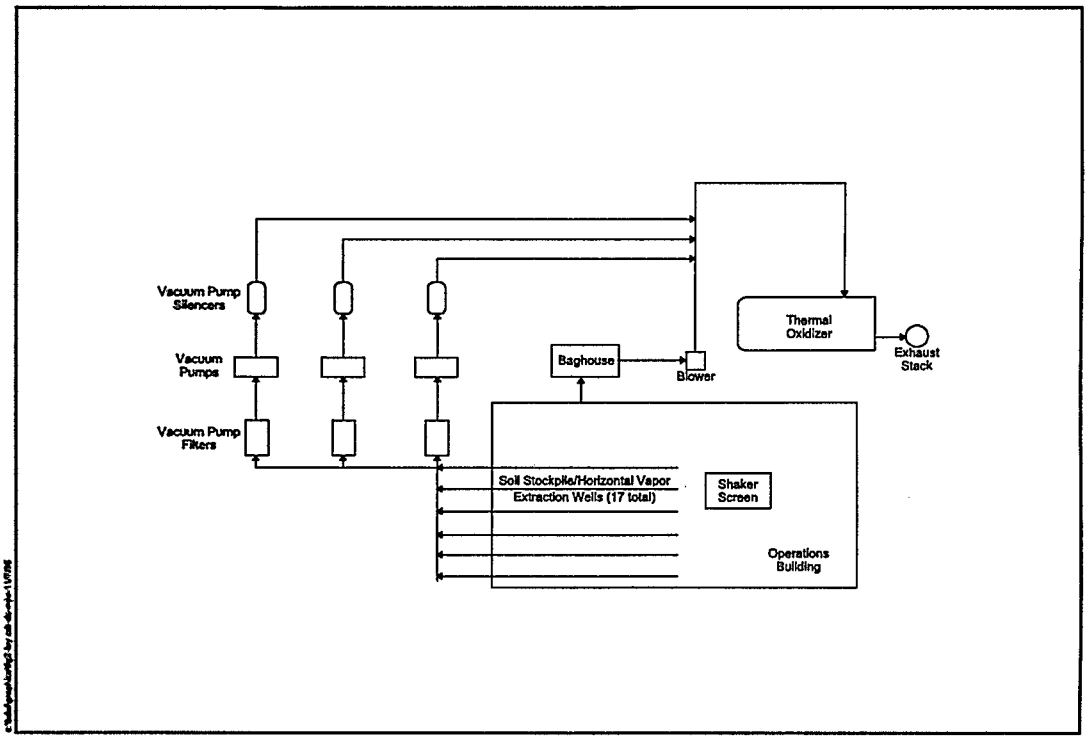

Figure 2. Treatment System Layout [2]

down to 0.5 microns. The system used 24-inch flexible duct work to route the vapors from the interior of the building to the exterior. Galvanized steel ducts were used to route the air through the baghouse and into the thermal oxidizer.

The thermal oxidizer was a three chamber, propane fired unit designed to treat 10,000 cfm of vapors with greater than 99% destruction and removal efficiency. Five 1,000-gallon propane tanks were staged on site to supply fuel for the unit.

System Operation [1, 2]

In October 1992, a trial burn of the thermal oxidizer was performed. Soil from the impoundment was exposed with a trackhoe and the soil was stirred to liberate VOCs. The contaminated vapor was routed through the duct work and into the thermal oxidizer which was operated at approximately 1,600°F. The residence time for the thermal oxidizer was not provided for this application. Mass emission rates were calculated for VOCs, semivolatile organic compounds, dioxins, and furans, and were reported to the Agency for Toxic Substances and Disease Registry (ATSDR - an agency of the U.S. Public Health Service). ATSDR determined that the predicted emissions from the thermal oxidizer would not pose a threat to public health. In addition,

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

ATSDR recommended that stack emissions be continuously monitored. In response to this recommendation, continuous emission monitors (total hydrocarbon analyzers) were installed at the inlet and outlet of the thermal oxidizer.

Full-scale operations began in November 1992. The area of contamination (60 feet wide by 80 feet long and varying in depth to up to 14 feet) was divided into forty-eight 10-foot by 10-foot grids. Excavation was performed within individual grids to limit the surface area of exposed soil. Rocks and debris larger than 2 inches were rejected by the power screen, and placed in roll-off boxes. Excavation was halted when solid homogeneous rock was encountered.

The vapor extraction system was operated continuously; VOC recovery associated with the excavation and screening operations was operated an average of 25 to 30 hours per week, during excavation and screening operations. All of the recovered VOCs were routed to the thermal oxidizer for treatment.

System Shutdown [2]

In February 1993, excavation and backfilling of the 48 grid sections was completed. The vapor extraction system was operated for three weeks after excavation to complete treatment of the soil.

The stockpiled soil was then divided into 20-foot grid sections and sampled. The results indicated that the VOC levels in the majority of the grid sections had met the target levels (see discussion under cleanup goals/standards). However, the results also showed that contamination above the target levels still remained in several grid sections. These grids were re-excavated and treated in the stockpile SVE system in March and April 1993. Analytical results showed that in April 1993 the soil met the target levels (see results under Treatment Performance Data) and the soil was transported to the BFI industrial waste landfill in Buford, Georgia. A total of 2,366.72 tons of soil was transported off site for disposal.

Approximately 100 tons of rocks and debris from the power screening operation were disposed of at the BFI facility in Buford, Georgia. Eighteen (18) cubic yards of excavated metal and crushed drums were also transported off site in April 1993 to the Laidlaw Hazardous Waste Landfill in Pinewood, South Carolina, where they were disposed by direct burial. Approximately 4,250 gallons of decontamination water (from health and safety activities - see discussion below) were transported off site in May 1993 by International Petroleum Corporation for treatment at their facility in Fairburn, Georgia.

In addition, nine drums containing paint waste were transported in May 1993 to the Thermal-Chem facility in Rock Hill, South Carolina, for incineration.

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

Site Restoration [2]

Site restoration activities included dismantling and removal of the operations building and other process equipment. The site was then regraded using on-site soil, and grass seed and straw were distributed throughout the areas affected by the removal. In August 1993, the application of seed was completed.

Health and Safety [1, 2]

One of the main concerns regarding the safety of the personnel inside the operations building was the buildup of VOCs from the soil excavation and screening and the possibility of a fire or an explosion. To address these concerns, a site safety officer was present inside the enclosure at all times when excavation was taking place. Workers wore Level B personal protective equipment (PPE) consisting of supplied air breathing apparatus, fire resistant coveralls, disposable outer suits and boots, and hard hats. Workers decontaminated reusable PPE on site.

The safety officer was responsible for monitoring air quality inside the enclosure. A Combustible Gas Indicator was used to monitor the concentration of combustible gas in the airspace. A limit of 10% of the Lower Explosive Limit (LEL) was set as an automatic cease-work condition. If 10% of the LEL was reached, all work stopped and the workers evacuated the building until the levels had dropped back into the safe range. A Photo-Ionization Detector (PID) was also used to monitor airborne contaminants as total hydrocarbons. A limit of 500 ppm total hydrocarbons in air was also set as a cease-work condition.

Another safety concern was the potential to develop an explosive atmosphere in the air handling duct work, both inside and outside the enclosure. A limit of 20% of the LEL was set for all components of the air handling system, including the vapor extraction piping, the flexible duct work, and the steel duct work. Eight LEL detectors were placed throughout the air handling system, and connected to a central control panel. Whenever any one of the eight detectors registered 15% of the LEL, an audible alarm would sound, and personnel inside the building would discontinue excavation. A reading of 20% of the LEL caused automatic interlocks to activate which shut down the blower.

According to the OSC, the 15% LEL level in the duct work was exceeded several times per day during excavation of highly contaminated areas. In addition, there were several times during the project when the 20% level was exceeded. [13]

In addition, air monitoring was conducted around the perimeter of the operations building and using off-site high volume air sampling equipment.

TREATMENT SYSTEM DESCRIPTION (CONT.)

Operating Parameters Affecting Treatment Cost or Performance

The major operating parameters affecting cost or performance for this technology and the values measured for each are shown in Table 3.

Table 3. Operating Parameters [13]

Parameter	Value	Measurement Method
Air Flow Rate	3,000 cfm	N/A
Operating Pressure/Vacuum	4 inches mercury	N/A

N/A - Measurement method not reported for this parameter because resulting value not expected to vary among measurement methods.

Timeline

A timeline for this application is shown in Table 4.

Table 4. Timeline [1, 2]

Start Date	End Date	Activity
April 1991		Action memorandum signed
April 1992	May 1992	Operations building constructed
October 1992		Trial Burn performed
November 1992	April 1993	Full-scale operations conducted
March 1993	May 1993	Treated soil disposed off site
May 1993	August 1993	Site restoration activities completed

TREATMENT SYSTEM PERFORMANCE

Cleanup Goals/Standards

The action memorandum identified treatment targets for stockpiled soil, including TC regulatory levels for selected volatile organic compounds (VOCs) and metals, and the California List regulatory level of 1,000 ppm for total HOCs, as shown in Table 5. [3]

Table 5. Stockpile Soil Treatment Targets [3]

Constituent/Parameter	Regulatory Level	Units
Trichloroethene (TCE) - TCLP	0.5	mg/L
Tetrachloroethene (PCE) - TCLP	0.7	mg/L
Benzene - TCLP	0.5	mg/L
2-Butanone (MEK) - TCLP	200	mg/L
Lead - TCLP	5.0	mg/L
Mercury - TCLP	0.2	mg/L
Total HOCs	1,000	mg/kg

According to the vendor, EPA and the State of Georgia identified a requirement that the thermal oxidation unit be at least 95% efficient for VOC destruction, although this is not described in the action memorandum. [14]

Treatment Performance Data

Treatment performance data for this application include results for treated soil stockpile samples, power screen reject samples, total VOC and specific VOC recovery data, thermal oxidizer VOC destruction efficiency data, and air emission results.

Treated Soil Stockpile Samples [2]

The treated soil stockpile was sampled using a 20-foot grid system (a layout of the grid system was not provided). The stockpile was divided into fourteen 20-foot by 20-foot grid sections, and four sample points were selected from each grid section. The 14 grid sections are labelled:

AB-6,5;	AB-12,11;	CD-8,7;	DE-3,4;	EF-10,9; and
AB-8,7;	BC-3,4;	CD-10,9;	EF-6,5;	EF-12,11.
AB-10,9;	CD-6,5;	CD-12,11;	EF-8,7;	

A hand auger was used to collect aliquots from 2-, 4-, and 8-foot depths at each of the four sample points within each grid section. All 12 aliquots were composited into one sample. The stockpile samples were analyzed by TCLP for TCE, PCE, benzene, MEK, lead, and mercury; and for total VOCs and total HOCs. The results from these analyses for the 14 grid sections are shown in Table 6.

Table 6. Treated Soil Stockpile Analytical Data [2]

Constituent/Parameter	Regulatory Level	Units	Sample Number						
			CD-10,9	EF-10,9	EF-12,11	CD-12,11	EF-6,5	CD-6,5	DE-3,4
Trichloroethene (TCE) - TCLP	0.5	mg/L	0.08	0.0015	BDL	BDL	0.0019	0.006	BDL
Tetrachloroethene (PCE) - TCLP	0.7	mg/L	0.12	0.038	0.019	0.0015	0.044	0.06	0.092
Benzene - TCLP	0.5	mg/L	0.001	0.0007	0.0003	0.0004	0.002	0.0017	0.017
2-Butanone (MEK) - TCLP	200	mg/L	0.7	0.066	BDL	BDL	0.52	0.83	1.5
Lead - TCLP	5.0	mg/L	0.75	0.71	1.1	0.6	0.28	0.27	0.62
Mercury - TCLP	0.2	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Total VOCs	N/A	mg/kg	249.91	38.47	0.347	0.382	70.04	166.59	230.8
Total HOCs	1,000	mg/kg	12.81	1.08	0.057	0.237	2.98	4.07	20.3

N/A - Not applicable - no cleanup goal established for this parameter.
BDL - Below detection limit (detection limit not provided).
MDL - Acronym not defined in references.

Table 6. Treated Soil Stockpile Analytical Data [2] (Continued)

Constituent/Parameter	Regulatory Level	Units	Sample Number						
			BC-3,4	AB-12,11	AB-10,9	AB-6,5	AB-8,7	CD-8,7	EF-8,7
Trichloroethene (TCE) - TCLP	0.5	mg/L	0.0024	BDL	BDL	0.0014	0.014	0.045	0.0007
Tetrachloroethene (PCE) - TCLP	0.7	mg/L	0.011	0.0013	0.17	0.011	0.13	0.26	0.046
Benzene - TCLP	0.5	mg/L	0.0022	0.0013	0.017	0.0015	0.019	0.025	0.0016
2-Butanone (MEK) - TCLP	200	mg/L	1.3	BDL	MDL	0.42	MDL	MDL	0.48
Lead - TCLP	5.0	mg/L	0.79	0.25	1.8	0.49	1.9	1.1	0.93
Mercury - TCLP	0.2	mg/L	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Total VOCs	N/A	mg/kg	131.489	0.142	1,570.7	73.77	738.5	721.42	108.671
Total HOCs	1,000	mg/kg	2.709	0.055	7.3	0.66	10.97	18	5.521

BDL - Below detection limit.
MDL - Acronym not defined in references.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Power Screen Reject Samples [2]

The roll-off boxes containing rocks and debris from the power screening operation were also sampled. Power screen reject sample data were not provided. However, the vendor indicated that the material met the target levels, and was disposed at the Industrial Waste Landfill in Buford, Georgia.

Total VOC Recovery Data [2]

The quantity of total VOCs recovered from the surface impoundment was calculated by the treatment vendor using analytical data for the concentrations of VOCs at the inlet to the thermal oxidizer and the flowrate to the oxidizer. The vendor summed the calculated mass recoveries for the following VOCs to calculate total VOCs: TCE, PCE, benzene, toluene, ethylbenzene, total xylenes, MEK, MIBK, and chlorobenzene. The quantities of total VOCs recovered on a weekly basis from November 1992 to February 1993 are shown in Table 7.

Specific VOC Recovery Data

Table 8 shows a breakdown by VOC and by month for the total VOCs recovered from November 1992 to February 1993.

Table 7. Quantity of Total VOCs* Recovered [2]

Operating Period	Quantity of Total VOCs* Recovered (lbs)
11/25 - 11/30/92	1,542.6
12/1 - 12/7/92	4,130.9
12/8 - 12/14/92	5,210.8
12/15 - 12/22/92	6,065.8
12/28 - 12/31/92	5,805.4
1/1 - 1/08/93	5,192.9
1/9 - 1/15/93	12,322.3
1/16 - 1/22/93	8,965.8
1/23 - 1/31/93	11,497.7
2/1 - 2/8/93	4,859.3
2/9 - 2/17/93	5,113
2/18 - 2/25/93	1,377.3
TOTAL	72,083.8

*Total VOCs recovered are defined as the sum of the mass recoveries for the following: TCE, PCE, benzene, toluene, ethylbenzene, total xylenes, MEK, MIBK, and chlorobenzene.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Table 8. Quantity of Specific VOCs Recovered [2, 5]

VOC	Quantity Recovered (lbs)				Total*
	November 1992	December 1992	January 1993	February 1993	
TCE	0	182.4	265.05	177.88	625.33
PCE	0	0	179.64	171.01	350.65
Benzene	0	0	26.72	0	26.72
Toluene	1,543	18,813.0	29,851.67	6,889.01	57,096.28
Ethylbenzene	0	42.1	315.32	132.93	490.35
Total Xylenes	0	402.4	1,126.75	571.89	2,101.04
MEK	0	783.3	1,670.70	638.31	3,092.31
MIBK	0	989.8	4,523.07	2,761.27	8,274.14
Chlorobenzene	0	0	19.99	10.53	30.52
TOTAL*	1,543	21,213	37,979	11,349	72,083.8

*Totals reflect rounding.

Thermal Oxidizer Destruction Efficiency Data

The destruction efficiency for the thermal oxidizer was measured based on the average daily inlet and outlet concentrations at the oxidizer. Table 9 shows these results for the months of November 1992, December 1992, January 1993, and February 1993.

Table 9. Thermal Oxidizer Destruction Efficiency [2, 5]

Operating Period	Average Daily Inlet Concentrations (ppmv)	Average Daily Outlet Concentrations (ppmv)	Destruction Efficiency (%)
11/25 to 11/30/92	10,944	573.60	95
12/1 to 12/31/92	181,032	3,828	98
1/1 to 1/31/93	432,960	3,878.4	99
2/1 to 2/25/93	149,328	1,125.6	99

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

The OSC speculated that the destruction efficiency performance improved during this application because the seals in the thermal oxidizer seated better after a 2-month break-in period. [13]

Air Emission Results

Airborne concentrations of VOCs inside the operations building occasionally approached 500 ppm (the stop work condition) and regularly ranged between 200 and 400 ppm. However, according to the OSC, no VOCs were detected during hourly air monitoring surveys around the perimeter of the operations building and no VOCs were detected in off-site high volume air samples. [1]

Performance Data Assessment

The soil stockpile analytical data shown in Table 6 indicates that the soil treatment targets were met for all 14 sampling grids after 6 months of treatment. As shown in Table 6, the TCLP results for the target compounds were as follows: TCE less than 0.1 mg/L, PCE less than 0.3 mg/L, benzene less than 0.03 mg/L, MEK less than 2.0 mg/L, and lead less than 2.0 mg/L. The TCLP results for mercury were all less than the reported detection limit. Also as shown in Table 6, total HOCs ranged from 0.055 to 20.3 mg/kg, and total VOCs from 0.142 to 1,570.7 mg/kg. The data in Table 6 also show that there were variations in concentrations among the 14 soil stockpile grid samples. For example, the total VOC data show a range over four orders of magnitude in the 14 grid samples (e.g., from 0.142 to 1,570.7 mg/kg).

Although no data are available to characterize the soil in the stockpile prior to treatment, the surface impoundment data shown in Table 1 present an approximation of the concentrations that may have been present in the stockpile prior to treatment. As shown in Table 1, total waste analysis concentrations in the surface impoundment ranged from Below Detection Limit (BDL) to 8,600 mg/kg for TCE, from BDL to 2,700 mg/kg for PCE, from 9,300 to 220,000 mg/kg for toluene, from BDL to 1,600 mg/kg for ethylbenzene, from 1,280 to 7,300 mg/kg for xylenes, from BDL to 23,000 mg/kg for MEK, and from 1,400 to 66,000 mg/kg for MIBK.

The data provided in Table 7 show that a total of 72,083.8 pounds of total VOCs were recovered from the soil stockpile in this application. This total includes VOCs recovered from the soil stockpile and the excavation and screening emissions. According to the OSC, 75 to 80% of the VOCs were recovered from the soil stockpile, with the remainder recovered from the excavation and screening processes. Table 7 also shows that the quantity of VOCs recovered varied over the course of the application. During the first six and latter three weeks of the application, total VOC recoveries averaged 4,400 lbs/week. However, during weeks 7, 8, and 9, total VOC recoveries averaged 11,000 lbs/week, approximately 2.5 times greater. According to the OSC, this was likely due to variations in VOC concentrations in the soils in the surface impoundment.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Performance Data Assessment (cont.)

Table 8 shows that toluene was the largest quantity VOC recovered during this application, accounting for approximately 80% of the total VOCs recovered. MIBK accounted for approximately 11% of the recovered VOC, with the remainder consisting of TCE, PCE, benzene, ethylbenzene, xylenes, MEK, and chlorobenzene. These results are consistent with the data shown in Table 1 for soil sampling in the surface impoundment prior to this application. As shown in Table 1, for the composite sample collected in May 1991, toluene was present in the highest concentration (11,000 mg/kg), followed by MIBK at 4,700 mg/kg.

The thermal oxidizer destruction efficiency data show that, while the monthly average inlet concentrations varied from 10,944 to 432,960 ppmv, the oxidizer consistently met the requirement for a destruction efficiency of at least 95%. In addition, during December 1992, January 1993, and February 1993, when the monthly average inlet concentrations were greater than 100,000 ppmv, the destruction efficiency was at least 98%.

Performance Data Completeness

Analytical data are available for the following: 1) the concentrations of contaminants in the surface impoundment prior to treatment; 2) the concentrations of contaminants in the soil stockpile after treatment was completed; 3) the quantity of total and specific VOCs recovered during 12 weeks of system operation; 4) the destruction efficiency for the thermal oxidizer; and 5) air emission results for inside the operations building, around the building perimeter, and at off-site locations.

No data are available to characterize the concentrations of contaminants in the soil stockpile just prior to system operation, or to compare with concentrations after treatment was completed.

Performance Data Quality

Quality assurance/quality control (QA/QC) activities for this application included use of standard EPA protocols for sampling, including chain-of-custody procedures for sample transport, use of standard analytical methods such as SW-846 Methods 8260 and 1311 for TCLP analysis of volatiles, Methods 6010 and 1311 for TCLP analysis of metals (except mercury), Methods 7470 and 1311 for TCLP analysis of mercury, and use of matrix spike, matrix spike duplicate, and blank samples. Limited exceptions to protocol were noted by the analytical laboratory for some QA/QC activities. For example, for 3 of the 14 soil stockpile grid samples (AB-12,11, CD-12,11, and EF-12,11), the TCE and toluene matrix spike recoveries were not able to be determined by the analytical laboratory because of co-eluting interferences. [2] These exceptions are not believed to substantially impact the results for this application.

TREATMENT SYSTEM COST

Procurement Process

EPA was supported in the remediation at the Basket Creek Surface Impoundment site by OHM under a Response Engineering and Analytical Contract (REAC), and by Roy F. Weston under a Technical Assistance Team (TAT) contract and a REAC. OHM supported EPA in system design, construction, and operation, and used several subcontractors for these efforts. Under the TAT contract, Weston was tasked to perform soil sampling (prior to treatment) and air monitoring during treatment. Under the REAC contract, Weston was tasked to perform the thermal oxidizer trial burn. Both OHM and Weston summarized results from the application. [2,4]

Subcontracts for equipment purchases and leases were bid competitively in this application. [13]

Treatment System Cost [1, 2, 12]

EPA reported total costs of approximately $2.2 million dollars for OHM and Weston during this application, as shown in Table 10. Approximately 90% of the total costs were attributed to OHM's activities. Table 10 shows the specific activities reported by EPA for OHM's and Weston's costs. No additional information is available on the specific activities included under each item (e.g., OHM's "other cost" of $1 million).

In order to standardize reporting of costs across projects, the total project cost was categorized according to the format for an interagency Work Breakdown Structure (WBS). The WBS specifies 9 before-treatment cost elements, 5 after-treatment cost elements, and 12 cost elements that provide a detailed breakdown of costs for activities directly associated with treatment.

Following the WBS, the OSC for the Basket Creek site categorized the total project cost into costs for before-treatment activities, shown in Table 11, costs directly attributed to treatment activities, shown in Table 12, and costs for after-treatment activities, shown in Table 13.

These costs were categorized using best professional judgement and experience with the application, as detailed invoices or other quantitative data were not available for this report. As such, the individual cost elements are estimated values based on an actual total project cost.

In categorizing the costs for this application according to the WBS, the OSC identified specific cost elements within the WBS and allocated a percentage of the total cost to each item. Tables 11, 12, and 13 show the cost elements identified by the OSC exactly as they appear in the WBS, and the specific activities identified by the OSC within each cost element. For example, under "site work" in Table 11, the OSC identified costs for excavation and soil preparation.

As shown in Table 11, approximately $1,300,000 were expended in this application for before-treatment activities, such as monitoring, sampling, testing, and analysis, site work, and air pollution/gas collection and control. Table 12 shows $660,000 expended for activities directly attributed to treatment, consisting of short-term operation (up to 3 years) and cost of ownership.

TREATMENT SYSTEM COST (CONT.)

Treatment System Cost (cont.) [1, 2, 12]

Table 13 shows $220,000 expended for after-treatment activities including disposal of residuals, site restoration, and demobilization.

Table 10. Total Costs Reported by EPA [2]

Activity	Actual Cost ($)
OHM	
Personnel	797,246.65
Equipment	67,809.90
Analytical	40,471.54
Transportation and Disposal	122,472.34
Other Cost	1,011,333.80
TOTAL OHM COST	2,039,334.23*
Weston	
Labor	98,736.06
Travel	136.38
Other Direct Costs	27,691.78
Project Administration	101,498.39
TOTAL WESTON COST	228,062.61**
TOTAL PROJECT COST	2,267,396.80

*These costs are totalled from four delivery orders (4003-F4-005, 4001-F4-025, 4001-F4-027, and 4001-F4-038), and are current as of August 1993.

**These costs are the actual direct and indirect cost incurred on this project from October 1990 through October 1994, and are current as of August 1993.

Table 11. Before-Treatment Costs Shown Using WBS* [1, 12]

Cost Element	Estimated Cost ($)
Monitoring, Sampling, Testing, and Analysis - Sampling, Analytical, Miscellaneous	260,000
Site Work - Excavation and Soil Preparation (Screening)	390,000
Air Pollution/Gas Collection and Control - Enclosure, Air Handling System, and Part of the Incinerator	650,000
Total	1,300,000

TREATMENT SYSTEM COST (CONT.)

Treatment System Cost (cont.) [1, 2, 12]

Table 12. Treatment Costs Shown Using WBS* [1, 12]

Cost Element	Estimated Cost ($)
Operation (Short-Term - Up to 3 Years) - Operating Costs, Personnel	130,000
Cost of Ownership - SVE System, Part of the Incinerator	530,000
Total	660,000

Table 13. After Treatment Costs Shown Using WBS* [1, 12]

Cost Element	Estimated Cost ($)
Disposal (Commercial)	130,000
Site Restoration	22,000
Demobilization	68,000
Total	220,000

*The costs shown in Tables 11, 12, and 13 were categorized by the OSC according to the WBS using best professional judgement and experience with the application. The OSC indicated that part of the costs for the incinerator were incurred for treatment of vapors extracted by the excavation and power screening steps (before-treatment costs) and part for treatment of vapors from the soil stockpile (treatment costs).

The $660,000 in costs directly attributed to treatment activities corresponds to $413 per cubic yard of soil treated (1,600 cubic yards of soil in the surface impoundment), $275 per ton of soil treated (2,400 tons), and $9.20 per pound of VOC removed (approximately 72,000 pounds VOC removed). These unit costs reflect treatment of a relatively small quantity of soil that contained a relatively high concentration of contaminants.

Cost Data Quality

The total costs described above represent actual costs for this treatment application as reported by EPA. Limited information is available on the specific activities included within the total cost figure.

The costs categorized according to the WBS shown in Tables 11, 12, and 13 are estimated values based on information provided by the OSC for this application. The estimates are based on best professional judgement and experience with the application.

OBSERVATIONS AND LESSONS LEARNED

Cost Observations and Lessons Learned

- Approximately $2.2 million were expended in this application, including $1.3 million for before-treatment activities, $660,000 for activities directly attributed to treatment, and $220,000 for after-treatment activities, including off-site disposal of treated soil. Because this ex situ application at Basket Creek was required to be performed in an enclosure, approximately $650,000 in before-treatment costs were expended for the building (enclosure), air handling system, and treatment of building vapors in an incinerator.

- The $660,000 in costs directly attributed to treatment activities corresponds to $413 per cubic yard of soil treated (1,600 cubic yards), $275 per ton of soil treated (2,400 tons), and $9.20 per pound of VOC removed (approximately 72,000 pounds VOC removed). These unit costs reflect treatment of a relatively small quantity of soil that contained a relatively high concentration of contaminants.

- The $2.2 million expended for the treatment application at Basket Creek was less than would have been expended for off-site incineration of soil. Based on bids ranging from $2,500 to $2,800 per ton, the projected cost for off-site incineration of 2,400 tons of soil would have been $6 to 6.7 million.

Performance Observations and Lessons Learned

- The soil stockpile analytical data indicates that the soil treatment targets were met for all 14 sampling grids after 6 months of treatment.

- In the 14 sampling grids, the TCLP results for TCE were consistently less than 0.1 mg/L, for PCE less than 0.3 mg/L, for benzene less than 0.03 mg/L, for MEK less than 2.0 mg/L, and for lead less than 2.0 mg/L. The TCLP results for mercury were all less than the reported detection limit. Total HOCs ranged from 0.055 to 20.3 mg/kg, and total VOCs from 0.142 to 1,570.7 mg/kg.

- The analytical data show that there were variations in concentrations among the 14 grid samples. For example, the total VOC data show a range over four orders of magnitude in the 14 grid samples, from 0.142 to 1,570.7 mg/kg.

- A total of 72,083.8 pounds of total VOCs were recovered in this application. This total includes VOCs recovered from the soil stockpile (75-80%) and the excavation and screening emissions (20-25%).

- The quantity of VOCs recovered varied over the course of the application. During the first six and latter three weeks of the application, total VOC recoveries averaged 4,400 lbs/week. However, during weeks 7, 8, and 9, total VOC recoveries averaged 11,000 lbs/week, approximately 2.5 times greater. According to the OSC, this was likely due to variations in VOC concentrations in the soils in the surface impoundment.

OBSERVATIONS AND LESSONS LEARNED (CONT.)

Performance Observations and Lessons Learned (cont.)

- Toluene was the largest quantity VOC recovered during this application, accounting for approximately 80% of the total VOCs recovered. MIBK accounted for approximately 11% of the recovered VOC, with the remainder consisting of TCE, PCE, benzene, ethylbenzene, xylenes, MEK, and chlorobenzene. Toluene and MIBK were also the contaminants measured in the highest concentrations in soil samples collected from the impoundment prior to the remediation.

- The analytical data show that the thermal oxidizer consistently achieved a destruction efficiency of at least 95% over 12 weeks of system operation. In addition, during December 1992, January 1993, and February 1993, when the monthly average inlet concentrations were greater than 100,000 ppmv, the destruction efficiency was at least 98%.

- Air emission results show elevated levels of VOCs inside the operations building; however, the concentration never exceeded 10% of the LEL or 500 ppm total hydrocarbons in the air, and work did not have to be stopped because of elevated levels in the building. In addition, no VOCs were detected during hourly air monitoring surveys around the perimeter of the operations building or in off-site high volume air samples.

- A comparison of data from soil samples in the impoundment prior to excavation and the soil stockpile after treatment show that the TCLP concentrations for TCE and MEK in the 14 sampling grids after treatment (TCE less than 0.1 mg/L; MEK less than 2.0 mg/L) were less than the TCLP concentrations in the pre-excavation samples. For example, in May 1991, TCE was measured as less than 11.0 mg/L, and MEK as 280 mg/L. However, it should be noted that there are no samples of untreated soil from the stockpile.

- While SVE was not expected to reduce the concentrations of lead and mercury in the soil, a comparison of data from soil samples in the surface impoundments prior to excavation and the soil stockpile after treatment show the TCLP concentrations for lead in the 14 sampling grids after treatment were less than the concentrations in the pre-excavation samples (for example, 32.6 mg/L before-treatment in May 1991, 0.25-1.9 mg/L after-treatment). However, as for the VOCs, there are no samples of untreated soil from the stockpile. As such, the OSC believed the reduction is due to the pre-excavation samples not being representative of the area of contamination as a whole, rather than as a result of treatment.

OBSERVATIONS AND LESSONS LEARNED (CONT.)

Other Observations and Lessons Learned

- EPA selected ex situ SVE for this application. In situ SVE was ruled out because of the low permeability of the contaminated soil. Low temperature thermal desorption was eliminated because the soil was too highly contaminated, and, during a treatability study, a soil sample ignited. Incineration was ruled out because it was estimated to be approximately three times more expensive than the selected remedy.

- The OSC made the following observations about this application:

  - The excavation and power screening activities associated with the ex situ SVE application greatly increased the soil permeability. The power screening shredded soil clumps and broke up the soil. Soil permeability was not, however, measured after the power screening.

  - There were limitations associated with the materials of construction used for the soil stockpile. While building the soil stockpile, there was trouble maintaining the spacing of the horizontal wells because they were made out of PVC and would bend under the weight of the soil. The OSC indicated that carbon steel pipes would have been more rigid, but would have cost more.

  - It was important to oversize the air handling system for venting the building. The oversized system helped to prevent safety problems due to an explosive atmosphere in the building and in the ductwork. For example, during excavation of hot spots, VOC concentrations in the ductwork of the building vent system were greater than 1,000 ppm.

  - Excavation within an enclosure takes much longer than outside due to the space constraints. The OSC indicated that the excavation at Basket Creek would have been completed within a few days. However, excavation within the enclosure at Basket Creek took 3 months.

REFERENCES

1. "Controlling Fugitive Emissions from Excavation of Contaminated Soil: A Case Study;" R. Donald Rigger, On-Scene Coordinator, U.S. Environmental Protection Agency Region 4, 345 Courtland Street, N.E., Atlanta, Georgia, 30365; undated.

2. Formal Report. Basket Creek Surface Impoundment Site. Douglasville, Douglas County, Georgia. Roy F. Weston, Incorporated. April 1, 1993.

3. Action Memorandum. Request for a Removal Action Ceiling Increase and Exemption from the $2 Million Limit at the Basket Creek Surface Impoundment Site in Douglasville, Douglas County, Georgia. April 11, 1991.

REFERENCES (CONT.)

4. Final Report. Basket Creek Impoundment Site. Douglasville, GA. Roy F. Weston, Inc. December, 1991.

5. Vapor Recovery/Treatment Progress Report. Basket Creek Surface Impoundment. Douglasville, Douglas County, GA. OHM Remediation Services Corp., Norcross, Georgia.

6. Final Report. Stack Sampling and Air Quality Dispersion Modeling. Basket Creek site. Douglasville, Georgia. Roy F. Weston, Inc. March 1993.

7. Basket Creek Impoundment Site. Douglas County, Georgia. Thermal Oxidizer Source Emission Test Report. Volume I. Roy F. Weston, Inc. March 1993.

8. Site Specific Test Plan. Emission Testing on Thermal Oxidizer Exhaust Stack. Basket Creek Impoundment Site. Douglas County, Georgia. August 1992.

9. Basket Creek Drum Disposal Site. Douglasville, Douglas County, Georgia. Site Investigation. May 2, 1990.

10. Letter from Don Rigger, OSC, to Mr. Nolan. January 15, 1993.

11. Meeting Notes. Meeting on 9/26/95 between Tim McLaughlin, Radian Corporation, and Don Rigger, OSC.

12. Meeting Notes. Meeting on 9/27/95 between Tim McLaughlin, Radian Corporation, and Don Rigger, OSC.

13. Comments from Don Rigger, OSC, provided to L. Fiedler, EPA, March 8, 1996.

14. OHM Corporation brochure, "Ex Situ Soil Vapor Extraction and VOC Treatment Project, USEPA Basket Creek Surface Impoundment, Douglasville, Georgia," not dated.

Analysis Preparation

This case study was prepared for the U.S. Environmental Protection Agency's Office of Solid Waste and Emergency Response, Technology Innovation Office. Assistance was provided by Radian Corporation under EPA Contract No. 68-W3-0001 and U.S. Army Corps of Engineers Contract No. DACA45-96-D-0016.

Soil Vapor Extraction at the Sacramento Army Depot Superfund Site, Burn Pits Operable Unit, Sacramento, California

Case Study Abstract

Soil Vapor Extraction at the Sacramento Army Depot Superfund Site, Burn Pits Operable Unit, Sacramento, California

Site Name:
Sacramento Army Depot Superfund Site, Burn Pits Operable Unit

Location:
Sacramento, California

Contaminants:
Organic Compounds; Volatiles-Halogenated
- Trichloroethene (TCE), tetrachloroethene (PCE), and 1,2-dichloroethene (DCE) each less than 0.01 mg/kg

Period of Operation:
May 1994 - September 1995

Cleanup Type:
Full-scale cleanup

Vendor:
Ashok Gopinath
OHM Remediation Services Corp.
5731 W. Las Positas Blvd.
Pleasanton, CA 94588
(510) 227-1100

SIC Code:
3471: Electroplating, Plating, Polishing, Anodizing, and Coloring
3479: Coating, Engraving, and Allied Services, Not Elsewhere Classified

Technology:
Soil Vapor Extraction
- System was OHM's patented Fluid Injection-Vacuum Extraction (FIVE) technology
- Included 10 shallow extraction/injection wells, 12 deep wells, 1 horizontal well, HEPA filters, and 2 trains of GAC units
- Shallow wells screened 10-25 ft below ground surface (bgs)
- Deep wells screened 50-80 and 17-47 ft bgs
- Some wells operated as injection wells and others as extraction wells

Cleanup Authority:
CERCLA
- Record of Decision Date 2/26/93
- U.S. Army Lead

Point of Contact:
Marlin Mezquita
USEPA Region 9
75 Hawthorne Street
San Francisco, CA 94105
(415) 744-2393

Waste Source:
Disposal Pit; Incineration Residuals Handling

Purpose/Significance of Application:
Full-scale application combining fluid injection and vacuum extraction wells in a complex subsurface environment.

Type/Quantity of Media Treated:
Soil
- 247,900 cubic yards
- Subsurface consists of interbedded sands, silts, and clays, with some coarse gravels
- Six facies identified during site investigation

Regulatory Requirements/Cleanup Goals:
- Soil cleanup standards for TCE, PCE, and DCE of 0.005 mg/kg
- Air emission limits identified for TCE, PCE, and DCE

Results:
- Soil cleanup goals met within 14 months of system operation
- Concentrations in treated soil were: TCE - 0.0021 mg/kg; PCE - 0.0013 mg/kg; and DCE - 0.0027 mg/kg
- Approximately 138 lbs of TCE, PCE, and DCE extracted

Cost Factors:
- Actual costs of $865,873 included $195,000 for before-treatment activities (drilling, soil gas survey, confirmatory borings, and chemical testing), and $670,500 for activities directly attributed to treatment (design, mobilization, construction, start-up/testing/permitting, SVE operations and maintenance, and demobilization)
- The unit cost for activities directly attributed to treatment was $2.70/yd^3 of soil treated, and $4,858/lb of VOC removed

Soil Vapor Extraction at the Sacramento Army Depot Superfund Site, Burn Pits Operable Unit, Sacramento, California (Continued)

Description:
The Burn Pits Operable Unit at SAAD was the location of two rectangular trenches constructed in the late 1950s and used intermittently as incineration pits until 1966. Materials reportedly buried and/or burned in the pits included plating shop wastes, oil and grease, batteries, and construction debris. Remedial investigations conducted from 1990 to 1993 showed average soil contaminant concentrations for TCE ranging from 0.0029 to 0.0069 mg/kg, PCE from 0.0029 to 0.0079 mg/kg, and DCE from 0.0038 to 0.0055 mg/kg. In addition, the Army's basewide contractor estimated the total mass of selected contaminants in the operable unit as follows: TCE - 22.3 lbs; PCE - 7.1 lbs; and DCE - 39.3 lbs.

A Record of Decision (ROD) addressing the Burn Pits O.U. was signed in March 1993. OHM's patented fluid injection/vapor extraction (FIVE) system was used to remediate the Burn Pits O.U. In the FIVE technology, pressurized air is injected into vadose zone soils to produce relatively larger subsurface pressure gradients and higher flow rates of extracted vapors than would be achieved solely with using vapor extraction technology. The vendor stated that this system "enhanced subsurface volatilization and shortened the period of remediation," however, no data were provided to support this statement. The FIVE system used at the SAAD Burn Pits consisted of 10 shallow extraction/injection wells, 12 deep extraction/injection wells, 1 horizontal extraction/injection well, air injection piping, vapor monitoring wells, liquid/vapor separators, high efficiency particulate filters, vapor phase granular activated carbon, and positive displacement blowers. The wells were screened up to 80 feet below ground surface.

Confirmatory soil borings showed that the average concentrations for each of the three target contaminants was less than the cleanup standards set in the ROD. TCE was reduced to an average concentration of 0.0021 mg/kg, PCE to 0.0013 mg/kg, and DCE to 0.0027 mg/kg. Approximately 138 lbs of TCE, PCE, and DCE were extracted during this application, or roughly two times as much VOCs as originally estimated to be present at the operable unit. Possible reasons for the discrepancy between the original estimate and the actual amount recovered identified by the treatment vendor include inaccuracies in the original estimate and for 1,2-DCE, a reductive dehalogenation mechanism that occurred in situ. According to the vendor, the use of the FIVE technology "enhanced subsurface volatilization and shortened the period of remediation"; however, no additional information comparing this technology to other SVE systems was provided.

COST AND PERFORMANCE REPORT

EXECUTIVE SUMMARY

This report presents cost and performance data for a soil vapor extraction (SVE) system at the Burn Pits Operable Unit, Sacramento Army Depot (SAAD) Superfund site in Sacramento California. The SVE system was used at the Burn Pits Operable Unit to treat soil contaminated with halogenated volatile organic compounds (VOCs), specifically trichloroethene (TCE), tetrachloroethene (PCE), and 1,2-dichloroethene (DCE).

The Burn Pits Operable Unit at SAAD was the location of two rectangular trenches constructed in the late 1950s and used intermittently as incineration pits until 1966. Materials reportedly buried and/or burned in the pits included plating shop wastes, oil and grease, batteries, and construction debris. Remedial investigations conducted from 1990 to 1993 showed average soil contaminant concentrations for TCE ranging from 0.0029 to 0.0069 mg/kg, PCE from 0.0029 to 0.0079 mg/kg, and DCE from 0.0038 to 0.0055 mg/kg. In addition, the Army's basewide contractor estimated the total mass of selected contaminants in the operable unit as follows: TCE - 22.3 pounds (lbs); PCE - 7.1 lbs; and DCE - 39.3 lbs.

A Record of Decision (ROD) addressing the Burn Pits Operable Unit was signed in March 1993 and specified soil cleanup standards of 0.005 mg/kg for each of the three VOCs identified above. Although not shown in the ROD, the treatment vendor reported the following air emission rate limits for this application: TCE - 0.0043 lbs/hr; PCE - 0.003 lbs/hr; and 1,2-DCE - 0.003 lbs/hr.

The SVE system used was a patented fluid injection/vapor extraction (FIVE) system. In the FIVE technology, pressurized air is injected into vadose zone soils to produce relatively larger subsurface pressure gradients and higher flow rates of extracted vapors than would be achieved solely with using vapor extraction technology. The vendor stated that this system "enhanced subsurface volatilization and shortened the period of remediation," however, no data were provided to support this statement. The FIVE system used at the SAAD Burn Pits consisted of 10 shallow extraction/injection wells, 12 deep extraction/injection wells, 1 horizontal extraction/injection well, air injection piping, vapor monitoring wells, liquid/vapor separators, high efficiency particulate filters, vapor phase granular activated carbon, and positive displacement blowers. The wells were screened up to 80 feet below ground surface.

The FIVE system was operated from May 1994 to January 1995, and again from March 1995 to September 1995, for a total of 347 days of run time. Confirmatory soil borings collected in September 1995 showed that the average concentrations for each of the three target contaminants was less than the cleanup standards set in the ROD. TCE was reduced to an average concentration of 0.0021 mg/kg, PCE to 0.0013 mg/kg, and DCE to 0.0027 mg/kg. Analytical data collected in this application showed that the rate of VOC removal decreased over the course of the remediation. For example, the VOC extraction rate decreased from an average of 4 lbs/day over the first 20 days of system run time to less than 1 lb/day after 40 days of system run time. Approximately 138 lbs of VOCs were extracted during this application, or roughly two times as much VOCs as originally estimated to be present at the operable unit. The vendor

EXECUTIVE SUMMARY (CONT.)

indicated that a possible reason for this result is an inaccuracy in the original estimate for the operable unit.

The total actual costs for this application were approximately $865,873. Of this total, approximately $195,000 were expended in before-treatment costs for drilling, soil gas survey, confirmatory boring, and chemical testing, and approximately $670,500 were expended for activities directly attributed to treatment, such as design, mobilization, construction, start-up/testing/permitting, SVE operations and maintenance, and demobilization. The $670,500 in costs directly attributed to treatment corresponds to $2.70 per cubic yard of soil treated (247,900 cubic yards) and $4,858 per pound of target VOC extracted (138 pounds of TCE, PCE, and DCE). These unit costs show that this application treated a relatively large volume of soil contaminated with relatively small concentrations of target VOCs.

SITE INFORMATION

Identifying Information:

Sacramento Army Depot
Sacramento, California
Operable Unit: Burn Pits
CERCLIS # CA0210020780
ROD Date: February 26, 1993

Treatment Application:

Type of Action: Remedial
Treatability Study Associated with Application? No
EPA SITE Program Test Associated with Application? No
Period of Operation: May 1994 - September 1995
Quantity of Material Treated During Application: 247,900 cubic yards of soil. The burn pits contain approximately 16,900 cubic yards of contaminated soil, and the surrounding area contains approximately 231,000 cubic yards of contaminated soil. [3] This quantity is based on an area of 78,750 square feet and a depth of 85 feet. [12]

Background [1, 2]

Historical Activity that Contributed to Contamination at the Site: Metal-plating and painting operations

Corresponding SIC Code(s):
3471: Electroplating, Plating, Polishing, Anodizing, and Coloring
3479: Coating, Engraving, and Allied Services, Not Elsewhere Classified

Waste Management Practice that Contributed to Contamination: Disposal Pit; Incineration Residuals Handling

Site History: The Sacramento Army Depot (SAAD) is a 485-acre U.S. Army support facility, located in Sacramento, California, as shown on Figure 1. Current and historical operations conducted at the facility include electro-optics equipment repair, emergency manufacturing of parts, shelter repair, metal plating and treatment, and painting. In conjunction with these operations, the Army maintained unlined oxidation lagoons and burn pits, a battery disposal area, areas designated for mixing pesticides, and a firefighter training area.

In 1978 and 1979, the U.S. Army Toxic and Hazardous Materials Agency (USATHMA) identified several areas at SAAD, based on historical data, where the use, storage, treatment, and disposal of toxic substances may have contributed to contamination of soil and/or groundwater. In 1981, the Army and the California Central Valley Regional Water Quality Control Board (CVRWQCB)

SITE INFORMATION (CONT.)

Background (cont.)

conducted investigations of soil and groundwater in the areas identified by USATHMA. The groundwater under the southwest corner of SAAD was determined to be contaminated with volatile organic compounds (VOCs) with the burn pits suspected as the main source of groundwater contamination.

Two burn pits were constructed at SAAD in the late 1950s, and served intermittently as incineration pits until 1966. The two burn pits are rectangular trenches, referred to as the "North Burn Pits" and "South Burn Pits." Each burn pit is about 30 feet wide, 330 to 345 feet long, and approximately 16 to 19 feet deep. Materials that were reportedly buried and/or burned in the burn pits include plating shop wastes, oil and grease, batteries, and uncontaminated construction debris. As of 1993, the burn pits were filled to the ground surface with soil and debris, including scrap metal, concrete, wood, and glass.

The Burn Pits Operable Unit occupies approximately 2 acres in the southwest portion of SAAD, and consists of the North and South Burn Pits and surrounding area. The operable unit is approximately 85 feet deep, extending through

Figure 1. Site Location

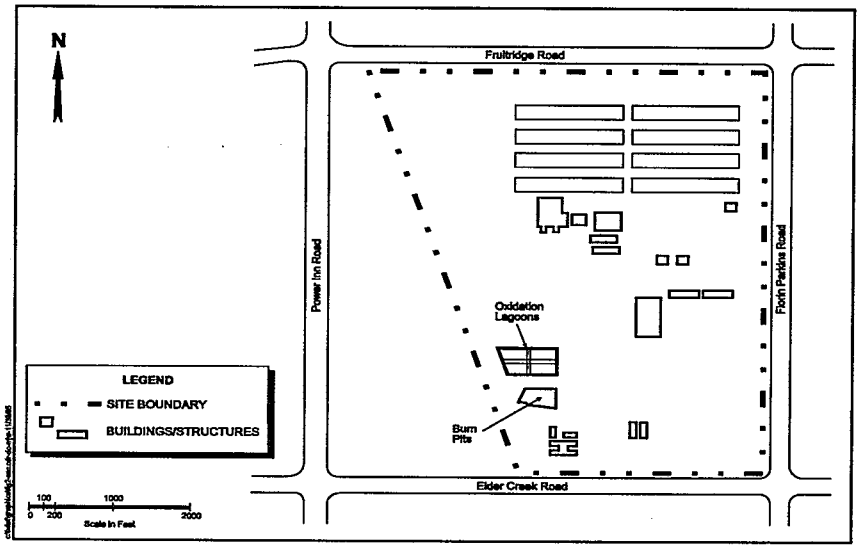

Figure 2. Location of Burn Pits at SAAD [1]

SITE INFORMATION (CONT.)

Background (cont.)

the vadose zone to the water table. A site map of the SAAD facility showing the location of the burn pits operable unit is shown on Figure 2.

The 1981 investigations also identified six other potential areas of contamination: the Tank 2 area, the oxidation lagoons, the Building 320 leach field, the pesticide mix area, the firefighter training area, and the battery disposal well. Operable units were defined for each of these areas of contamination. A remedial investigation identified several volatile and non-volatile organic and metal constituents in the soil at SAAD. As a result of these investigations, SAAD was placed on the National Priorities List (NPL), effective August 21, 1987.

Regulatory Context: In December 1988, the Army, EPA, and the State of California signed a Federal Facility Agreement (FFA) under CERCLA Section 120, to address the entire facility, including the contaminated groundwater and the following seven areas of suspected contamination on the SAAD facility:

- Burn Pits;
- Tank 2;
- Oxidation Lagoons;
- Building 320 Leach Field;
- Pesticide Mix Area;
- Firefighter Training Area; and
- Battery Disposal Well.

The FFA also required a RCRA Facility Assessment to identify other solid waste management units that needed further characterization and cleanup. Under the FFA, the U.S. Army was the lead agency responsible for implementing the environmental response activities at SAAD.

A Record of Decision (ROD) for the Burn Pits Operable Unit was signed by the Army, California EPA, and the U.S. EPA in March 1993. The ROD required:

- Soil vapor extraction (SVE) of all soils in the Burn Pits Operable Unit;
- Excavation of soils which contained non-volatile contaminants;
- Stabilization of the excavated soils;
- Backfill of the excavation with stabilized soil; and
- Implementation of institutional controls in the form of a deed restriction and notices, to prohibit future disturbances of the stabilized soil mass.

SITE INFORMATION (CONT.)

Background (cont.)

The ROD identified soil cleanup standards of 0.005 mg/kg for three VOCs: trichloroethene (TCE), tetrachloroethene (PCE), and 1,2-dichloroethene (1,2-DCE).

For non-volatile contaminants, the ROD required soils to be solidified so that the waste extract did not exceed the following levels: arsenic, 5 mg/L; cadmium, 1 mg/L; chromium, 5 mg/L; and lead, 5 mg/L.

Remedy Selection: Six alternatives were considered for remediation of the burn pits operable unit. The remedy described above was selected based on a comparative analysis of the six alternatives, in terms of short- and long-term effectiveness, permanence, reduction of toxicity, mobility, and volume, implementability, and cost.

Site Logistics/Contacts

Site Management: U.S. Army-lead
Oversight: EPA

Remedial Project Manager:
Marlin Mezquita
U.S. EPA Region 9
75 Hawthorne Street
San Francisco, CA 94105
(415) 744-2393

U.S. Army Project Manager:
Dan Oburn (primary contact for this application)
U.S. ACE, Sacramento District
1325 J Street
Sacramento, CA 95814-2922
(916) 557-7936

Treatment Vendor:
Ashok Gopinath
OHM Remediation Services Corp.
5731 W. Las Positas Blvd.
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MATRIX DESCRIPTION

Matrix Identification

Type of Matrix Processed Through the Treatment System: Soil (in situ)

Contaminant Characterization

Primary Contaminant Groups: Organic Compounds; Volatiles-Halogenated

The Army divided the Burn Pits Operable Unit into five "units" to evaluate health risks and develop remediation plans,. The average concentrations of selected organics and metals in the five units were quantified during a 1990-1993 remedial investigation (RI), as shown in Table 1.

In addition, as part of the remediation planning process, the mass of the three VOCs present in the operable unit was estimated as follows (5):

- trichloroethene (TCE) - 22.3 lbs;
- tetrachloroethene (PCE) - 7.1 lbs; and
- 1,2-dichloroethene (1,2-DCE) - 39.3 lbs.

Table 1. Summary of Average Soil Concentrations of Organics and Metals Measured During 1990-1993 Remedial Investigation [1]

Organics	Average Concentrations* (mg/kg)	Metals	Average Concentrations* (mg/kg)
Trichloroethene	0.0029 - 0.0069	Antimony	6.0
Tetrachloroethene	0.0029 - 0.0079	Arsenic	6.0
1,2-Dichloroethene	0.0038 - 0.0055	Boron	6.5
Ethylbenzene	0.003 - 0.0061	Cadmium	4.9
Toluene	0.0029 - 0.0092	Chromium (total)	51.9
Xylene	0.0029 - 0.0072	Copper	68.4
Di-n-butyl phthalate	0.1721 - 0.2147	Lead	64.5
Arochlor 1254	0.14	Manganese	380
Arochlor 1260	0.06	Mercury	0.1
2,3,7,8-TCDD equivalent	0.000098	Molybdenum	1.1
		Silver	0.23
		Zinc	158.6

*Average concentrations for volatile organics are shown in Table 1 as a range of concentrations quantified in the five units of the Burn Pits Operable Unit. For arochlors 1254 and 1260, 2,3,7,8-TCDD, and all metals shown, an average concentration was identified only for one of the five units. For these constituents, only a single value is shown in Table 1.

MATRIX DESCRIPTION (CONT.)

Contaminant Characterization (cont.)

At an unspecified date prior to remediation, OHM collected "baseline" soil samples. These samples were collected from a depth of 80 feet bgs. Soil samples were collected in brass sleeves placed inside a split-spoon sampler and sent to an off-site laboratory certified by the state of California. The soil samples were analyzed by USEPA Method 8240 for volatile organic compounds. In the baseline soil samples, the concentrations of TCE, PCE, and 1,2-DCE were all below the analytical detection limits (0.001 mg/kg for these samples), with one exception. In well SVW13, TCE was detected at a concentration of 0.012 mg/kg. The baseline samples contained lower concentrations of VOCs in soil than measured during the RI (see Table 1).

Matrix Characteristics Affecting Treatment Cost or Performance

The major matrix characteristics affecting cost or performance for this technology and the values measured for each are shown in Table 2.

Table 2. Matrix Characteristics [3, 12]

Parameter	Value	Measurement Method
Soil Classification	See discussion under site geology	
Clay Content and/or Particle Size Distribution	See discussion under site geology	
Moisture Content	Not measured but vendor estimated moisture content would be between 5-15%	N/A
Air Permeability	Not measured	N/A
Porosity	Not measured	N/A
Total Organic Carbon	Not measured	N/A
Nonaqueous Phase Liquids	Not present	Not reported

N/A - Not applicable because value not measured.

Site Geology/Stratigraphy

SAAD is located in the Great Valley of California, a broad asymmetric trough filled with a thick assemblage of flat-lying marine and non-marine sediments. The most recent formations deposited in the Great Valley are non-marine sediments derived from the Sierra Nevada foothills and mountains on the west side of the valley and from the Coast Ranges on the east side of the valley. [1]

MATRIX DESCRIPTION (CONT.)

Site Geology/Stratigraphy (cont.)

The upper 250 feet of sediments under SAAD consist of interbedded sands, silts, and clays, with some coarse gravels underlying the north side of the facility at an approximate depth of 40 feet. Older buried stream channels exist at various locations and depths in the area. These streams have deposited materials ranging in size from gravel to clay. Multiple discontinuous hardpans (cemented clays), representing ancient soil horizons, exist throughout the site. [1]

As part of this remediation, the treatment vendor performed extensive investigations into site geology, including a "facies analysis" to collect data concerning the sedimentary structures and scales of heterogeneity in strata within the vadose zone. The results of the facies analysis were used in the design of the SVE system, particularly in the locations and depths of the extraction wells. Facies were defined by grain size classified according to the Unified Soil Classification System (USCS), color classified according to the Munsell chart, moisture, physical properties, sorting, roundness, composition, contacts, and sedimentary structures. The facies analysis also incorporated standard practices for description and identification of soils as described in ASTM Method D2488-90. [3]

Six facies were identified during this investigation. The most common facies were artificial fill (AF), sandy silt (ML), silty sand (SM), and sand (SP). The least common facies were clay (CL) and clayey sand (SC). Table 3 shows the range of percentages of facies measured in extraction well borings. [3] According to the vendor, the subsurface at the Burn Pits consisted mainly of debris till 20 feet and then silty sand to sandy silt to sand. [12]

Table 3. Range of Percentages of Facies in Extraction Well Borings [3]

Facie	Range of Percentages of Facies in Extraction Wells (%)
Sandy Silt (ML)	3 - 66
Silty Sand (SM) - weak to moderate cementation - moderate to strong cementation	 10 - 53 3 - 52
Sand (SP)	2 - 55
Clay (CL)	2 - 18

The California Department of Water Resources has divided the water-bearing sediments in the soil at SAAD into two hydraulically isolated sections: the superjacent (upper) series, at depths of about 80 to 250 feet beneath the site; and, the subjacent (lower) series, at depths below about 250 feet. [1]

TREATMENT SYSTEM DESCRIPTION

Primary Treatment Technology Type: Soil Vapor Extraction

Supplemental Treatment Technology Type: Post-Treatment (Air) - Carbon Adsorption

Soil Vapor Extraction System Description and Operation

The SVE system used at the Burn Pits Operable Unit was OHM's patented fluid injection-vacuum extraction (FIVE) technology. The FIVE technology consists of injection of pressurized air into vadose zone soils, and extraction of vapors from vadose zone soils. This approach is intended to produce relatively larger subsurface pressure gradients, and higher flow rates of extracted vapors, than would be achieved solely with using vapor extraction technology. [6]

System Design [5, 6, 12]

The SVE system used at the Burn Pits Operable Unit consisted of 10 shallow extraction/injection wells, 12 deep (nested) extraction/injection wells, 1 horizontal extraction/injection well, air injection piping, 6 "SEAMIST" monitoring wells (in-ground vapor measurement wells), liquid/vapor separators, high efficiency particulate (HEPA) filters, vapor phase granular activated carbon, and positive displacement blowers. Figure 3 shows the locations of the extraction/injection and monitoring wells relative to the North and South Burn Pits, and Figure 4 shows the SVE system.

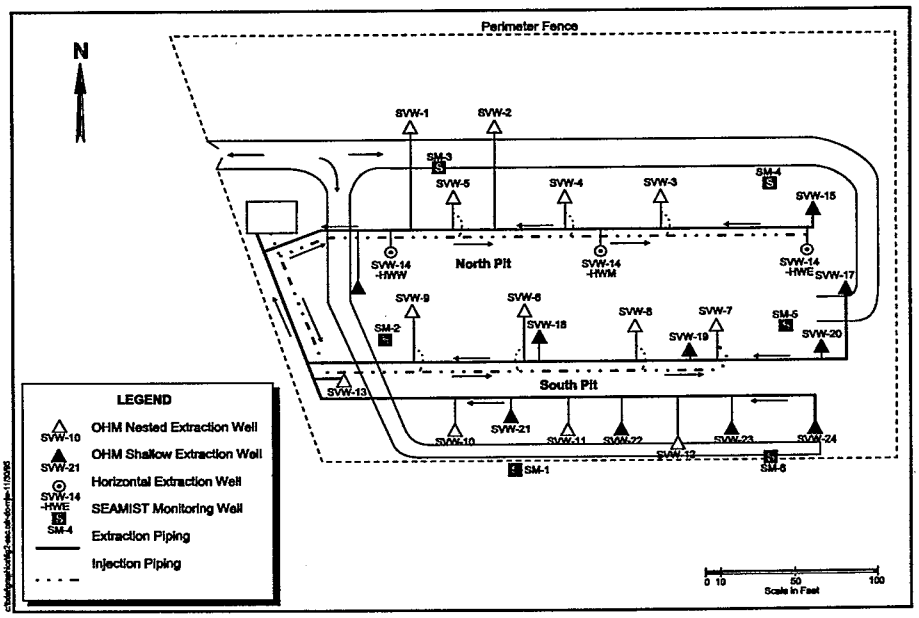

Figure 3. Well Locations at Burn Pits Operable Unit [4]

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

The shallow wells contained a 15-foot well screen extending from 10 to 25 feet below ground surface (bgs). The screen interval was located in sediments adjacent to and below the bottom of the artificial fill placed in the burn pits. In addition, a distinct well-cemented paleosol was present at the site at a depth of approximately 20 to 25 feet bgs. The shallow wells were located at this depth because the well-cemented paleosol had lower permeability than surrounding sediments, and the downward migration of volatile and semivolatile organic compounds would be temporarily restricted at this point.

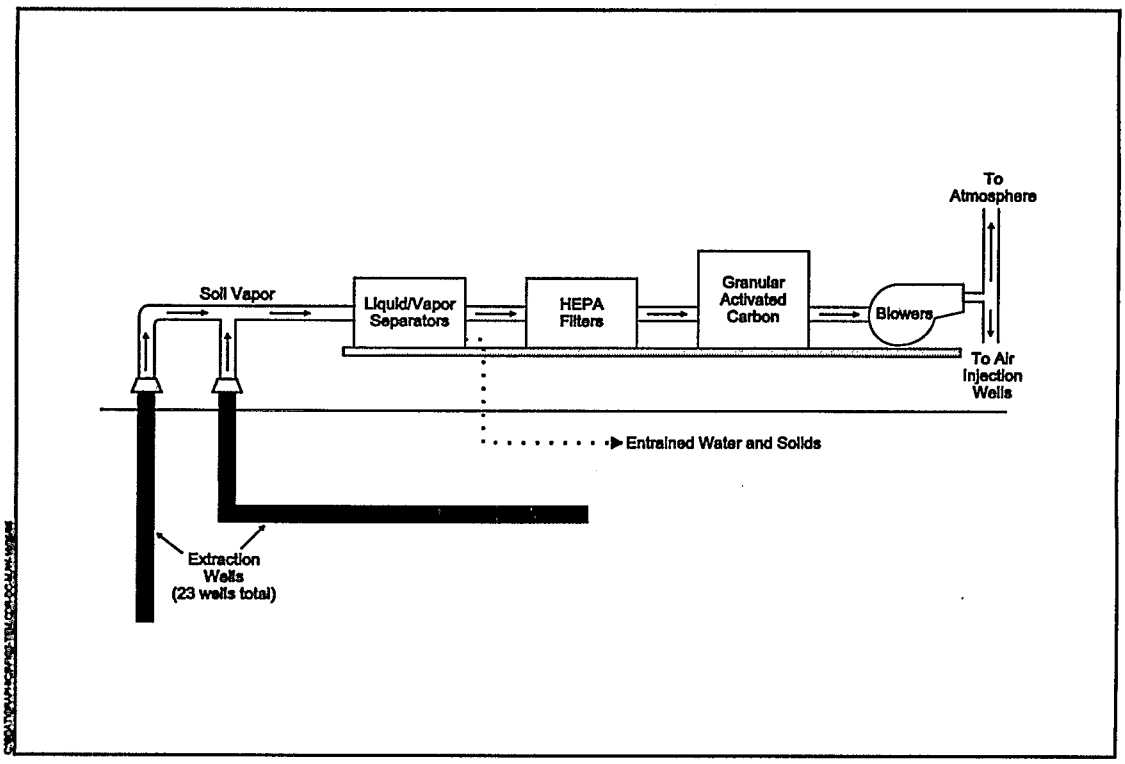

Figure 4. SVE System Schematic [Based on 2,6]

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

The deeper (nested) wells contained two screened areas in a single borehole, including 50 to 80 feet bgs, and 17 to 47 feet bgs. Two screen intervals were incorporated into the deeper well design to enhance air flow and vapor extraction throughout the 80-foot vadose zone. The two screened areas in the deeper wells were separated by a 2-foot (minimum thickness) bentonite seal. A 325-foot horizontal well was included in the SVE system design because it had been installed by a previous contractor (prior to OHM). It was not reported if this well was located in the shallow or deep zones.

As shown in Figure 4, soil vapors extracted through the vertical and horizontal wells were first treated using liquid/vapor separators. Entrained water (predominantly perched groundwater) and solids were removed from the vapor stream in the separators. Water and solids removed from the vapor stream were shipped off site to licensed disposal facilities in California. From the separators, the vapor stream passed through the HEPA filters which were designed to remove particulates larger than 0.3 microns.

The filtered vapor stream was then treated to remove VOCs using two parallel trains of vapor phase granular activated carbon adsorption units (each containing primary and secondary units). The granular activated carbon units contained a total of 8,400 pounds of carbon, and were designed to have an overall VOC removal efficiency of 99 percent. The design basis for the system assumed the following mass extraction rates:

- TCE - 0.33 lbs/hr;
- PCE - 0.5 lbs/hr; and
- 1,2-DCE - 0.23 lbs/hr.

Treated vapor was injected into the vadose zone or released to the atmosphere using two rotary, positive displacement blowers, each having a capacity of 1,000 scfm.

Injection Wells

The instrumentation and piping for each vertical and horizontal well was designed to be operated in either extraction or injection mode. Valves were installed at the well head to isolate the piping that was not in use. These valves were adjusted manually during system operation. In addition, valves of the manifold system were adjusted to allow sections of the wellfield to operate in pressure or vacuum mode or to control makeup vapor and the degree of re-injection to the vadose zone.

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

System Controls

The FIVE system was designed with both mechanical and electrical controls. The controls monitored parameters such as VOC concentration, temperature, and pressure at multiple points in the system. The system was designed to shut off if a high pressure situation was encountered in the process components.

System Operation [6, 10, 12]

Start-up Testing

During start-up testing, each individual well was developed independently to determine the maximum flow rate and vacuum that could be expected. Analytical results for vapor samples collected during start-up testing were used to predict mass extraction rates for each well. According to the vendor, during this analytical testing, the highest concentrations of the target compounds were found in the deep screen intervals of the nested wells to the north and west of the north burn pit.

Operating Modes

Subsurface flow in the vadose zone was controlled by directing vapor transport between injection (pressure mode) and extraction (vacuum mode) wells on opposite sides of the burn pits, and by controlling flow between adjacent nested wells. All peripheral wells (SVW-1, 2, 3, 4, 5, 10, 11, 12, 13, 16, 17, 20, 21, 22, 23, and 24) were operated in vacuum mode. Interior wells (SVW-6, 7, 8, 9, 18, and 19) were operated alternately in pressure and vacuum modes. Horizontal well SVW-14, near the bottom of the North Burn Pit, was primarily operated in pressure mode to drive volatile contaminants laterally to adjacent vertical wells operated in vacuum mode. In general, air was injected at 25-50% of capacity.

System Shutdown

System operation continued from May 1994 through January 1995. In July 1994, the system was shut down for a one-week period due to a carbon changeout from the granular activated carbon vessels. In addition, the system was shut down from January 18 until March 16, 1995 to assess rebound of TCE, PCE, and 1,2-DCE in soil vapor monitoring wells. The system was operated again from March through September 1995. System shutdown took place in September 1995, and confirmatory soil borings were collected at that time.

TREATMENT SYSTEM DESCRIPTION (CONT.)

Operating Parameters Affecting Treatment Cost or Performance

The major operating parameters affecting cost or performance for this technology and the values measured for each are shown in Table 4.

Table 4. Operating Parameters [12]

Parameter	Value	Measurement Method
Air Flow Rate	1,400 scfm	N/A
Operating Pressure/Vacuum	8 inches Hg	N/A

N/A - Measurement method not reported for this parameter because resulting value not expected to vary among measurement procedures.

Timeline

A timeline for this application is shown in Table 5.

Table 5. Timeline [4, 5, 12]

Start Date	End Date	Activity
August 1987	-	SAAD placed on NPL
March 1993	-	ROD signed for Burn Pits Operable Unit
January 1994	April 1994	SVE system construction and well installation
April 1994	-	Start-up testing
May 1994	January 1995	System operation
January 18, 1995	March 16, 1995	System operation shutdown
March 1995	September 1995	System operation
September 1995	-	Confirmatory soil borings
August 1995	September 1995	Demobilization

TREATMENT SYSTEM PERFORMANCE

Cleanup Goals/Standards

The ROD for the Burn Pits Operable Unit identified the following soil cleanup standards for the SVE application [1]:

- trichloroethene (TCE) - 0.005 mg/kg;
- tetrachloroethene (PCE) - 0.005 mg/kg; and
- 1,2-dichloroethene (1,2-DCE) - 0.005 mg/kg.

In addition, the following soil vapor goals (referred to as "initial soil vapor target goals") were calculated by the basewide contractor to assess remediation progress [4]:

- TCE - 1.88 μg/L;
- PCE - 3.14 μg/L; and
- 1,2-DCE - 8.11 μg/L.

OHM stated the following as an interim requirement for wellhead equilibrium vapor concentrations [6]:

- TCE - 1.7 mg/kg;
- PCE - 1.7 mg/kg; and
- 1,2-DCE - 0.7 mg/kg.

OHM reported that the following air emission rate limits were identified for this application [12]:

- TCE - 0.0043 lbs/hr (0.103 lbs/day, assuming 24 hrs/day operation);
- PCE - 0.003 lbs/hr (0.072 lbs/day, assuming 24 hrs/day operation); and
- 1,2-DCE - 0.003 lbs/hr (0.072 lbs/day, assuming 24 hrs/day operation).

Additional Information on Goals

The soil cleanup goals were developed based on a risk assessment which considered the following as the primary potential future risks to public health:

- Migration of contamination from soil to groundwater; and
- Public exposure to contamination via inhalation of dust, direct contact with, or ingestion of, contaminated soil. [1]

According to the vendor, the air emission rate limits were developed based on a risk-based analysis with a target cancer risk criterion of 1 x 10-6, with a "100 fold" margin of safety. [12]

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data

Treatment performance data for the SVE application at the Burn Pits Operable Unit consists of confirmation soil borings, soil vapor sampling (from the SEAMIST wells), mass extraction data, and extraction well vapor concentrations.

Confirmatory Soil Borings [6, 10, 11, 12]

In September 1995, OHM collected 21 confirmation soil borings from 8 locations near the burn pits, at depths ranging from 20 to 80 feet bgs. The borings were analyzed for TCE, PCE, trans-1,2-DCE, and cis-1,2-DCE. Figure 5 shows the location of the confirmation borings relative to the burn pits at SAAD, and Table 6 shows the results on a dry-weight basis for the four constituents measured in the 21 confirmation soil borings. In addition, Table 6 shows the boring number, depth, and sample identification number. As shown on Table 6, OHM calculated the "statistical mean" (average) result for each constituent in the 21 confirmation soil borings. For analytical results reported as less than the detection limit, OHM assumed a value of one-half the reported detection limit for computing the average value (e.g., for a sample reported as less than 0.002 mg/kg, OHM assumed an actual value of 0.001 mg/kg). Also as shown in Table 6, OHM calculated the average both with and without the quality control (QC) sample results. With the QC results, the average for the four constituents ranged from 0.0013 to 0.0021 mg/kg, and without the QC results the average ranged from 0.001 to 0.0016 mg/kg.

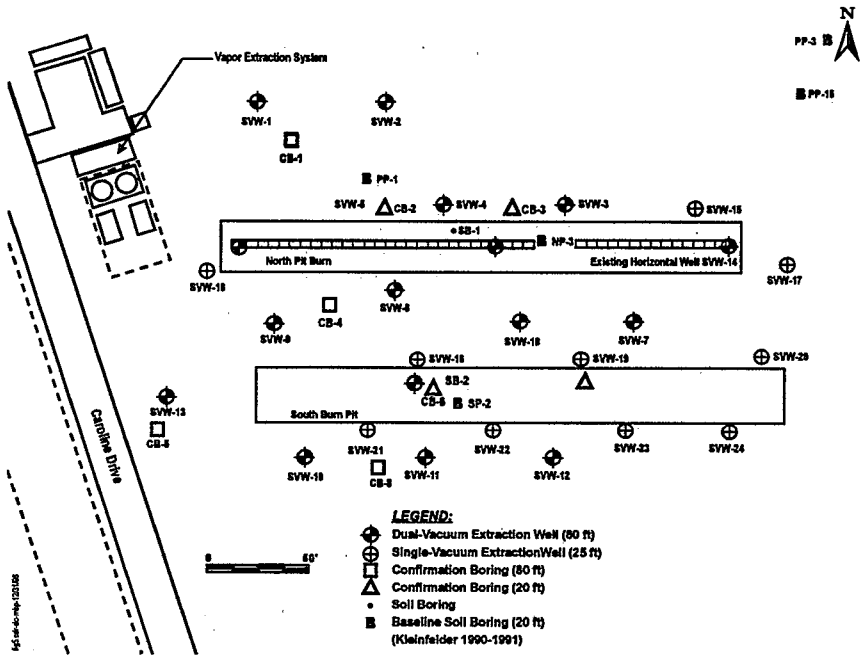

Figure 5. Location of Confirmation Soil Borings [12]

Table 6. Dry Weight Analytical Results for Confirmation Soil Boring Samples [12]

Boring	Depth (ft.)	Sample-ID No.	Analyte Concentration (mg/kg)			
			TCE	PCE	1,2 Trans-DCE	1,2 cis-DCE
CB1	20	SAADCB1-20	<0.002	<0.002	<0.002	<0.002
CB1	39	SAADCB1-39	<0.002	<0.002	<0.002	0.005
CB1	60	SAADCB1-60	<0.002	<0.002	<0.002	<0.002
CB1	78	SAADCB1-78	<0.002	<0.002	<0.002	<0.002
CB2	20	SAADCB2-20	<0.002	<0.002	<0.002	<0.002
CB2	20	SAADCB2-20QC	<0.006	<0.006	<0.006	<0.006
CB4	20	SAADCB3-20	<0.002	<0.002	<0.002	<0.002
CB4	20	SAADCB4-20	<0.002	<0.002	<0.002	<0.002
CB4	40	SAADCB4-40	<0.002	<0.002	<0.002	<0.002
CB4	59	SAADCB4-59	<0.002	<0.002	<0.002	<0.002
CB5	78	SAADCB4-78	<0.002	<0.002	<0.002	<0.002
CB5	20	SAADCB5-20	<0.002	<0.002	<0.002	<0.002
CB5	41	SAADCB5-41	<0.002	<0.002	<0.002	<0.002
CB5	60	SAADCB5-60	<0.002	<0.002	<0.002	<0.002
CB6	78	SAADCB5-78	0.010	<0.002	<0.002	<0.002
CB7	78	SAADCB5-78QC	<0.007	<0.007	<0.007	<0.007
CB8	20	SAADCB6-20	<0.002	<0.002	<0.002	<0.002
CB8	20	SAADCB7-20	<0.002	<0.002	<0.002	<0.002
CB8	20	SAADCB8-20	<0.002	<0.002	<0.002	<0.002
CB8	39	SAADCB8-39	<0.002	<0.002	<0.002	<0.002
CB8	59	SAADCB8-59	<0.002	<0.002	<0.002	<0.002
CB8	59	SAADCB8-B	0.003	<0.002	<0.002	<0.002
CB8	78	SAADCB8-78	0.003	<0.002	<0.002	<0.002
CB8	78	SAADCB8-78QC	0.011	<0.008	<0.008	<0.008
Statistical Mean* (with QC Results)			0.0021	0.0013	0.0013	0.0015
Statistical Mean* (without QC Results)			0.0016	0.001	0.001	0.0012

*Mean (average) values calculated assuming results reported as less than detection limit were present at one-half detection limit.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Soil Vapor Sampling [4]

To assess the progress of the remediation, soil vapor samples were collected from six SEAMIST wells. As shown in Figure 3, the six SEAMIST wells were located throughout the soil vapor extraction wellfield. Five SEAMIST wells contained 10 sample ports each, and one well contained 9 ports. The sample ports in each SEAMIST well were vertically distributed in the primary stratigraphic units determined from site investigation borings and well logs. Figure 6 shows a SEAMIST well construction detail, and Table 7 shows the sample port depths for the six wells.

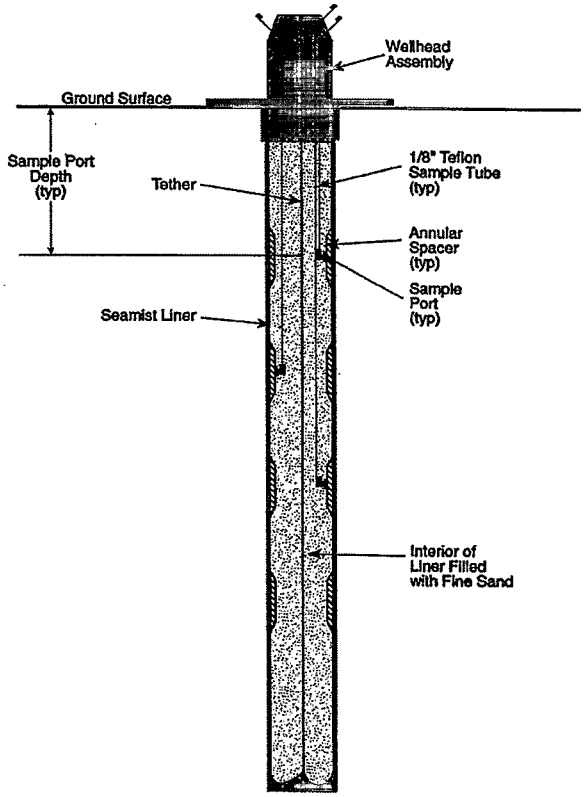

Figure 6. Seamist Well Construction Detail [4]

The SEAMIST well vapor samples were collected in 1-liter Summa™ canisters and analyzed for TCE, PCE, and 1,2-DCE using a modified EPA Method TO-14. Table 8 shows the range of soil vapor concentrations for TCE, PCE, and 1,2-DCE before and during shutdown (on January 18, 1995 and February 28, 1995) in the six SEAMIST wells. In addition, Table 8 shows the range of baseline concentrations for TCE in soil vapor in April 1994, prior to SVE system startup.

Table 7. Sample Port Depths for SEAMIST Wells [4]

Well ID	Sample Port 1	2	3	4	5	6	7	8	9	10
	Depth (feet)									
SM-1	8	18	31	37	44	53	60	66	72	77
SM-2	10	20	28	35	42	48	55	65	72	N/A
SM-3	10	18	26	33	39	46	53	63	73	79
SM-4	10	18	26	34	42	48	56	64	72	80
SM-5	12	20	28	36	44	53	59	65	73	80
SM-6	10	15	20	35	45	53	58	65	72	80

N/A - Not applicable; well SM-2 had only 9 sample ports.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Table 8. Range of Soil Vapor Concentrations Before and During Shutdown [4]

Compound	Initial Soil Vapor Target Goal (μg/L)	Baseline Concentrations (April 1994) (μg/L)	Before Shutdown Concentrations (January 18, 1995) (μg/L)	During Shutdown Concentrations (February 28, 1995) (μg/L)
Trichloroethene (TCE)	1.88	0.4 - 199.6	ND - 12.9	ND - 7.6
Tetrachloroethene (PCE)	3.14	N/A	ND	ND
1,2-Dichloroethene (1,2-DCE)	8.11	N/A	ND - 2.9	ND - 3.3

N/A - Data not available
ND - Not detected (detection limit not provided).

Extraction Well Vapor Concentrations [6, 12]

Extraction well vapor concentrations were measured in February 1994 during drilling of wells at depths of 20 to 25, 45, 55, 65, and 75 feet bgs. A metal probe containing well screen openings at its tip was hydraulically thrust into the soil ahead of the augers. The probe was connected to Teflon™ tubing which extended up to the surface. The Teflon™ tubing was purged of air prior to collection of a vapor sample. After purging, the Teflon™ tubing was attached to a Tedlar bag within a vacuum chamber. As the chamber was evacuated by an air pump, the bag filled with soil gas. To prevent cross-contamination, the equipment was cleaned and new Teflon tubing was used to collect each sample.

Vapor analyses were conducted both at an on-site laboratory and by a third party laboratory. The maximum concentrations of TCE, PCE, and 1,2-DCE measured during drilling of the shallow and deep wells, reported by the off-site laboratory, are shown in Table 9. The highest concentrations of TCE, PCE, and 1,2-DCE were generally found at approximately 50 to 60 feet bgs and 70 to 80 feet bgs. In addition, Table 9 shows the interim results from July 1994 (system operation began in May 1994) at the wellheads for TCE, PCE, and 1,2-DCE.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Table 9. Concentrations in Extraction Well Vapors [6, 12]

Compound	Vendor Interim Requirement (goal) (mg/kg)	Maximum During Drilling (mg/kg)		Interim Results at Wellheads - July 1994 (mg/kg)
		Shallow Well	Deep Well	
Trichloroethene (TCE)	1.7	3.248	10.37	0.41
Tetrachloroethene (PCE)	1.7	0.665	3.422	0.20
1,2-Dichloroethene (1,2-DCE)	0.7	2.4	4.1	0.58

Mass Extraction Data [6, 12]

The mass extraction (removal) rates of TCE, PCE, and 1,2-DCE over the first six months of system operation are shown in Figure 7. The cumulative mass of TCE, PCE, and 1,2-DCE removed over this six-month period is presented in Figure 8. Tables 10 and 11 show the data used to prepare Figures 7 and 8, respectively, for the run times from 42 to 170 days, and for day

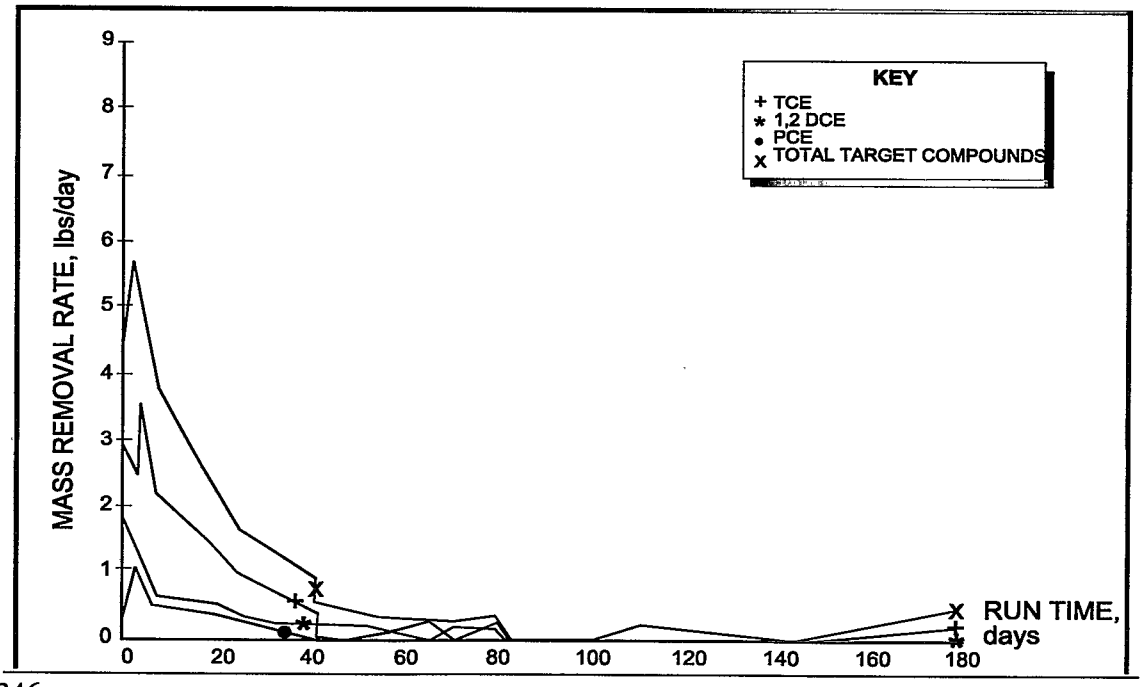

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Figure 7. Mass Removal Rates of TCE, PCE, and 1,2-DCE [6]

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

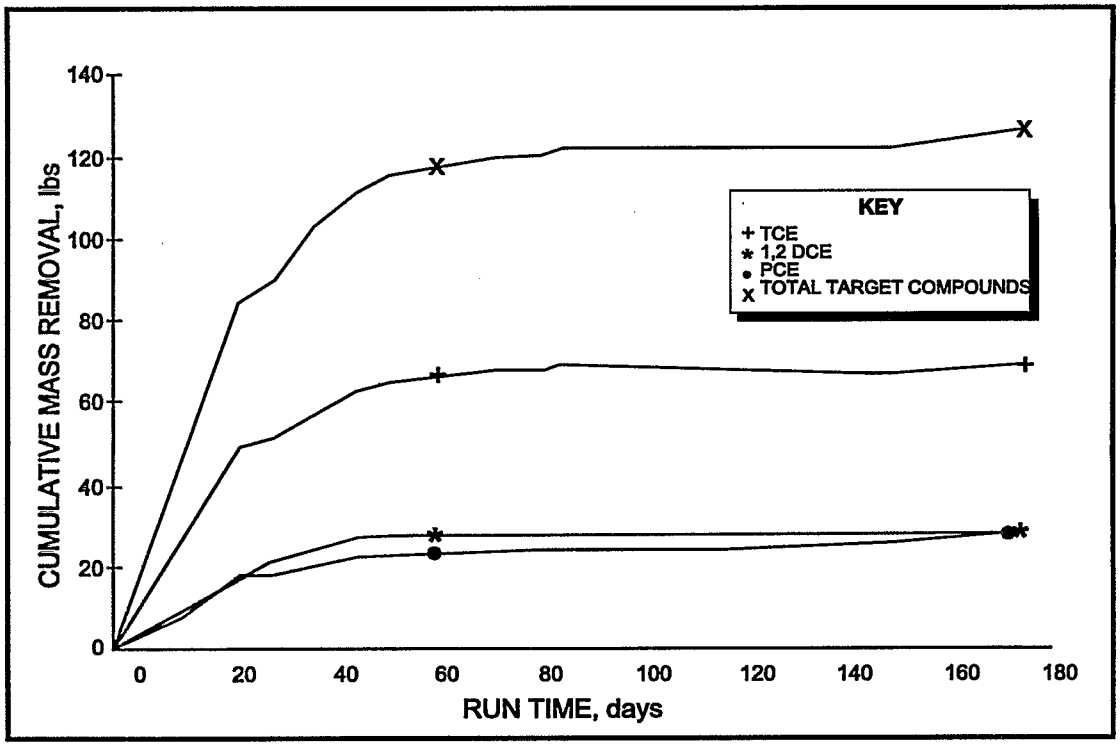

Figure 8. Cumulative Mass Extracted of TCE, PCE, and 1,2-DCE [6]

Note that Tables 10 and 11 do not show the removals from the beginning of system operation through the 42nd day of run time (these data were not provided by the vendor).

Air Emissions [12]

Table 10 shows the air emissions from system operation at the outlet from the secondary carbon unit. As shown in Table 10, for the run times from 42 to 170 days, the actual air emissions ranged from 0 to 0.51 lbs/day, shown as a total for the three target compounds. Actual air emissions were not provided by the vendor for the run time from 0 to 42 days.

Table 10. Mass Removal Rates of TCE, PCE, and 1,2-DCE [12]

Cumulative Run Time* (days)	TCE			PCE			1,2-DCE		
	Inlet to Primary Carbon (lbs/day)	Outlet from Secondary Carbon (lbs/day)	Amount Removed by Carbon (lbs/day)	Inlet to Primary Carbon (lbs/day)	Outlet from Secondary Carbon (lbs/day)	Amount Removed by Carbon (lbs/day)	Inlet to Primary Carbon (lbs/day)	Outlet from Secondary Carbon (lbs/day)	Amount Removed by Carbon (lbs/day)
Air Emission Limit	-	0.103	-	-	0.072	-	-	0.072	-
42.05	0.34	0	0.34	0.19	0	0.19	0.16	0.18	(0.02)**
48.58	0.29	0	0.29	0	0	0	0.06	0.24	(0.18)**
54.56	0.1	0	0.1	0.05	0	0.05	0.07	0.3	(0.23)**
63.5	0.15	0	0.15	0	0	0	0	0.42	(0.42)**
69.5	0	0	0	0	0	0	0.08	0.51	(0.43)**
78.5	0.05	0	0.05	0.12	0	0.12	0	0.23	(0.23)**
82.5	0	0	0	0	0	0	0	0.29	(0.29)**
91.53	0	0	0	0	0	0	0	0	0
99.54	0	0	0	0	0	0	0	0.08	(0.08)**
109.87	0	0	0	0.11	0	0.11	0	0.08	(0.08)**
140.52	0	0.09	(0.09)**	0	0	0	0	0	0
147.63	0	0	0	0	0	0	0	0	0
172.58	0.15	0.1	0.05	0.21	0.06	0.15	0	0	0
346.60	0	0	0	0	0	0	0	0	0

*Cumulative run time as shown for inlet to primary carbon unit

**Values shown in parentheses ( ) indicate that the quantity in the outlet from the secondary carbon was greater than the quantity in the inlet to the primary carbon.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Table 11. Cumulative Mass Extracted of TCE, PCE, and 1,2-DCE* [12]

Cumulative Run Time (days)	TCE (lbs)	PCE (lbs)	DCE (lbs)	Total Target Compounds (lbs)
42.05	62.97	22.84	26.62	112.43
48.58	64.86	23.45	27.25	115.56
54.56	66.01	23.6	27.63	117.24
63.5	67.09	28.8	27.91	123.8
69.5	67.55	23.81	28.15	119.51
78.5	67.77	24.35	28.52	120.64
82.5	67.87	24.6	28.52	120.99
91.53	67.87	24.6	28.52	120.99
99.54	67.87	24.6	28.52	120.99
109.87	67.87	25.17	28.52	121.56
140.52	67.87	26.88	28.52	123.27
147.63	67.87	26.88	28.52	123.27
172.58	69.7	29.5	28.52	127.72
346.60	73.86	35.12	28.61	137.6

*Data reported for inlet to primary carbon unit; cumulative run time for blower no. 7681.

Performance Data Assessment

The FIVE system achieved the specified soil cleanup goals for all three target constituents - TCE, PCE, and 1,2-DCE. As shown on Table 6, the average value for the 21 confirmation soil borings was less than the cleanup goals of 0.005 mg/kg for TCE, PCE, and 1,2-DCE. Table 6 shows that the average TCE value was 0.0021 mg/kg, PCE was 0.0013 mg/kg, and 1,2-DCE was 0.0028. (These values include the QC samples; the average results without the QC samples are slightly lower.) As shown on Table 6, OHM reported the 1,2-DCE values separately for the trans and cis isomers of this constituent; however, these results were added together to compare with the cleanup standard. Of the 96 analytical values shown on Table 6, only two (TCE in SAADCB5-78 at 0.010 mg/kg and in SAADCB8-78QC at 0.011 mg/kg) were greater than the target cleanup goal of 0.005 mg/kg. In addition, only 5 of the 96 values were reported as detected values; the remainder were all reported as not-detects with a detection limit ranging from 0.002 to 0.008 mg/kg.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Performance Data Assessment

There were a limited quantity of soil vapor data collected during this application, with samples collected at "baseline" (April 1994), before shutdown (January 1995), and during shutdown (February 1995). Based on these limited data, it appears that the TCE soil vapor concentration was greater than the soil vapor target goal, PCE (at ND), and 1,2-DCE (at a maximum of 3.3 μg/L) appear to have met their soil vapor target goals.

In addition, there were a limited quantity of extraction well vapor data collected during this application, with samples collected during drilling and in July 1994. The data in Table 9 show that the interim results at the wellheads for July 1994 met the vendor's interim requirement (goal) for all three target contaminants.

The vendor indicated that the FIVE technology is intended to produce relatively larger subsurface pressure gradients and higher flow rates of extracted vapors than would be achieved solely with using vapor extraction technology. The vendor stated that this process "enhanced subsurface volatilization and shortened the period of remediation" [6], however, no data were provided to support this statement. For example, the vendor did not estimate how much additional time would have been required to reach the cleanup goals solely using vapor extraction technology.

Figures 8 and 9 show rapid extraction of target VOCs during the first 40 days of system operation, and more gradual extraction over the next 140 days. For example, the mass extraction rates decreased by more than 75% from an average of 4 pounds per day (lbs/day) over the first 20 days of system run time to less than 1 lb/day after 40 days of system run time. As shown in Table 11, the cumulative quantity of contaminant extracted from the subsurface over 347 days of run time was approximately 138 lbs, consisting of 74 lbs of TCE, 35 lbs of PCE, and 29 lbs of 1,2-DCE. More than 80% of the total mass was extracted during the first 42 days of run time, and almost 93% of the total mass was extracted during the first 173 days. More than half of the total mass extracted was TCE, and the remainder consisted of nearly equal quantities of PCE and 1,2-DCE.

The 138 lbs of target VOCs extracted during system operation is approximately two times greater than the originally estimated mass of TCE, PCE, and 1,2-DCE existing beneath the site. The quantity of TCE extracted is more than three times greater than the original estimate. Possible reasons identified by the treatment vendor include inaccuracies in the original estimate, and, for 1,2-DCE, a reductive dehalogenation mechanism that took place in situ.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Performance Data Assessment (cont.)

The data in Table 10 show that air emissions (as measured at the outlet from secondary carbon) from days 42 through 172 sometimes were greater than the limits described above. TCE and PCE met their air emission limits, however, 1,2-DCE exceeded its air emission limit. For example, on Day 42, 1,2-DCE was emitted at a rate of 0.18 lbs/day, which is greater than the limit of 0.072 lbs/day. 1,2-DCE emissions from run time 42 to 172 days ranged from 0.08 to 0.51 lbs/day, exceeding the emissions limit on nine sampling dates.

The data in Table 10 also show that the carbon columns were not effective in removing 1,2-DCE from the extracted air, in that more DCE was released from the carbon than was extracted from the subsurface. Based on a sum of the daily inlet and outlet quantities from run times 42 to 172 days, the carbon showed an average TCE removal rate of 82%, and for PCE of 91%. Note that because the carbon was not effective in removing 1,2-DCE, the calculation of the cumulative amount removed by carbon for the three target contaminants is a negative number.

Performance Data Completeness

Analytical data are available for the following: 1) the concentrations of contaminants in the soil prior to treatment; 2) the concentrations of contaminants in soil vapors and extraction well vapors; 3) mass extraction rate and cumulative mass extraction data; 4) soil boring confirmation samples measuring concentrations of contaminants in the soil after treatment; and 5) air emissions from the carbon units.

Performance Data Quality

The treatment vendor reported that confirmation soil borings were analyzed using standard EPA methods 8240, 8270, and 8080, and that three duplicate field samples were collected and analyzed. The field duplicates confirmed that the target analytes were below detected values, however the detection limits for the duplicates were 3 to 4 times greater than those for the original samples. No additional information was provided on why the detection limits were higher for the field duplicates. [12]

TREATMENT SYSTEM COST

Procurement Process

OHM was awarded a contract by the USACE, Sacramento District, for the design, construction, and operation of an enhanced SVE system with pressurized injection. [5] According to the vendor, the procurement was a "non-programmatic open governmental bidding process". [12] No

TREATMENT SYSTEM COST (CONT.)

Procurement Process (cont.)

information was provided on the number of bidders or the basis for selecting OHM as the treatment vendor.

Kleinfelder provided support to the Army at SAAD under a basewide contract, and was tasked by the USACE, Sacramento District, with monthly sampling of monitoring wells during OHM's operation, and other activities. [4]

Treatment System Cost [5, 12]

OHM reported a total cost of $865,873 for this application. In order to standardize reporting of costs across projects, the costs were broken down according to the format for an interagency Work Breakdown Structure (WBS). The WBS specifies 9 before-treatment cost elements, 5 after-treatment cost elements, and 12 cost elements that provide a detailed breakdown of costs directly associated with treatment.

Following the WBS, the total cost reported by OHM was broken down in before-treatment costs, shown in Table 12, and costs directly attributed to treatment activities, shown in Table 13. No costs were incurred for after-treatment activities in this application. Tables 12 and 13 present the cost elements exactly as they appear in the WBS. As shown in Table 12, approximately $195,000 were expended in before-treatment costs for drilling, soil gas survey, confirmatory boring, and chemical testing. Table 13 shows that approximately $670,500 were expended for activities directly attributed to treatment, such as design, mobilization, construction, start-up/testing/permitting, SVE operations and maintenance, disposal of carbon, and demobilization.

The $670,500 in costs directly attributed to treatment corresponds to $2.70 per cubic yard of soil treated (247,900 cubic yards) and $4,858 per pound of target VOC removed (for the 138 pounds of TCE, PCE, and 1,2-DCE removed,).

Table 12. Before-Treatment Costs [5]

Cost Element	Cost ($)
Monitoring, Sampling, Testing, and Analysis - drilling/soil/gas survey: $161,497 - confirmatory borings (including chemical testing): $33,865	195,362

TREATMENT SYSTEM COST (CONT.)

Treatment System Cost (cont.) [5, 12]

Table 13. Costs Directly Attributed to Treatment [5, 12]

Cost Element	Cost ($)
Mobilization/Setup - design package: $44,486 - mobilization/construction: $159,877	204,363
Startup/Testing/Permits	26,764
Operation (short-term - up to 3 years)	418,812
Demobilization	20,572
Total	670,511

Cost Data Quality

The costs described above represent actual costs for this treatment application as reported by OHM. Limited information is available on the specific activities included within the cost elements for monitoring, sampling, testing, and analysis, and mobilization/setup. No information is available on the specific activities included within the other reported cost elements.

Vendor Input

OHM reported that costs for similar projects can be reduced by the following methods [12]:

- Remediation-based RI/FS studies should be conducted;
- Realistic cleanup goals should be established by the regulators; and
- Innovative- and contaminant-based treatment technologies for off-gas treatment should be implemented.

OBSERVATIONS AND LESSONS LEARNED

Cost Observations and Lessons Learned

- The treatment vendor reported a total actual cost of $865,873 for this application. Of this total, approximately $195,000 were expended in before-treatment costs for drilling, soil gas survey, confirmatory boring, and chemical testing, and approximately $670,500 were expended for activities directly attributed to treatment, such as design, mobilization, construction, start-up/testing/permitting, SVE operations and maintenance, and demobilization.

- The $670,500 in costs directly attributed to treatment corresponds to $2.70 per cubic yard of soil treated (247,900 cubic yards) and $4,858 per pound of target VOC removed (138 pounds of TCE, PCE, and 1,2-DCE). These unit costs show that this application treated a relatively large volume of soil contaminated with relatively small concentrations of target VOCs.

Performance Observations and Lessons Learned

- The soil boring confirmation data show that the SVE system used at the Burn Pits Operable Unit met the soil cleanup goals for VOCs within 14 months of system operation.

- The system consisted of a patented fluid injection/vacuum extraction (FIVE) technology designed to produce relatively larger subsurface pressure gradients and higher flow rates of extracted vapors than would be achieved solely with using vacuum extraction technology. The system had approximately 347 days of run time over the 14 month operating period (81% run time). The vendor stated that this system "enhanced subsurface volatilization and shortened the period of remediation."

- Soil concentrations were reduced from a maximum of 0.012 mg/kg (for TCE) to less than the cleanup goals (e.g., less than 0.005 mg/kg). TCE was reduced to an average of 0.0021 mg/kg, PCE to 0.0013 mg/kg, and 1,2-DCE to 0.0027 mg/kg.

- Approximately 138 lbs of the three target VOCs (TCE, PCE, and 1,2-DCE) were extracted during 347 days of system run time. The VOC extraction rate decreased by more than 75% from an average of 4 pounds per day (lbs/day) over the first 20 days of system run time to less than 1 lb/day after 40 days of system run time.

- The 138 lbs of VOCs extracted during this application is approximately two times greater than the original estimate for mass of TCE, PCE, and 1,2-DCE existing beneath the site. The quantity of TCE extracted is more than three times greater than the original estimate. Possible reasons identified by the treatment vendor for 1,2-DCE included a reductive dehalogenation mechanism that took place in situ.

OBSERVATIONS AND LESSONS LEARNED (CONT.)

Performance Observations and Lessons Learned (cont.)

- Air emissions for TCE and PCE met their air emission limits, however, 1,2-DCE exceeded its limit on nine sampling dates from run time days 42 through 172. According to the vendor, these exceedances were not of concern because of the safety factor included in the emission limits (see discussion on goals).

Other Observations and Lessons Learned

- As part of this remediation, the treatment vendor performed extensive investigations into site geology, including a "facies analysis" to collect data concerning the sedimentary structures and scales of heterogeneity in strata within the vadose zone. The results of the facies analysis were used in the design of the SVE system, particularly in the location and depths of the extraction wells.

- The extraction/injection wells included in the system design proved to be useful for adjusting to site conditions. For example, it was very wet during mid-winter system operation, and the vendor increased the injection rate and decreased the extraction rate to minimize the amount of water that was extracted at that time.

REFERENCES

1. Superfund Record of Decision: Sacramento Army Depot Burn Pits Operable Unit. Sacramento, California. February 26, 1993.

2. Fact Sheet. Burn Pits - Record of Decision. Sacramento Army Depot. June 1993. Number 3.

3. Soil Venting System Startup Report. Remediation of Burn Pits Sacramento Army Depot, Sacramento, California. OHM Remediation Services Corp. June 1994.

4. Rebound Sampling Summary Report, Seamist Monitoring Wells, South Post Burn Pits, Sacramento Army Depot, Sacramento, California. Kleinfelder, Inc. May 16, 1995.

5. Correspondence from Ashok Gopinath, Project Engineer, to Tim McLaughlin, Radian Corporation, regarding Cost and Performance Data for the Soil Vapor Extraction System at the Sacramento Army Depot (SAAD) Burn Pits Site. August 24, 1995.

6. Proceedings of the Ninth National Outdoor Action Conference and Exposition, Aquifer Remediation/Groundwater Monitoring/Geophysical Methods presented by the National Ground Water Association. May 2-4, 1995.

REFERENCES (CONT.)

7. Telephone Call Record from Tim McLaughlin, to Pamela Wee, regarding Information on SAAD Burn Pits OU. May 9, 1995.

8. Telephone Call Record from Tim McLaughlin, to Dan Oburn, regarding Information on SAAD Burn Pits OU. May 10, 1995.

9. Telephone Call Record from Tim McLaughlin, to Pamela Wee, regarding Information on SAAD Burn Pits OU. May 18, 1995.

10. Conversation from Tim McLaughlin, Radian Corporation, to Ashok Gopinath, OHM, regarding Followup on Sacramento Army Depot Burn Pits Superfund Site. October 9, 1995.

11. Correspondence from Ashok Gopinath, Project Engineer, to Tim McLaughlin, Radian Corporation, regarding Cost and Performance Data for the Soil Vapor Extraction System at the Sacramento Army Depot (SAAD) Burn Pits Site. November, 6, 1995.

12. Letter from A. Gopinath, OHM Remediation Services Corp., to L. Fiedler, U.S. EPA, "Remediation Case Study Report, Soil Vapor Extraction at the Burn Pits Operable Unit, Sacramento Army Depot, Sacramento, California, November 1995," March 26, 1996.

Analysis Preparation

This case study was prepared for the U.S. Environmental Protection Agency's Office of Solid Waste and Emergency Response, Technology Innovation Office. Assistance was provided by Radian International LLC under EPA Contract No. 68-W3-0001 and U.S. Army Corps of Engineers Contract No. DACA45-96-D-0016.

Soil Vapor Extraction at the Sand Creek Industrial Superfund Site, Operable Unit No. 1, Commerce City, Colorado

Case Study Abstract

Soil Vapor Extraction at the Sand Creek Industrial Superfund Site, Operable Unit No. 1, Commerce City, Colorado

Site Name:
Sand Creek Industrial Superfund Site, Operable Unit No. 1

Location:
Commerce City, Colorado

Contaminants:
Volatiles - Halogenated: chloroform, methylene chloride, tetrachloroethene (PCE), and trichloroethene (TCE); Volatiles - Nonhalogenated: TPH
- Maximum soil concentrations: chloroform - 0.820 mg/kg; methylene chloride - 5.8 mg/kg; TCE - 0.087 mg/kg; and PCE - 9.34 mg/kg

Period of Operation:
September 24, 1993 - April 27, 1994

Cleanup Type:
Full-scale cleanup

Vendor:
Christopher Strzempka
Project Technical Mgr. for OU-1
OHM Remediation Services Corp.
16406 U.S. Route 224 East
Findlay, OH 45840
(800) 537-9540

SIC Code:
2879 (Pesticides and Agricultural Chemicals, NEC)
2911 (Petroleum Refining)

Technology:
Soil Vapor Extraction
- System was OHM's patented Fluid Injection-Vacuum Extraction (FIVE) technology
- Included 31 vertical wells and 1 horizontal well, and catalytic oxidizer
- Wells screened 3-32.5 ft below ground surface (bgs)
- Some wells operated as injection wells and others as extraction wells

Cleanup Authority:
CERCLA
- Action Memorandum Date 9/29/89
- Federal Lead/Fund Financed

Point of Contact:
Erna Waterman, 8 EPR-SR
USEPA Region VIII
999 18th Street, Suite 500
Denver, CO 80202-2466
(303) 312-6762

Waste Source:
Manufacturing Process

Purpose/Significance of Application:
Full-scale application combining fluid injection and vacuum extraction wells to treat VOC-contaminated soil.

Type/Quantity of Media Treated:
Soil
- Estimates of quantity treated ranged from 31,440 - 52,920 yd^3
- Sandy loams, loamy sands
- Silt and clay - 19.99-24.71%
- LNAPL plume also identified at site

Regulatory Requirements/Cleanup Goals:
- Soil cleanup goals specified for 4 VOCs as follows: chloroform - 0.165 mg/kg; methylene chloride - 0.075 mg/kg; TCE - 0.285 mg/kg; and PCE - 1.095 mg/kg

Results:
- Soil cleanup goals met within 6 months of system operation
- Maximum concentrations in treated soil were: chloroform - 0.0099 mg/kg; methylene chloride - ND; TCE - 0.10 mg/kg; and PCE - 0.28 mg/kg
- Approximately 3,250 lbs of chloroform, methylene chloride, TCE, and PCE extracted (primarily PCE)
- Approximately 176,500 lbs of total VOCs extracted

Soil Vapor Extraction at the Sand Creek Industrial Superfund Site, Operable Unit No. 1, Commerce City, Colorado (Continued)

Cost Factors:

- Approximately $2,140,000 were expended for this application, including $81,231 for before-treatment activities, and $2,058,564 for activities directly attributed to treatment
- The unit cost for activities directly attributed to treatment was $39-65/yd^3 of soil treated, and $11.70/lb of VOC removed
- EPA's decision to revise air emissions control equipment from activated carbon with off-site regeneration to catalytic oxidation resulted in a significant cost savings to the government

Description:

The Sand Creek O.U. 1 site was the location of pesticide manufacturing companies in the 1960s and 1970s, and prior to that, by a petroleum refinery. The pesticide manufacturing companies had two fires in the period from 1968-1977, and were reported to have unsatisfactory waste management practices. Remedial investigations conducted from 1984 to 1988 showed three subareas of soil contamination at Sand Creek O.U. 1 with the following maximum soil concentrations of halogenated VOCs: chloroform - 0.820 mg/kg, methylene chloride - 5.8 mg/kg, TCE - 0.087 mg/kg, and PCE - 9.34 mg/kg. Based on these concentrations, EPA estimated the total mass of the four target contaminants in the operable unit as 684 pounds.

A Record of Decision (ROD) addressing Sand Creek O.U. 1 was signed in September 1989 and an Explanation of Significant Differences (ESD) modifying the 1989 ROD was issued in September 1993. OHM's patented fluid injection/vapor extraction (FIVE) system was used to remediate O.U. 1. In the FIVE technology, pressurized air is injected into vadose zone soils to produce relatively larger subsurface pressure gradients and higher flow rates of extracted vapors than would be achieved solely with using vapor extraction technology. The FIVE system used at O.U. 1 consisted of 32 extraction/injection wells (31 vertical, 1 horizontal), three positive displacement blowers (for extraction), one liquid/vapor separator, one catalytic oxidizer, and two blowers (for injection). The wells were screened up to 32.5 feet below ground surface.

Confirmatory soil borings showed that the concentrations for all four target contaminants were less than the cleanup standards set in the ROD. The maximum concentration of target contaminants measured in the confirmation soil borings was: chloroform - 0.0099 mg/kg, methylene chloride - not detected, TCE - 0.10 mg/kg, and PCE - 0.28 mg/kg. Approximately 176,500 pounds of total VOCs were extracted during this application, including 3,250 pounds of the four target contaminants. The mass of target compounds removed was almost 5 times greater than the original estimate. According to the RPM, possible reasons for this discrepancy include VOC losses during pre-remediation sampling and analysis, which can cause the results to be biased low; and results not representative of the zone of influence of the SVE wells.

COST AND PERFORMANCE REPORT

EXECUTIVE SUMMARY

This report presents cost and performance data for a soil vapor extraction (SVE) system at the Sand Creek Superfund site, Operable Unit (O.U.) 1, in Commerce City, Colorado. The SVE system was used at the Sand Creek O.U. 1 site to treat soil contaminated with halogenated volatile organic compounds (VOCs), specifically chloroform, methylene chloride, trichloroethene (TCE), and tetrachloroethene (PCE), and nonhalogenated VOCs, including mixed petroleum hydrocarbons.

The Sand Creek O.U. 1 site was the location of pesticide manufacturing companies in the 1960s and 1970s, and prior to that, by a petroleum refinery. The pesticide manufacturing companies had two fires in the period from 1968-1977, and were reported to have unsatisfactory waste management practices. Remedial investigations conducted from 1984 to 1988 showed three subareas of soil contamination at Sand Creek O.U. 1 (referred to as Subareas 1,2, and 3), with the following maximum soil concentrations of halogenated VOCs: chloroform - 0.820 mg/kg, methylene chloride - 5.8 mg/kg, TCE - 0.087 mg/kg, and PCE - 9.34 mg/kg. Based on these concentrations, EPA estimated the total mass of the four target contaminants in the operable unit as 684 pounds. No information was provided in the available references on the concentrations or mass of nonhalogenated VOCs in the three subareas.

A Record of Decision (ROD) addressing Sand Creek O.U. 1 was signed in September 1989 and an Explanation of Significant Differences (ESD) modifying the 1989 ROD was issued in September 1993. The modified ROD specified soil cleanup standards for the four target VOCs as follows: chloroform - 0.165 mg/kg, methylene chloride - 0.075 mg/kg, TCE - 0.285 mg/kg, and PCE - 1.095 mg/kg. No soil cleanup standards were identified for the nonhalogenated VOCs.

The SVE system used in this application was a patented fluid injection/vapor extraction (FIVE) system. In the FIVE technology, pressurized air is injected into vadose zone soils to produce relatively larger subsurface pressure gradients and higher flow rates of extracted vapors than would be achieved solely with using vapor extraction technology. The FIVE system used at Sand Creek O.U. 1 consisted of 32 extraction/injection wells (31 vertical, 1 horizontal), three positive displacement blowers (for extraction), one liquid/vapor separator, one catalytic oxidizer, and two blowers (for injection). The wells were screened up to 32.5 feet below ground surface.

The FIVE system was operated from September to December 1993, and again from January to April 1994, for a total of approximately six months of run time. Confirmatory soil borings collected in April 1994 showed that the concentrations for all four target contaminants were less than the cleanup standards set in the ROD. The maximum concentration of target contaminants measured in the confirmation soil borings was: chloroform - 0.0099 mg/kg, methylene chloride - not detected, TCE - 0.10 mg/kg, and PCE - 0.28 mg/kg. Approximately 176,500 pounds of total VOCs were extracted during this application, including 3,250 pounds of the four target contaminants. The 3,250 pound value was roughly 4.75 times greater than the original estimated mass of target contaminants (685 pounds). An air emissions operating permit was not obtained for this application, however, air emissions were regulated

EXECUTIVE SUMMARY (CONT.)

under an Air Pollution Emission Notice issued by the Colorado Department of Health. Approximately 6,200 pounds of total VOCs were released to the atmosphere through stack emissions.

The total actual costs for this application were approximately $2,140,000. Of this total, about $82,000 were expended in before-treatment costs, such as for mobilization and preparatory work, confirmatory sampling, and QA/QC laboratory analyses, and $2,058,000 were expended for activities directly attributed to treatment, such as subcontractor costs, project management/administrative, SVE remedial work, and cost of ownership. The costs directly attributed to treatment correspond to $39-65 per cubic yard of soil treated (based on a range of soil quantity treated estimates of 31,440 to 52,920 cubic yards, as provided by the vendor) and $11.70 per pound of VOC removed (based on 176,500 pounds).

SITE INFORMATION

Identifying Information:

Sand Creek Industrial Superfund site
Operable Unit No. 1
Commerce City, Colorado
CERCLIS # COD980717953
Action Memorandum Date: September 29, 1989

Treatment Application:

Type of Action: Remedial
Treatability Study Associated with Application? Remedial
(see discussion under remedy selection)
EPA SITE Program Test Associated with Application? Remedial
Period of Operation: September 24, 1993 to April 27, 1994
Quantity of Material Treated During Application: There are varying estimates of the quantity of soil treated during this application. These differences are attributed to the different methods used to estimate soil volume for an in-situ application. The following estimates are based on input from the vendor and have been reviewed by the RPM.

The treatment vendor (OHM) provided estimates for quantity of material treated based on (1) the mean (average) groundwater depth and (2) the mean smear zone screen length, as shown below for the three SVE system areas. (Smear zone is the area immediately above the groundwater table, which, in this application, was the area from the top of the well screens to the water table , and which was contaminated by hydrocarbons.) The vendor identified the areal extent of the three SVE areas based on information in their solicitation and used average groundwater depth and smear zone lengths to calculate soil quantity treated. [14]

Treatment Vendor Estimate of Soil Quantity Treated-Mean Depth to Groundwater [14]

SVE Area	Area (ft^2)	Mean (Average) Groundwater Depth (ft)	Volume (ft^3)	Volume (yd^3)
1	29,300	12.4	363,320	13,456
2	30,872	27.2	839,718	31,100
3	7,238	31.2	225,826	8,364
Total (based on mean groundwater depth)				52,920

SITE INFORMATION (Cont.)

Treatment Application (cont.):

Treatment Vendor Estimate of Soil Quantity Treated-Mean Smear Zone Screen Length [14, 16]

SVE Area	Area (ft^2)	Mean Smear Zone Screen Length (ft)	Volume (ft^3)	Volume (yd^3)
1	29,300	8.1	237,330	8,790
2	30,872	17.7	546,434	20,238
3	7,238	9	65,142	2,412
			Total (based on mean smear zone)	31,440

According to the vendor, the estimate based on groundwater depth (52,920 yds^3) assumes that all soil in the three SVE areas was contaminated, including the clean backfill in Area 2, while the estimate based on smear zone (31,440 yds^3) is a "conservatively low estimate". [14]

Background

Historical Activity that Contributed to Contamination at the Site: Pesticide Manufacturing, Petroleum Refinery

Corresponding SIC Code: 2879 (Pesticides and Agricultural Chemicals, NEC), 2911 (Petroleum Refining)

Waste Management Practice that Contributed to Contamination: Manufacturing Process

Site History: The Sand Creek Industrial Superfund site (Sand Creek) covers approximately 550 acres and is located in Commerce City, Adams County, Colorado, as shown in Figure 1. O.U. 1, which covers approximately 13 acres of the Sand Creek site, was used by Times Chemical for pesticide manufacturing and petroleum refining from 1960 to 1968. Prior to Times Chemical, the land was used by the Oriental Refinery; no additional information is provided in the available references on Oriental Refinery's operations. Around 1968, Times Chemical changed its name to Colorado International Company (CIC). In 1968, a fire destroyed three buildings at the CIC facility. An inspection of CIC by Tri-County District Health Department personnel in June 1974 indicated unsatisfactory waste management practices and unsatisfactory worker safety conditions. [1, 2, 14, 15]

SITE INFORMATION (CONT.)

Background (cont.)

In March 1976, the Colorado Department of Health (CDH) conducted a field inspection at CIC. The inspectors observed 55-gallon drums containing pesticides, including parathion, stored in various locations at the CIC facility. In addition, they observed washwater, storm drainage, and boiler feed water draining into a common surface drainage that flowed off property towards Sand Creek. A second fire occurred at CIC in December 1977, releasing parathion fumes over northeast Denver. The state of Colorado issued an Emergency Cease and Desist Order in 1978 against CIC to clean up the property and adjacent areas contaminated by the fire. CIC declared bankruptcy and re-opened the operations as Colorado Organic Chemical Company (COC). COC operations were essentially the same as CIC operations. [1]

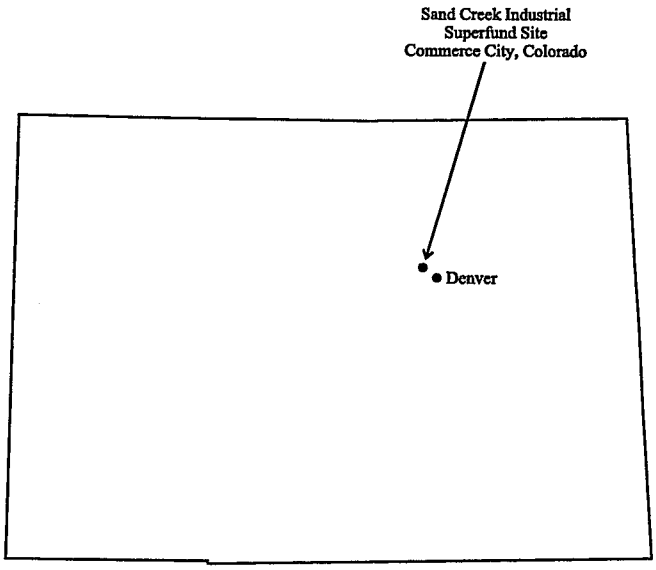

Figure 1. Site Location

Soil sampling at COC in early 1978 revealed elevated levels of halogenated organic compounds, such as organophosphate pesticides and thermally-altered pesticides, and volatile organic compounds (VOCs). In 1980, COC was cited for unsafe drum storage and improper storage areas. In 1982, a consent agreement and final order were issued for RCRA violations. In March 1983, EPA deferred to the Department of Justice the matter of COC's RCRA violations and violation of the consent agreement. In June 1983, a spill of the herbicide 2,4-dichlorophenoxy acetic acid (2,4-D) resulted in an additional compliance order to clean up the spill and to comply with previous orders. EPA issued a CERCLA 106 order in March 1984 for cleanup of the site. Between April and September 1984, COC removed drummed wastes, product, and contaminated soil from the site and fenced the site. [1]

Initial remedial actions at the site, which were conducted primarily in 1992, involved excavation and incineration of contaminated soils, tank wastes, and pesticides. Approximately 40,000 pounds of material, consisting of several drums of toxaphene and pentachlorophenol and soil contaminated with 2,4-D, were excavated and incinerated off site. Four buildings and four railcars were demolished, and several storage tanks and other debris were removed from the site. [2]

SITE INFORMATION (CONT.)

Background (cont.)

Regulatory Context: In September 1989, EPA issued a Record of Decision (ROD) for O.U. 1 at the Sand Creek site. O.U. 1 addressed contaminated soils, buildings, and tanks at the COC facility. The ROD required excavation and off-site incineration for highly contaminated soils (greater than or equal to 1,000 mg/kg of halogenated organic compounds); soil vapor extraction (SVE) for soil contaminated with volatile organic compounds (VOCs); and demolition and treatment of contaminated buildings and tanks in accordance with the RCRA Land Disposal Restrictions. In addition, the ROD required groundwater monitoring at the site for 30 years, and performance of a public health evaluation once every five years following remediation. [1]

In September 1993, EPA issued an Explanation of Significant Differences (ESD) to modify the 1989 ROD for O.U. 1. The ESD modified the ROD by limiting the areal extent for operation of soil vapor extraction technology, and by identifying additional costs for disposal of tanks from the facility. [2]

In July 1994, EPA issued a ROD for Operable Unit No. 4 (O.U. 4) at the Sand Creek site. O.U. 4 involved remediation of a light non-aqueous phase liquid (LNAPL) plume at the site using a combination SVE and dual vapor extraction (DVE) process (SVE/DVE). This treatment was selected because the SVE system was already in place at the site. [12] The application of O.U. 4 is not discussed further in this report.

Remedy Selection: Soil vapor extraction was selected as the remedy for treatment of VOC-contaminated soil in O.U. 1. According to the treatment vendor, the generally permeable nature of the soil matrix indicated that the volatile fractions at Sand Creek, containing the more toxic compounds, could be readily removed with SVE. [14] In 1990, EPA conducted a treatability study to determine if the technology could adequately extract VOCs from O.U. 1 soils and to determine the radius of influence for SVE wells at the site. The study showed that SVE was a feasible remedial technology for the site and that a radius of influence of 60 feet could be achieved at the site. [2,4]

SITE INFORMATION (CONT.)

Site Logistics/Contacts

Site Management: Federal Lead/Fund Financed
Oversight: EPA

Remedial Project Manager:

Ms. Erna Waterman, 8 EPR-SR
U.S. Environmental Protection Agency
Region VIII
999 18th Street, Suite 500
Denver, Colorado 80202-2466
(303) 312-6762
(303) 312-6897 (fax)

ARCs Contractor:

John Chinnock
URS Consultants, Inc.
1099 18th Street, Suite 700
Denver, Colorado 80202-1907
(303) 296-9700

Remedial Design/Construction/Operation Subcontractor (Treatment Vendor):

Christopher Strzempka
Project Technical Manager for OU-1
OHM Remediation Services Corp.
16406 U.S. Route 224 East
Findlay, OH 45840
(800) 537-9540

MATRIX DESCRIPTION

Matrix Identification

Type of Matrix Processed Through the Treatment System: Soil (in situ)

Contaminant Characterization

Primary Contaminant Groups: Volatiles - Halogenated: chloroform, methylene chloride, tetrachloroethene, and trichloroethene; Volatiles - Nonhalogenated: TPH.

EPA conducted a Remedial Investigation (RI) at the site from 1984 to 1988. [3] Soils identified as contaminated with pesticides (e.g., 2,4-D) were excavated and hauled off site for incineration. Additional soil contamination at the site was identified by the vendor as consisting of mixed petroleum and halogenated hydrocarbons, with some of the hydrocarbons classified as semivolatile or non-volatile, including hydrocarbons of aromatic range and heavier hydrocarbons to C-24. [11, 14]

Three subareas of contaminated soil were identified during the RI, labelled Subareas 1, 2, and 3. The maximum concentrations of VOCs in the soil identified by the RI are shown in Table 1. Based on these data, the prime contractor estimated the total mass of chloroform, methylene chloride, TCE, and PCE in the soil as 684 pounds. [4]

Table 1. Maximum Concentrations of Halogenated VOCs in Soil as Identified by RI [2]

Contaminant	Maximum Concentration (mg/kg)
Chloroform	0.820
Methylene Chloride	5.8
Trichloroethene (TCE)	0.087
Tetrachloroethene (PCE)	9.34

In addition to the VOC contamination in the soil, a light non-aqueous phase liquid (LNAPL) plume was identified floating on the groundwater at the COC facility. LNAPL plume thickness was measured at the COC facility in October 1990, April 1991, November 1991, and September 1992. Table 2 shows the LNAPL Plume Thickness in five wells at the COC facility at those times. As shown in Table 2, LNAPL thickness ranged from 1.69 to 4.72 feet in the five wells and averaged from 2.29 to 3.69 feet over the 2-year sampling period. [5]

Figure 2 shows the relative locations of the three contaminated soil areas and LNAPL plume at the Sand Creek site.

MATRIX DESCRIPTION (CONT.)

Contaminant Characterization (cont.)

Table 2. LNAPL Plume Thickness [5]

Well	Measured LNAPL Thickness (ft)			
	10/90	04/91	11/91	09/92
URS-3	4.31	2.25	3.49	2.48
URS-4	3.10	2.43	3.60	3.82
URS-5	3.95	2.26	4.45	4.72
URS-6	3.18	2.43	3.34	1.69
URS-14	2.07	2.07	3.58	3.01
Average	3.32	2.29	3.69	3.14

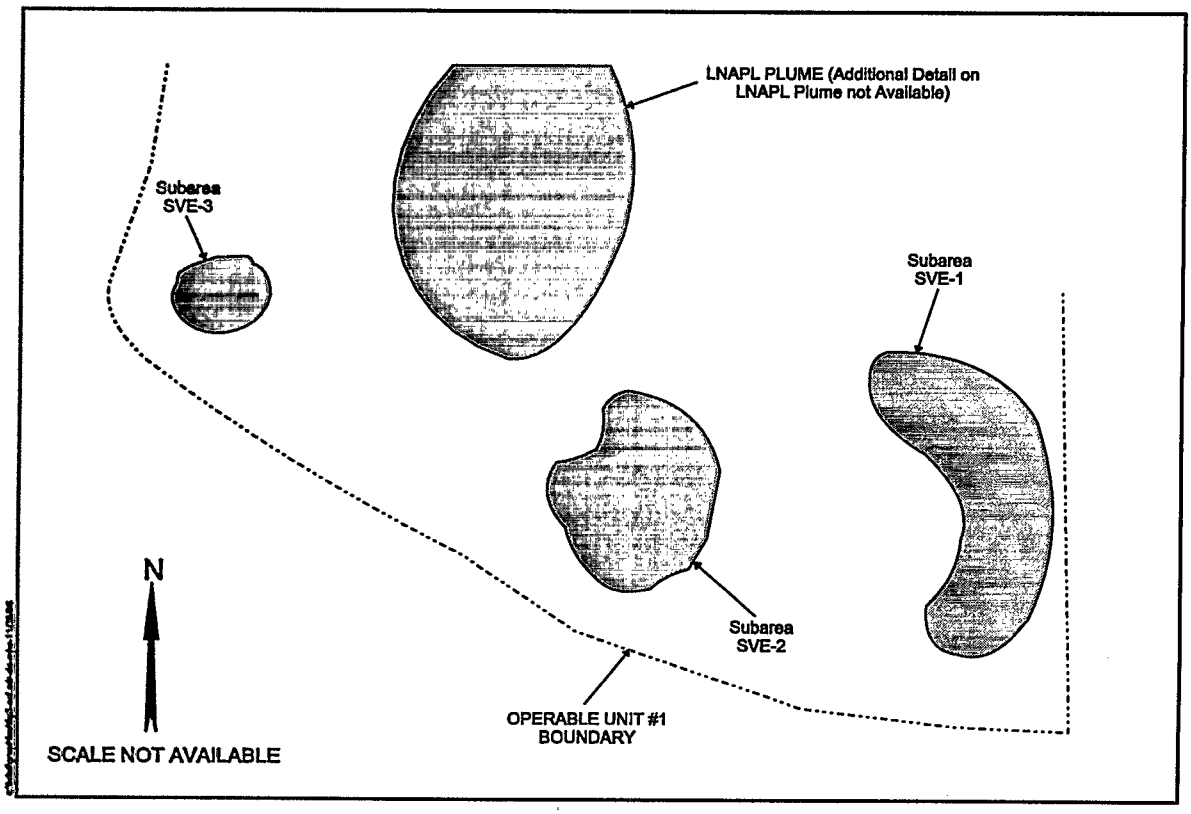

Figure 2. Locations of Contaminated Soil Areas and LNAPL Plume [11]

MATRIX DESCRIPTION (CONT.)

Matrix Characteristics Affecting Treatment Cost or Performance

The major matrix characteristics affecting cost or performance for this technology and the values measured for each are shown in Table 3.

Table 3. Matrix Characteristics [3, 4, 12, 14]

Parameter	Value	Measurement Method
Soil Classification	Sandy loams, loamy sands	USDA Soil Conservation Service
Clay Content and/or Particle Size Distribution	Larger than 1/4" 0.34 - 3.66% Granules (10 mesh to 1/4") 3.98 - 8.35% Medium to very coarse sand (60 to 10 mesh) 35.48 - 40.38% Very fine to fine sand (200 to 60 mesh) 30.01 - 34.99% Silt and clay (less than 200 mesh) 19.99 - 24.71%	U.S. Standard Sieves
Moisture Content	3.0 - 30.1%	Measured values in 13 observations during well installation
Air Permeability	Not measured*	
Porosity	Not measured**	N/A
Total Organic Carbon	Not measured***	N/A
Nonaqueous Phase Liquids	LNAPL layer present	Measured on site

*Although air permeability testing was not conducted, the vendor reported the following: (1) the soils were predominantly sandy, and well screens of 5-ft lengths in the vadose zone were producing extraction flows in excess of 100 SCFM at relatively low vacuums; (2) using a simple steady-state facial flow equation for compressible flow described by Johnson et al (1990), air permeabilities in excess of 2×10^{-7} cm^2 (20 darcies) could be expected; and (3) moisture content in the capillary fringe and saturated zones was the chief impediment to flow.

**Porosity measurements were not made during the project. Some interbedded silts and clays were found at O.U. 1, but soils were predominantly sandy with estimated air-filled porosity in the vadose zones of 30 percent. [14]

***TOC analyses of soils were not made. The bulk of the soils were predominantly sands and silts characterized normally by low TOC. [14]

N/A - Measurement method not reported for this parameter because resulting value not expected to vary among measurement procedures.

MATRIX DESCRIPTION (CONT.)

Site Geology/Stratigraphy

The RI indicated that the site is underlain by alluvial deposits consisting of high-permeability sands and gravels, interbedded with low-permeability clayey and silty layers. Two groundwater units underlie the site, separated by a relatively impermeable layer 10 to 20 feet thick. The upper deposit is up to 40 feet thick and is primarily unsaturated (i.e., contains little to no groundwater). The lower deposit is up to 44 feet thick and generally exists under confined conditions. [1] A simplified schematic of the alluvial groundwater system at the Sand Creek site is shown in Figure 3.

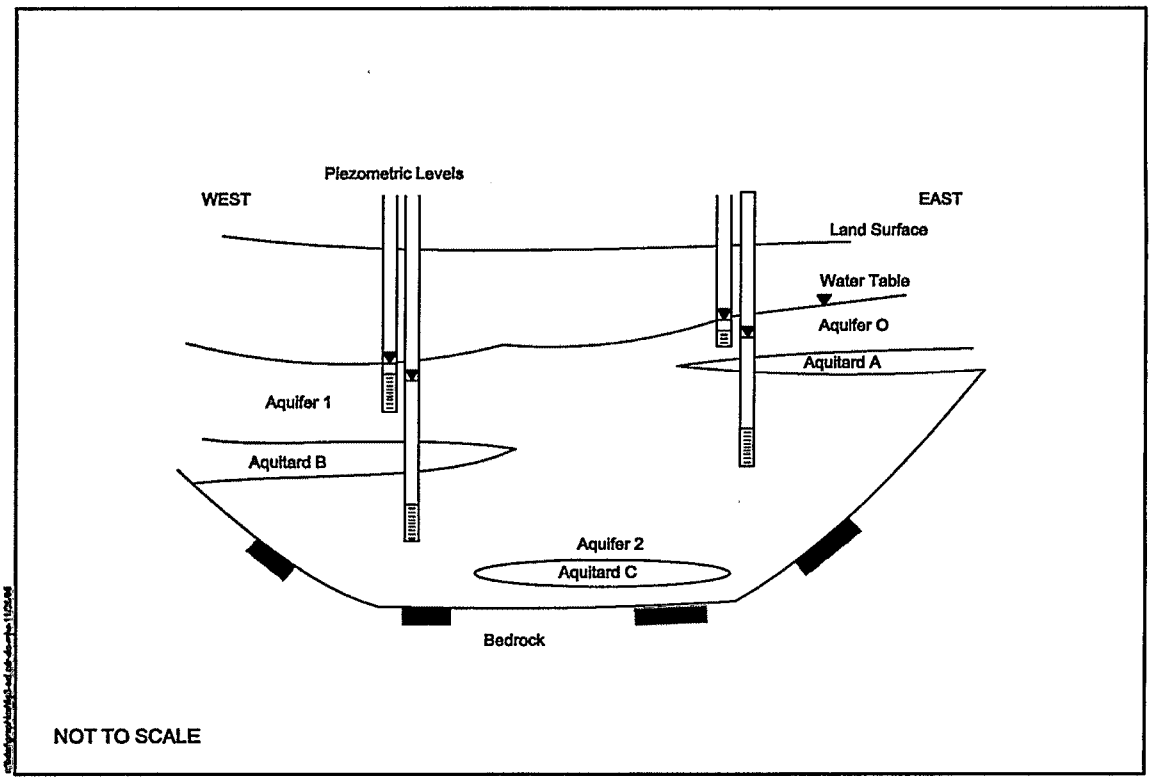

Figure 3. Simplified Schematic of Alluvial Groundwater System at the Sand Creek Site [3]

TREATMENT SYSTEM DESCRIPTION

Primary Treatment Technology Type: Soil Vapor Extraction

Supplemental Treatment Technology Type: Catalytic oxidization

Soil Vapor Extraction System Description and Operation

System Description [4, 8, 10, 12, 14]

The soil vapor extraction system used at Sand Creek consisted of 31 vertical wells and 1 horizontal well, and was thermally-enhanced by fluid injection with vacuum extraction (referred to as the FIVE system). The wells were grouped into three subareas at the site: SVE-1, SVE-2, and SVE-3. Thirteen vertical wells and the horizontal well were located in SVE-1 (wells 101 through 113 and H12). SVE-2 contained 12 wells (wells 201 through 212) and SVE-3 contained 6 wells (wells 301 through 306). The location of these wells at the site is shown in Figure 4. As shown on Figure 4, well H12 is a horizontal well, and all other wells are vertical. For several of the wells in each subarea, operation of the wells was alternated between vacuum extraction and air injection during the course of remediation.

In their bid for the project, the vendor stated that both horizontal and vertical wells would be included in the system, with "preference" given to horizontal wells because the vendor believed such wells would increase the radius of influence. However, only one horizontal well was included in the SVE system at Sand Creek. During installation of the initial horizontal well at Sand Creek, the vendor discovered buried concrete blocks and other construction debris in the subsurface. This created problems of increased friction during installation of the prepackaged well screens resulting in delays. Therefore, after installation of the one horizontal well, the vendor decided to replace the remaining planned horizontal wells with multiple vertical wells.

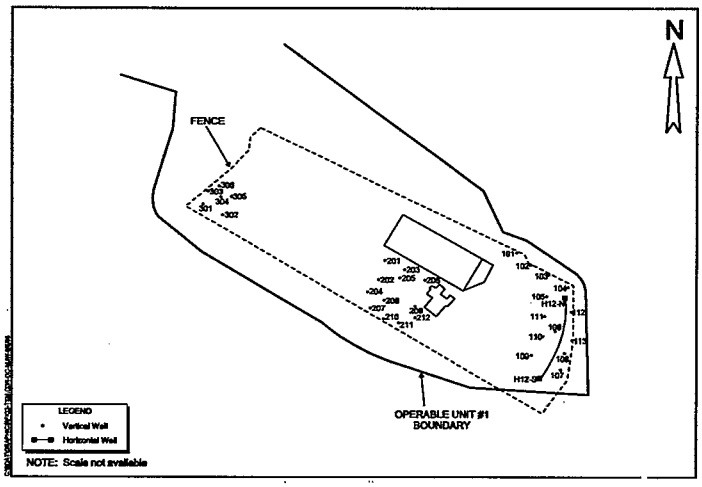

Figure 4. SVE Well Pattern [8]

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

The screened intervals and depths for the wells at Sand Creek are as follows [14]:

SVE System	Well No.	Screened Interval (ft. bgs)	Total Depth (ft. bgs)
1	SVE-101	4.5 - 11.5	11.5
	SVE-102	6.5 - 11.5	11.5
	SVE-103	4.0 - 11.5	11.5
	SVE-104	4.0 - 11.5	11.5
	SVE-105	4.0 - 11.5	11.5
	SVE-106	3.0 - 10.5	10.5
	SVE-107	5.5 - 13.0	13.0
	SVE-108	5.0 - 12.5	12.5
	SVE-109	5.0 - 12.5	12.5
	SVE-110	5.0 - 12.5	12.5
	SVE-111	5.0 - 12.5	12.5
	SVE-112	5.0 - 12.5	12.5
	SVE-113	4.0 - 11.5	11.5
	H12	10	10
2	SVE-201	8.0 - 15.5	15.5
	SVE-202	8.0 - 20.5	20.5
	SVE-203	7.5 - 17.5	17.5
	SVE-204	11.5 - 21.5	21.5
	SVE-205	10.5 - 20.5	20.5
	SVE-206	10.5 - 20.5	20.5
	SVE-207	9.5 - 24.5	24.5
	SVE-208	8.0 - 25.5	25.5
	SVE-209	10.0 - 22.5	22.5
	SVE-210	15.0 - 30.0	30.0
	SVE-211	13.0 - 30.5	30.5
	SVE-212	14.0 - 32.5	32.5
3	SVE-301	11.0 - 28.5	28.5
	SVE-302	9.5 - 27.5	27.5
	SVE-303	13.5 - 26.0	26.0
	SVE-304	10.5 - 23.0	23.0
	SVE-305	10.5 - 23.0	23.0
	SVE-306	9.0 - 24.0	24.0

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

Figure 5 shows a schematic of the SVE system. As shown in Figure 5, three 1,500 ACFM positive displacement blowers were used to create a vacuum, with two of the three blowers operated at one time. Extracted water was separated from the vapors using an air/water separator. Following separation, extracted vapors were diluted with ambient air (between 12% and 50% by volume) and treated using a catalytic oxidizer. The emissions from the catalytic oxidizer were either re-injected into the soil through the vertical and horizontal wells, or released to the atmosphere. The system included two blowers for air injection, operated one at a time. The vendor reported that the FIVE system is described in the following reference: Kirk, J.L. and J.R. Ohneck, "A Portable Method for Decontaminating Earth," U.S. Patent No. 4,435,492, U.S. Patent and Trademark Office, Washington, D.C., March 6, 1984.

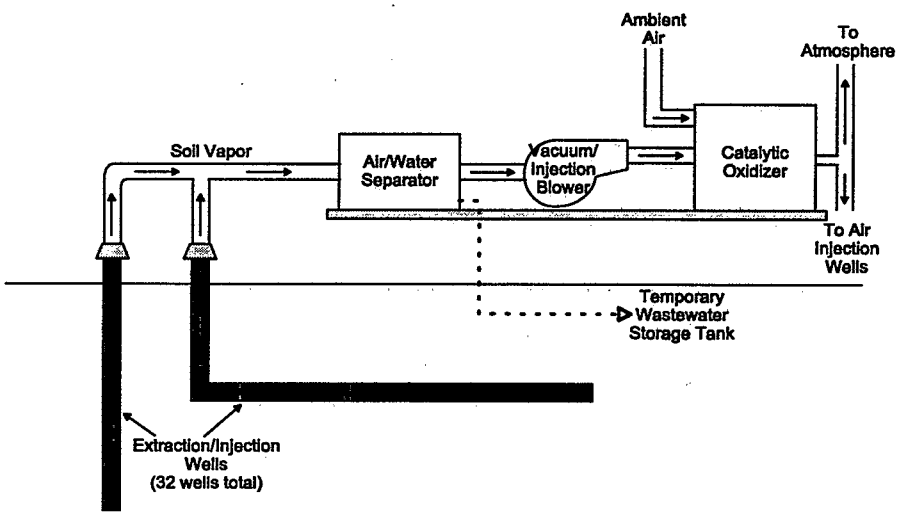

Figure 5. SVE System Schematic [based on 8, 10]

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

Operation [8, 12, 14]

The SVE system was operated for two periods - September to December 1993, and January to April 1994. SVE system start-up activities began on September 24, 1993 and the system became fully operational by October 12, 1993.

Start-up activities focused on well development (initial purging activities), which took place 24 hours a day. Well development was limited to 2 to 3 wells per day to balance the relatively high concentrations of VOCs in the vapors extracted during development and the capacity of the catalytic oxidizer.

Extraction quantities varied during the remediation based on the capacity of the catalytic oxidation (CATOX) unit (extracted vapors had to be maintained at less than 25% of the lower explosive limit (LEL) of vapors in air). Early in the remedial action, the concentration of VOCs in the extracted vapors was high and few wells could be used for extraction because of "over-heating" of the CATOX unit. Later on, the concentration of VOCs in the extracted vapors was less, and all wells in the system could be used in extraction mode.

Treated vapors were intermittently injected into the soil. In October 1993, approximately 25% of the extracted and treated vapors (i.e., after CATOX) were re-injected into Subareas 2 and 3. In November 1993, approximately 15% of the extracted and treated vapors were re-injected into all three subareas. During December 1993, vapors were re-injected into Subarea 1 for nine days. Treated vapors were released directly to the atmosphere during January through April 1994.

The treatment vendor described their general approach to determining injection quantities as follows: (1) at the start of a remediation (when highly concentrated vapors are being extracted), injection must be limited to prevent fugitive emissions from the ground surface or uncontrolled migration of vapor plumes; (2) later on in the remediation, additional injection wells could be brought into service to thermally enhance volatilization, reduce contaminant liquid viscosity, and improve flushing efficiency between adjacent injection and extraction wells; and (3) towards the end of a remediation (when VOC contaminant concentrations are lowest, and are least amenable to further extraction), lower injection flows (and corresponding lower extraction volumes) would lead to conditions conducive to biodegradation (e.g., oxygen enhancement, elevated temperature, adequate moisture). At Sand Creek, it appears that the vendor used limited injection throughout the remediation (25% in Month 1, 15% in Month 2, limited in Month 3, and none in Months 4-7). No data were provided in the available references on any potential fugitive emissions or uncontrolled migration at Sand Creek, or on how much the use of injection improved treatment system performance through thermally-enhanced volatilization, reduced contaminant liquid viscosity, improved flushing efficiency, or biodegradation.

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

System operation generally took place without equipment failure or shutdown. However, in March 1994, the system was automatically shut down twice. On March 1, a shutdown occurred because the high temperature set point was exceeded on the catalytic oxidizer. The system was restarted after about 5 hours. On March 8, the system shut down a second time because of flame failure. The system was restarted one-half hour later.

Groundwater Removal and Disposition [8, 12, 14]

From October 1993 through April 1994, the extraction wells removed entrained groundwater from the subsurface, however, no provisions were made for a water treatment system. The water was temporarily stored on site in a storage tank until disposal at an approved facility. On February 21, 1994, approximately 3,750 gallons of entrained water were disposed at Enviroserve, Inc. Between February 21, 1994 and April 27, 1994, approximately 1,700 gallons of entrained water were collected. No additional information was provided on the disposition of water collected between February and April 1994.

The water extraction rate varied with rainfall, and the presence of perched water and fluctuating water tables. The extraction rate of entrained groundwater from October 1993 to February 1994 was estimated as 10 gallons per day. During March 1994, the rate of entrained groundwater extraction increased to approximately 30 gallons per day, possibly due to a spring snow melt. In April, the rate dropped to about 25 gallons per day.

System Shutdown [8, 12]

The soil vapor extraction system was temporarily shut down on April 19, 1994 for soil confirmation sampling and to assess cleanup of the site. Based on these results (presented under treatment performance data), no additional operation of the SVE system was needed and the system was permanently shut down by April 27.

The treatment performance data shown later in this report indicate that cleanup criteria were met in November 1993, however, according to the RPM, system operation was continued until April 1994 because of the structure of the contract and information about non-target VOC removal quantities. According to the RPM, system operation was performed under a fixed-price contract, where the only benefit to an earlier shutdown would be for oversight costs paid to the prime contractor. These oversight costs were less than the estimated costs for demobilization and a possible subsequent remobilization (for example, if vapor headspace concentrations had increased after a shutdown period), and the RPM determined that shutdown in November 1993 would not be "cost efficient." In addition, during the November 1993-April 1994 operating period, the RPM reported that "significant" quantities of non-target VOCs were being removed by the SVE system.

TREATMENT SYSTEM DESCRIPTION (CONT.)

Soil Vapor Extraction System Description and Operation (cont.)

On June 22 and June 23, 1994, the extraction wells were abandoned in place. They were grouted with a 9 to 1 ratio of cement/bentonite. The vacuum extraction/injection blowers, catalytic oxidizer, LEL monitoring control system, and decontamination trailer were reconditioned and reconfigured to be used in remediation of O.U. 4 at the Sand Creek site.

Operating Parameters Affecting Treatment Cost or Performance

The major operating parameters affecting cost or performance for this technology and the values measured for each are shown in Table 4.

Table 4. Operating Parameters [8]

Parameter	September to December 1993	January to April 1994	Measurement Method
Air Flow Rate	2,681 scfm	2,910 scfm	N/A
Operating Pressure/Vacuum	22-24 inches of water column	13.4 to 23.8 inches of water column	N/A
Air Injection Rate	605 scfm under 12 inches of water column pressure	483 scfm under 18.3 inches of water column pressure	N/A

N/A - Measurement method not reported for this parameter because resulting value not expected to vary among measurement procedures.

Timeline

A timeline for this application is shown in Table 5.

Table 5. Timeline [4, 8, 14]

Start Date	End Date	Activity
1982	-	Sand Creek site placed on NPL
1984	1988	Site-wide Remedial Investigation conducted
September 29, 1989	-	ROD signed for O.U. 1
September 8, 1993	-	ESD signed for O.U. 1
September 24, 1993	October 12, 1993	System started up and wells developed
September 1993	December 1993	First period of operations
December 22, 1993	January 5, 1994	System temporarily shutdown for the holiday season
January 1994	April 1994	Second period operations
April 19, 1994	April 27, 1994	System shut down for confirmation soil boring
April 27, 1994	-	Shutdown of SVE system
June 22, 1994	June 23, 1994	Extraction wells abandoned in place
December 20, 1996	-	Sand Creek site removed from NPL (61 FR 67233)

TREATMENT SYSTEM PERFORMANCE

Cleanup Goals/Standards

The ROD for O.U. 1 specified soil cleanup goals for four VOCs, as shown in Table 6.

Table 6. Soil Cleanup Goals for VOCs at O.U. 1 [1]

Compound	Cleanup Goals (mg/kg)
Chloroform	0.165
Methylene Chloride	0.075
Trichloroethene (TCE)	0.285
Tetrachloroethene (PCE)	1.095

An air emissions operating permit was not obtained for this application, however, air emissions were regulated under an Air Pollution Emission Notice (APEN) effective December 30, 1992, issued by the Colorado Department of Health under Regulation No. 3. The notice required reporting of air emission quantities, but did not limit the emissions. [14]

Addition Information on Goals

The soil cleanup goals for VOCs were developed based on the results of a risk assessment for the site. The risk assessment identified a groundwater ingestion pathway as the most significant route for exposure to VOCs, based on a review of the relatively low partitioning coefficients for the specific contaminants. The cleanup goals were calculated based on this pathway and using a 10^{-6} risk level. [1]

Treatment Performance Data

Treatment performance data for the SVE application at O.U. 1 consists of confirmation soil borings, equilibrium headspace sampling, mass extraction data, and catalytic oxidizer destruction efficiency data.

Confirmation Soil Borings [8]

On April 19, 1994, OHM began confirmation soil boring. Thirty-two confirmation soil borings were performed in O.U. 1. Sixteen soil borings were performed in SVE-1, 11 borings were performed in SVE-2, and 5 borings were performed in SVE-3. Confirmation soil borings were performed using a CME-55 truck mounted drilling rig with 7-inch, outside diameter, hollow-stem augers. Soil samples were collected using a series of 2-inch outside diameter by 2-foot long California Split Spoon Samplers in accordance with ASTM Method D-1586.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Following decontamination of the split spoon samplers, four 6-inch brass sleeves were placed into the sampler.

Once the sampler was retrieved from the boring, the split barrel was opened and the brass sleeves removed. Teflon sheeting was placed over each end of each 6-inch brass sleeve and capped with Teflon caps. For each split spoon sampler retrieved, four soil samples were generated, one for lithology characterization using the Unified Soil Classification System (USCS, ASTM Method D-2488), one for backup, one for on-site analytical screening, and one for off-site laboratory analysis. In addition, QA/QC samples were collected during the field sampling event. These samples included trip blanks, field blanks, and equipment rinse water.

Field analyses of the soil boring samples were performed according to Method 8010B, published in SW-846, "Test Methods for Evaluating Solid Waste," and using a Hewlett Packard Series II Gas Chromatograph (GC), configured with a Tekmar ALS 2016 Purge and a Tekmar LSC 2000 Trap for sample introduction. An OI Corp. 5220 Electrolytic Conductivity Detector (ECD) was used for quantitation of the target compounds.

Off-site laboratory analyses were performed by Great Lakes Analytical Laboratory in Buffalo Grove, Illinois. Trip blanks and equipment blanks also were analyzed by Great Lakes Analytical Laboratory.

Table 7 shows the results from the off-site laboratory analyses for the four target constituents in the confirmation soil borings. Only those borings where at least one constituent was measured at a detectable concentration are shown on Table 7. Samples for off-site analysis were collected between April 19 and May 2, 1994.

Equilibrium Headspace Sampling [8]

Equilibrium headspace sampling was performed in September, November, and December 1993, and in March 1994. Prior to sampling, the SVE system was shut down by closing the valves in the system, including 10-inch headers located in the equipment pad area, 4-inch well head valves, and extraction/injection manifold 4-inch valves. The SVE system was shut down for a minimum of 48 hours to allow sufficient time for the vapors in the wells to reach a state of equilibrium. After equilibration, the SVE system was re-started and operated 5 to 10 minutes, and well head (static vapor) samples were collected.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Table 7. Analytical Results from Off-Site Laboratory for Confirmation Soil Borings* [11]

Soil Boring	Depth (ft bgs)	Chloroform (mg/kg)	Methylene Chloride (mg/kg)	Trichloroethene (mg/kg)	Tetrachloroethene (mg/kg)
Cleanup Goal	-	0.165	0.075	0.285	1.095
CB-1	5-7	ND	ND	ND	0.200
CB-1	10-12	ND	ND	ND	0.005
CB-2	3-5	ND	ND	ND	0.032
CB-12	11-13	ND	ND	ND	0.280
CB-17	7-9	0.0078	ND	ND	ND
CB-18	15-17	0.0069	ND	ND	ND
CB-18	17-19	0.0099	ND	0.10	ND
CB-19	7-9	ND	ND	ND	0.0063
CB-19	9-11	ND	ND	ND	0.0059
CB-21	19.5-20	0.0071	ND	ND	0.066

ND - Not detected (detection limits not provided).
*Off-site laboratory analyses were performed for 61 samples (i.e., soil borings at specific depths). Only those 10 samples where at least one constituent was measured at a detectable concentration are shown on this table. All other samples were reported as ND for all four target constituents.

Table 8 summarizes the results from equilibrium headspace sampling in Subareas 1, 2, and 3 during September, November, and December 1993, and March 1994. As shown in Table 8, an equilibrium headspace equivalent to the soil cleanup goals was identified for the four VOC target contaminants. This value was calculated using Henry's Law Constant as an indicator of the relationship between headspace soil vapor concentrations and soil concentrations. Headspace equivalent values were calculated with values taken from the technical literature, and field sampling to validate Henry's Constant, porosity, moisture content, temperature, or partition coefficients used to compute headspace equivalent was not conducted.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Table 8. Equilibrium Headspace Results for VOCs in O.U. 1 - Maximum Concentrations (mg/L) [8]

Sampling Date/Location	Chloroform	Methylene Chloride	Trichloro-ethene	Tetrachloro-ethene	Total VOCs
Equilibrium Headspace Equivalent to Soil Cleanup Goal*	0.139	0.05	0.311	0.856	Not calculated
September 1993					
Subarea 1	BDL	BDL	BDL	0.06	57.7
Subarea 2	0.0178	BDL	0.154	6.9	14.0
Subarea 3	BDL	BDL	BDL	0.3	2.4
November 1993					
Subarea 1	0.001	BDL	0.002	0.001	33.6
Subarea 2	BDL	BDL	BDL	0.078	0.547
Subarea 3	0.001	BDL	BDL	0.002	0.10
December 1993					
Subarea 1	NA	NA	NA	NA	NA
Subarea 2	BDL	BDL	0.001	0.104	1.55
Subarea 3	BDL	BDL	BDL	0.001	0.064
March 1994					
Subarea 1	NA	NA	NA	NA	NA
Subarea 2	NA	NA	NA	NA	NA
Subarea 3	0.001	BDL	0.001	0.005	0.005

*Calculated using Henry's Law - see text.
NA - Data not contained in available references.
BDL - Below detection limit.

Mass Extraction Data [8, 12, 14]

Table 9 summarizes the mass extraction rates and mass removal quantities for the target VOCs and total VOCs during the first and second periods of SVE operation. Removal rates shown in Table 9 represent the average rates measured during the time period.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Table 9. Mass Extraction Rates and Mass Removal Quantities for SVE System Operation [8]

Parameter	September to December 1993	January to April 1994
Average Removal Rate for Target Compounds (lbs/day)	33.86	3.15
Average Removal Rate for Total VOCs (lbs/day)	1,482.6	482.4
Mass Extracted for Target Compounds (lbs)	2,899.7	349.6
Mass Extracted for Total VOCs (lbs)	122,456.6	53,547

NOTE: Total VOCs were analyzed using a modified EPA Method 8015. Non-halogenated VOCs, including the volatile portions of any semivolatiles present were measured, with gasoline range hydrocarbons prevalent in the chromatographs. Average mass extraction rates of contaminants were computed by multiplying the mean concentration by the mean volumetric flow rate between successive sampling episodes and converting to a daily rate (lb/day).

Table 10 shows the cumulative mass of target compounds and total VOCs extracted from the three subareas, released to the atmosphere through stack emissions, and re-injected into the soil. Data in Table 10 represent the cumulative mass over the entire period of system operation, from September 24, 1993 to April 27, 1994.

Total VOCs were analyzed using a modified EPA Method 8015. Non-halogenated VOCs, including the volatile portions of any semivolatiles present were measured, with gasoline range hydrocarbons prevalent in the chromatographs. Average mass extraction rates of contaminants were computed by multiplying the mean concentration by the mean volumetric flow rate between successive sampling episodes and converting to a daily rate (lb/day).

Catalytic Oxidizer Destruction Efficiency Data

The destruction efficiencies for the catalytic oxidizer are shown in Table 11, by operating period. Average destruction efficiencies are shown for target compounds and total VOCs. Destruction efficiency was calculated as follows [14]:

TREATMENT SYSTEM PERFORMANCE (CONT.)

Treatment Performance Data (cont.)

Table 10. Cumulative Mass of Contaminants Extracted, Released to the Atmosphere, and Re-injected - September 24, 1993 through April 27, 1994 (lbs) [8]

	Target Compounds					
	Methylene Chloride	Chloroform	Trichloro-ethene	Tetrachloro-ethene	Total Target Compounds*	Total VOCs*
Extraction						
Subarea 1	0.0	0.0	0.0	5.2	5.2	69,096.7
Subarea 2	0.0	0.40	35.2	3,130.7	3,166.3	106,232.6
Subarea 3	0.0	13.4	0.0	69.8	83.2	1,175.2
Total	0.0	13.8	35.2	3,205.7	3,254.7	176,504.5
Release to Atmosphere						
Stack Emission	0.0	0.0	0.0	209.6	209.6	6,210.3
Injection						
Total	0.0	0.0	0.0	0.74	0.74	638.9

*Totals reflect rounding.

Table 11. Catalytic Oxidizer [8]

Parameter	September to December 1993	January to April 1994
Target Compounds Destruction Efficiencies (%)	92.9	99.1
Total VOCs Destruction Efficiencies (%)	95.5	98.8

Destruction Removal Efficiency = $[1 - [(M_{inj} + M_s)/M_{ext}]] \times 100\%$

where: M_{inj} = Mass of contaminant injected to the subsurface (lb/day)
M_s = Mass of contaminant emitted from the stack (lb/day)
M_{ext} = Mass of contaminant extracted from the subsurface (lb/day)

TREATMENT SYSTEM PERFORMANCE (CONT.)

Performance Data Assessment

The treatment performance data shown in Table 7 indicate that the SVE system used at Sand Creek met the soil cleanup goals for VOCs within 6 months of operation. Soil concentrations were reduced from as high as 9.34 mg/kg (the maximum concentration shown in the RI for tetrachloroethene) to less than the cleanup goals. The maximum concentration of target constituents measured by the off-site laboratory for the confirmation soil borings was: chloroform - 0.0099 mg/kg; methylene chloride - not detected; trichloroethene - 0.10 mg/kg; and tetrachloroethene - 0.28 mg/kg. In addition, as discussed in Table 7, less than 20% of the soil boring samples (i.e., soil borings at specific depths) contained at least one target constituent measured at a detectable concentration.

Equilibrium headspace results shown in Table 8 indicate a reduction in contaminant levels over the course of the remediation. For example, these data show a reduction for tetrachloroethene from 6.9 mg/L in September 1993 (Subarea 2) to 0.104 mg/L in December 1993 (Subarea 2), and from 0.3 mg/L in September 1993 (Subarea 3) to 0.005 in March 1994 (Subarea 3). The headspace results also provide an indication of the variations in contaminant levels between subareas. For example, these data show a relatively higher level of contamination in Subarea 2 than in Subareas 1 or 3. The relatively higher concentrations in Subarea 2 are further supported by the cumulative mass extraction data shown in Table 10. For example, Table 10 shows that 3,166.3 lbs of the 3,254.7 lbs (97.3%) of target compounds were extracted from Subarea 2.

Mass extraction rate and mass removal quantity data provided in Table 9 also show a reduction in contaminant quantities over the course of the remediation. For example, the average removal rate for target compounds was reduced ten-fold from the first to second periods, from 33.86 to 3.15 lbs/day.

As shown in Table 10, approximately 3,250 lbs of the four target VOC compounds and 176,500 lbs of total VOCs were extracted from the three subareas at O.U. 1. Tetrachloroethene accounted for approximately 98.5% of the mass of target compounds extracted from the subareas. Table 10 also shows that during the 6 months of SVE operation, approximately 6,200 lbs of total VOCs were released to the atmosphere, including approximately 209.6 lbs of tetrachloroethene. An estimated 0.74 lbs of tetrachloroethene were re-injected into the soil.

As shown in Table 11, the average destruction efficiencies for the catalytic oxidizer ranged from 92.9 to 99.1% during the 7 months of SVE system operation. Treatment performance data are not provided in the available references to compare actual air emissions with regulatory levels.

TREATMENT SYSTEM PERFORMANCE (CONT.)

Performance Data Completeness

Analytical data are available for the following: 1) the maximum concentrations of contaminants in the soil prior to treatment, as reported in the RI; 2) the range of operating conditions of the SVE system during treatment; 3) analytical data for soil boring confirmation samples; 4) the reduction in equilibrium headspace concentrations over the course of the remediation; and 5) other process parameters, such as rate and mass of extracted VOCs, release of VOCs to the atmosphere, and destruction efficiency of the catalytic oxidizer.

No data are available to characterize the actual soil concentrations in 1993, at the time just prior to treatment system operation. Data are available from the mid-1980s for VOCs in the soil when the RI was performed.

Performance Data Quality

The treatment vendor performed quality assurance/quality control (QA/QC) procedures as part of this application, including use of standard EPA analytical methods, analysis of duplicate samples, trip blanks, and equipment blanks. No deviations to the QA/QC protocols were noted by the vendor. [8]

Soil samples from confirmation soil borings were processed in accordance with the URS-approved Chemical Quality Management/Sampling Plan, Soil Vapor Extraction Remedial Action, Sand Creek Industrial Superfund Site, OU-1 Commerce City, Colorado," dated October 20, 1993, and "Subcontractor Quality Control Plan, OHM Remediation Services Corp.," June 17, 1993. The QA/QC results are contained in OHM's "Cleanup Demonstration Results for Subarea SVE-1, SVE-2 and SVE-3," (Appendix C), dated March 17, 1995. [14]

TREATMENT SYSTEM COST

Procurement Process

The SVE application at Sand Creek O.U. 1 was procured by EPA Region 8 through an ARCs contract with URS Consultants, Inc. (URS). URS prepared detailed bidding and subcontract requirements for the SVE application, including a description of the work, summary of site conditions, and startup, testing, and operating requirements. URS selected OHM Remediation Services Corp. (OHM) under a fixed price subcontract to design, construct, and operate the SVE system in accordance with a URS performance specification. [4, 8, 14] According to the RPM, the remediation was competitively bid, with four bidders. Selection was based on technical criteria and cost, including use of a best and final offer (BAFO) approach. [12]

During the procurement period, EPA revised the air emissions control equipment from activated carbon to catalytic oxidation because of the relatively large quantity of non-target VOCs in the soil (approximately 98% of the total VOCs removed). The ARCs contractor estimated that carbon disposal costs would have exceeded the cost for catalytic oxidation by approximately $600,000 to $750,000. [11] The treatment vendor indicated that savings from use of catalytic oxidation rather than carbon with off-site regeneration may have been greater than the estimate of $600,000 to $750,000, based on the following analysis: A total of approximately 176,500 lbs of VOC were extracted from site soils. If a carbon adsorption capacity of 10 percent was assumed, 10 lbs of carbon would be needed to adsorb one pound of VOC, and approximately 1,765,000 lbs of carbon costing $1.50/lb or a total of $2,647,500 would be required for this application. The vendor stated that this suggested that nearly $2 million might have been saved by selecting catalytic oxidation. [14]

Treatment System Cost [1, 2, 12]

Actual treatment system costs of approximately $2.14 million were provided by EPA Region 8 for this treatment application. This value does not include costs for demobilization activities; costs for these activities are not available at this time. [9]

In order to standardize operating costs across projects, costs reported by Region 8 were categorized according to an interagency Work Breakdown Structure (WBS), as shown in Tables 12 and 13. Table 12 shows that $81,231 in costs for this application were incurred for before-treatment activities such as mobilization and preparatory work, and monitoring, sampling, testing, and analysis. Table 13 shows that $2,058,564 were incurred for activities directly attributed to treatment, such as short-term operation and cost of ownership. Approximately 82% of the costs directly attributed to treatment were for the treatment vendor for this application.

As discussed under the section on Quantity of Soil Treated, the estimates for the quantity of soil treated during this application varied from 31,440-52,920 cubic yards. Because of this, the cost per cubic yard of soil treated is presented as a range, rather than a single cost number. Therefore, the $2,058,564 in costs attributed to treatment corresponds to $39-65 per cubic yard of soil treated (31,440-52,920 cubic yards) and $11.70 per pound of VOC removed (176,500 lbs).

TREATMENT SYSTEM COST (CONT.)

Treatment System Cost (cont.)

Table 12. Before Treatment Costs [9]

Cost Element	Unit Cost ($)	Cost ($)
Mobilization and Preparatory Work		31,254
- Work plan revisions, addendum, and response to interrogatories	4,117	
- Coordination with Operable Units 4 and 5	27,137	
Monitoring, Sampling, Testing, and Analysis		49,947
- Confirmatory sampling	15,569	
- QA/QC laboratory analyses	34,408	
Total		81,231

Table 13. Treatment Costs [9]

Cost Element	Unit Cost ($)	Cost ($)
Operation (short-term - up to 3 years)		2,116,910
- Subcontractor costs	1,693,260	
- Project management/administrative	234,859	
- SVE remedial work (1993)	105,899	
- SVE remedial work (1994)	55,216	
- Other costs (RA, Area 1, 2, 3, SVE, community relations, TSOPs, travel, ODCs, reporting, and closeout)	27,676	
Cost of Ownership		(58,346)[a]
- Overhead adjustment	(55,088)[a]	
- Unallowable costs	(3,258)[a]	
Total		2,058,564

[a]Values in parentheses represent credits (i.e., amount that vendor deducted from total treatment cost).

Cost Data Quality

The costs described above represent actual costs for this treatment application as reported by EPA Region 8. Limited information is available on the specific activities included within several of these cost elements. Tables 12 and 13 show the available information.

Vendor Input

URS (the prime contractor) provided the following information on SVE remediation [13]:

There are a number of items that can affect the cost and opportunities for reductions in costs for similar projects to be completed in the future.

(1) The most important factor is to adequately characterize the site and to identify the aerial extent and the vertical zones of contamination. This is necessary to adequately

TREATMENT SYSTEM COST (CONT.)

Vendor Input (cont.)

remediate the site and prevent cost growth during remediation as a result of "unforeseen site conditions." Change orders during cleanup will substantially impact the ultimate remediation cost. The detailed site characterization should be performed as part of the remedial design phase rather than the RI/FS phase. This will ensure that the design engineers obtain the "design related data" rather than less detailed and specific data required to produce the RI.

(2) The site must be adequately characterized to ensure that all soil contaminants that will impact the SVE process are quantified. As a case in point, only approximately 2% of the total contaminants removed were target analytes. There are cases where the total quantity of contaminants were not characterized, resulting in large project cost increases because inappropriate air pollution control technologies were specified.

(3) Innovative contracting strategies can provide opportunities for cost reductions. For example, rather than using a traditional firm fixed price contract, a two step procurement with a fixed price variable quantity contracting strategy could be used. This contracting strategy would provide for a firm fixed price for mobilization, installation and startup of the SVE system. There would also be a firm fixed price for a base period of operation. At the Sand Creek Industrial Superfund Site this could have been two months. The base period of system operation would then be followed by multiple fixed price option time periods. This approach will provide the selection of the best technical approach at the lowest estimated cost. It will also allow EPA to take advantage of cost reductions when a quick site cleanup occurs and pay a reasonable cost if the remediation takes longer. There will also be corresponding reductions to the Remediation Contractor's pricing because of reduced risk for the Contractor.

OHM (the treatment vendor) indicated that cost reduction is directly related to increasing productivity, reducing remediation time, and encouraging innovation. [14]

OBSERVATIONS AND LESSONS LEARNED

Cost Observations and Lessons Learned

- Approximately $2.14 million were expended for SVE treatment of O.U. 1 at Sand Creek, including $81,231 in before-treatment costs, and $2,058,564 in costs directly attributed to treatment.

- The $2,058,564 in costs directly attributed to treatment corresponds to $39-65 per cubic yard of soil treated (31,440-52,920 cubic yards) and $11.70 per pound of VOC removed (176,500 pounds). A range of costs is presented because of the variation in estimates of the quantity of soil treated. Estimates were provided using the average groundwater depth and average smear zone depth to calculate soil quantity treated.

- EPA's decision to revise the air emissions control equipment from activated carbon with off-site regeneration to catalytic oxidation (CATOX) resulted in a cost savings to the government. The prime contractor estimated the savings to be $600,000 to $750,000, while the treatment vendor estimated the savings as nearly $2,000,000. EPA revised the control to CATOX because of the relatively large quantity of non-target VOCs in the soil.

- The RPM stated that there was limited benefit in shutting down the system in November 1993 when the operating data indicated that the cleanup criteria for target contaminants had been met. For example, the system was still removing significant quantities of non-target petroleum hydrocarbons. Although operating data (e.g., wellhead vapors) are becoming more acceptable as an indicator of soil concentrations, the vendor indicated that there was reluctance to perform confirmation soil borings in November 1993, and the system continued to operate until April 1994 when confirmation soil borings indicated the cleanup criteria had been met. Early shutdown would have saved EPA from paying oversight costs to the prime contractor (URS). However, had EPA shut down the system in November 1993, and then found an increase in wellhead vapor concentrations, EPA would have incurred additional costs for demobilization and remobilization.

OBSERVATIONS AND LESSONS LEARNED

Cost Observations and Lessons Learned (cont.)

- The prime contractor identified several items that should be considered in future SVE applications for reducing costs:

  a detailed site characterization should be performed as part of the remedial design rather than the RI/FS, to identify the aerial extent and vertical zones of contamination, and to identify the total quantity of contaminants, including target and non-target contaminants. At Sand Creek, only approximately 2% of the total contaminants removed were target analytes.

  innovative contracting strategies may provide a potential for cost savings with this technology as alternatives to traditional firm fixed-price contracts. For example, a two-step procurement with a fixed price contract for mobilization, installation, and system startup, followed by multiple fixed price option periods for system operation, would likely result in lower costs for SVE projects.

Performance Observations and Lessons Learned

- Analytical data from off-site laboratory analyses of confirmation soil borings indicate that the SVE system used at Sand Creek met the soil cleanup goals for VOCs within 6 months of operation.

- Soil concentrations were reduced from as high as 9.34 mg/kg (the maximum concentration shown in the RI for tetrachloroethene) to less than the cleanup goals. The maximum concentration of target constituents measured by the off-site laboratory for the confirmation soil borings was: chloroform - 0.0099 mg/kg; methylene chloride - not detected; trichloroethene - 0.10 mg/kg; and tetrachloroethene - 0.28 mg/kg. In addition, less than 20% of the soil boring samples (i.e., soil borings at specific depths) contained at least one target constituent measured at a detectable concentration.

- Equilibrium headspace results, and VOC extraction rate and mass results, indicate a reduction in contaminant levels and quantities over the course of the remediation. For example, equilibrium headspace results show a reduction for tetrachloroethene from 6.9 mg/L in September 1993 to 0.104 mg/L in December 1993 (Subarea 2), and from 0.3 mg/L in September 1993 to 0.005 mg/L in March 1994 (Subarea 3).

- Approximately 3,250 lbs of the four target VOC compounds and 176,500 lbs of total VOCs were extracted from the three subareas at O.U. 1. Tetrachloroethene accounted for approximately 98.5% of the mass of target compounds extracted from the subareas.

OBSERVATIONS AND LESSONS LEARNED (CONT.)

Other Observations and Lessons Learned

- The average quarterly destruction efficiency for the catalytic oxidizer ranged from 92.9 to 99.1% during the 6 months of SVE system operation.

- The mass of target compounds removed from the soil (3,250 pounds) was approximately 4.75 times greater than the original estimated mass of target compounds (684 pounds), determined based on preremedial target compound concentrations and estimated in situ soil volume reported in the remedial design report. According to the RPM, the reason for the difference was based on sampling and analysis for VOCs in the soil prior to remediation. According to the RPM, sampling and analysis of VOCs in soil can often be biased low, because of VOC losses in the sampling processes. In addition, according to the RPM, the pre-remediation VOC results may not have been representative of the zone of influence of the SVE wells.

- The treatment vendor used their patented Fluid Injection/Vapor Extraction (FIVE) technology in this application. The vendor stated that this system "enhanced subsurface volatilization and shortened the period of remediation."

- The CATOX unit was a limiting factor in determining the number of wells that could be used for extraction. Early in the application, the concentration of contaminants in the extracted soil vapors was high, and the number of wells had to be limited so as not to overheat the CATOX unit. Later in the application, when the vapor concentrations were less, all wells in the system could be used for extraction.

- The vendor's bid for this application included use of both horizontal and vertical wells, with "preference" given to horizontal wells, because the vendor believed that horizontal wells would increase the radius of influence. At that time, the use of horizontal wells for SVE was not widely practiced, and was considered an emerging technology. However, during installation of the first horizontal well at Sand Creek, the vendor discovered buried concrete blocks and other construction debris in the subsurface, and these items caused an increase in the cost and time required for horizontal well installation. As a result, the vendor abandoned their plan to give preference to horizontal wells. Instead of installing two additional horizontal wells, additional vertical wells were installed.

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Analysis Preparation

This case study was prepared for the U.S. Environmental Protection Agency's Office of Solid Waste and Emergency Response, Technology Innovation Office. Assistance was provided by Radian International under EPA Contract No. 68-W3-0001 and U.S. Army Corps of Engineers Contract No. DACA45-96-D-0016.

ENHANCEMENTS/ADDITIONS CASE STUDIES

In Situ Enhanced Soil Mixing, U.S. Department of Energy, X-231B, Portsmouth Gaseous Diffusion Plant, Piketon, Ohio

Case Study Abstract

In Situ Enhanced Soil Mixing, U.S. Department of Energy, X-231B, Portsmouth Gaseous Diffusion Plant, Piketon, Ohio

Site Name:
U.S. Department of Energy (DOE), Portsmouth Gaseous Diffusion Plant X-231B

Location:
Piketon, Ohio

Contaminants:
Chlorinated Aliphatics
- 13 VOCs were identified in the soil at PGDP
- Most prevalent VOCs were Trichloroethene (TCE), 1,1,1-Trichloroethane (TCA), 1,1-Dichloroethene (DCE), and methylene chloride
- Concentrations ranged from several hundred to several thousand $\mu g/kg$

Period of Operation:
June 1992

Cleanup Type:
Field demonstration

Technical Information:
Robert L. Siegrist, Prin. Inv., ORNL, (303) 273-3490
Vendors:
Jim Brannigan, Millgard, (313) 261-9760
Steve Day, Geo-Con, (916) 858-0480

SIC Code:
9711 (National Security)
Others - information not provided

Technology:
In Situ Enhanced Soil Mixing (ISESM)
- ISESM consists of soil mixing combined with additional technology
- Four additional technologies were demonstrated at PGDP: vapor extraction with ambient air injection (stripping); vapor extraction with hot air injection (stripping); hydrogen peroxide injection; and grout injection for solidification/stabilization
- 12 soil columns, each 10 ft in diameter and 15 ft deep, were treated in the demonstration
- One additional column was treated by hot air stripping to a depth of 22 ft
- Another additional column was used for a tracer study

Cleanup Authority:
State: Ohio EPA

Points of Contact:
Dave Biancosino, DOE, (301) 903-7961
Jim Wright, DOE, (803) 725-5608

Waste Source:
Waste Treatment Plant/Disposal Pit (waste oil biodegradation units)

Purpose/Significance of Application:
Application of ISESM to remediate fine-grained soils that are difficult to treat with other technologies alone; technology is particularly suited to shallow applications, above the water table.

Type/Quantity of Media Treated:
Soil
- Detailed information provided on soil characteristics, including physical, chemical, and biological properties
- Clay content ranged from 12 to 25%
- 78% of VOCs were present in uppermost 12 ft of soil

Regulatory Requirements/Cleanup Goals:
- Closure plan required 70% mass removal
- No RD&D permit was required

Case Study Abstract

In Situ Enhanced Soil Mixing, U.S. Department of Energy, X-231B, Portsmouth Gaseous Diffusion Plant, Piketon, Ohio (Continued)

Results:
- Soil mixing with each of the 4 additional technologies performed better than the 70% VOC mass removal requirement
- Soil mixing with ambient air stripping achieved >90% removal after 3.75 hrs of treatment
- Soil mixing with hot air stripping achieved >95% removal after 3.75 hrs of treatment
- Soil mixing with peroxidation achieved >70% removal after 1 hr of treatment
- Soil mixing with solidification achieved >90% capture after 1 hr of treatment
- Soil mixing with hot air (thermal) stripping was selected as the remedial option for the site, with cleanup and closure completed in 1994; 628 soil columns at a depth of 22 ft were treated in remediation

Cost Factors:
- Actual capital costs of $1,956,000 were expended for the demonstration, including $481,000 for labor and $500,000 for vendor subcontracts
- Equipment operating costs during demonstration were estimated at $20,000 per day
- Demonstration costs for all four technologies reported as ranging from $150-200/yd^3
- Hot air stripping costs were 5% greater than for ambient air stripping, but achieved cleanup goals faster

Description:
The X-231B waste management unit at the DOE Portsmouth Gaseous Diffusion Plant (PGDP) consists of two waste oil biodegradation areas. The unit was used from 1976 to 1983 for treatment and disposal of waste oils and degreasing solvents, and contributed to contamination of soil and shallow ground water with VOCs. Thirteen VOCs were identified in the soil, including TCE, TCA, DCE, and methylene chloride, at concentrations ranging from several hundred to several thousand μg/kg. The site consists of relatively low permeability soils with elevated clay content.

In situ enhanced soil mixing (ISESM) was demonstrated at the site in 1992. ISESM consists of soil mixing combined with an additional technology. The following four additional technologies were demonstrated at PGDP: vapor extraction with ambient air stripping; vapor extraction with hot air stripping; hydrogen peroxide injection; and grout injection for solidification/stabilization. Three demonstration soil columns were completed for each of the four technologies (12 total). The 12 soil columns were each 10 ft in diameter and 15 ft deep. One additional column was treated by hot air stripping to a depth of 22 ft, and a second additional column was used for a tracer study.

Performance results showed that all four technologies performed better than the 70% VOC mass removal requirement specified by the Ohio EPA. Removals ranged from >70% (for peroxidation) to >95% (for hot air stripping). Based on the results of the demonstration, hot air stripping was selected for site remediation, which was completed in 1994. In situ solidification was more complicated than originally anticipated due in part to difficulty in effectively mixing the dense clay soil in situ and delivering the proper volume of grout. In addition, the solidification process generated secondary liquid wastes from grout delivery trucks and equipment cleanup. An improved "grout-on-demand" system has been developed to minimize waste.

SECTION 1

SUMMARY

Technology Description

In Situ Enhanced Soil Mixing (ISESM) is a treatment technology that has been demonstrated and deployed to remediate soils contaminated with volatile organic compounds (VOCs). The technology has been developed by industry and has been demonstrated with the assistance of the U.S. Department of Energy's Office of Science and Technology and the Office of Environmental Restoration.

- ISESM encompasses a number of in situ soil treatment technologies that can treat contaminated soils, especially those of a fine-grained nature, which are difficult to treat with other remediation technologies. Contaminants are either removed from the soils or stabilized in place. The mixing process allows good access for reagent delivery to all soil particles and the interstices between particles. The technology is particularly suited to shallow applications, above the water table, but can be used at greater depths.

- ISESM technologies demonstrated for this project include:

  ◊ soil mixing with vapor extraction combined with ambient air injection [Contaminated soil is mixed with ambient air to vaporize volatile organic compounds (VOCs). The mixing auger is moved up and down to assist in removal of contaminated vapors. The vapors are collected in a shroud covering the treatment area and run through a treatment unit containing a carbon filter or a catalytic oxidation unit with a wet scrubber system and a high efficiency particulate air (HEPA) filter.]

  ◊ soil mixing with vapor extraction combined with hot air injection [This process is the same as the ambient air injection except that hot air or steam is injected.]

  ◊ soil mixing with hydrogen peroxide injection [Contaminated soil is mixed with ambient air that contains a mist of diluted hydrogen peroxide (H_2O_2) solution. The H_2O_2 solution chemically oxidizes the VOCs to carbon dioxide (CO_2) and water.]

  ◊ soil mixing with grout injection for solidification/stabilization [Contaminated soil is mixed as a cement grout is injected under pressure to solidify and immobilize the contaminated soil in a concrete-like form.]

- The soils are mixed with a single-blade auger or with a combination of augers ranging in diameter from 3 to 12 feet. Mixing is likely to be effectively applied to depths of 40 feet, although commercial vendors have worked at depths as great as 100 feet with the smaller diameter augers. Enhancements such as injection of heated air in combination with vapor extraction, injection of oxidants, or injection of grout are utilized based on the specific system selected for a particular site.

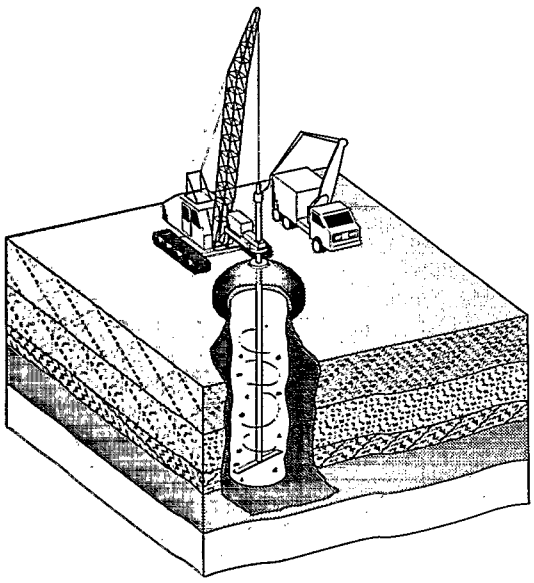

Illustration of the continuously mixed subsurface soil reactor concept. (Note: treatment agents are delivered through the mixing blade with emissions captured in the shroud covering the mixed region.) Rigs can have single or multiple shafts.

Technology Status

- In situ soil mixing, also known as deep soil mixing, shallow soil mixing, soil mixing wall, auger mixing, etc., has been used for a number of years in the construction industry. Cement grout is typically mixed with soil to create a foundation system or barrier wall. Soil mixing with stabilization (Geo-Con/IWT) was demonstrated under the EPA SITE Program in 1990 at a General Electric Shop in Hialeah Florida where soils were contaminated with PCB's.

- The above four ISESM treatment technologies were selected for evaluation during a full-scale field demonstration at the Department of Energy (DOE) Portsmouth Gaseous Diffusion Plant (PGDP), near Piketon Ohio. The field demonstration was conducted at the X-231B Unit in June 1992. Replicated tests of in situ vapor stripping, peroxidation, and solidification were made in soil columns measuring 10 ft in diameter and 15 - 22 ft deep.

- The X-231B Unit was used from 1976 to 1983 as a land disposal site for waste oils and solvents. Soils beneath the unit were contaminated with VOCs, such as TCE at approximately 100 parts per million (ppm), and low levels of radioactive substances. The shallow ground water (12–14 ft depth) was also contaminated, and some contaminants were above drinking water standards. Approximately 78% of the VOCs were located in the upper 12 ft.

- Geologically the site contains low permeability sediments, composed of silt and clay deposits with hydraulic conductivities of less than one millionth of a centimeter per second ($K < 10^{-6}$ cm/s).

- A computerized data acquisition system linked to approximately 60 sensors enabled near-continuous monitoring of process operation and performance. Nearly 500 soil and gas samples were collected before, during, and after soil treatment for analyses of physical, chemical, and biological parameters. Soil matrix, soil vapor, and off-gas VOC measurements were made.

- The technology demonstration was a public/private partnership effort between Oak Ridge National Laboratory (six divisions), DOE-Portsmouth Field Office, Lockheed Martin Energy Systems at Portsmouth, University of Tennessee, Michigan Technological University, Chemical Waste Management, Millgard Environmental Corporation, Envirosurv, and NovaTerra.

- After the demonstrations were completed, the most effective of the four technologies, thermal vapor extraction, was selected as the remedial option for the site. Cleanup and closure of the site was completed in 1994. This innovative treatment technology resulted in a total cost savings of $80 million as compared to traditional excavation and treatment approaches. Closure activities were completed by Geo-Con.

- A number of companies provide ISESM technology commercially(see U.S. EPA VISITT database and DOE Commercial Environmental Cleanup, 1995). However, this demonstration was unique in that four different ISESM technologies were compared at a single site.

- ISESM will be demonstrated at the DOE Kansas City Plant in the spring of 1996. Mixing to a depth of 45 feet will be accomplished and additives such as potassium permanganate, lime and bionutrients will be tested.

KEY RESULTS

In situ treatment of VOCs in clay soils was effectively (>85% reduction) and rapidly accomplished at acceptable costs.

- Vapor stripping processes-ambient air and hot air injection:

  ◊ Treatment performance improved with longer mixing times. 50% of the target VOCs were removed in approximately 90 minutes, whereas 92 to 98% of the contaminants could be removed in the top fifteen feet of soil if mixing were continued for 225 minutes.

  ◊ Extension of the zone of treatment to 22-ft depth exhibited only a moderately reduced removal efficiency (i.e. average of approximately 88%).

  ◊ Soil bacteria levels were increased by several orders of magnitude following ambient air stripping.

- In situ peroxidation:
  - ◊ In situ peroxidation was found to treat soil more rapidly than vapor stripping.VOC treatment efficiency was approximately 72% mass removal in 75 minutes to a depth of fifteen feet.
- In situ solidification:
  - ◊ VOC treatment efficiency was over 90%. Limited VOCs were removed in the off-gas during grout injection and mixing.
- In situ treatment of VOCs in clay-rich soils was rapidly accomplished (e.g., >15 cubic yards per hour [yd^3/h]).
- Treatment costs for each of the four technologies was comparable, ranging from $150 to $200 per cubic yard for the demonstration. Further experience has brought treatment costs down (see cost section).
- Use of a hydraulic probe for soil sampling with on-site VOC analyses, followed by three-dimensional visualization, provided enhanced information compared with conventional sampling, off-site analyses, and routine data treatment.

CONTACTS

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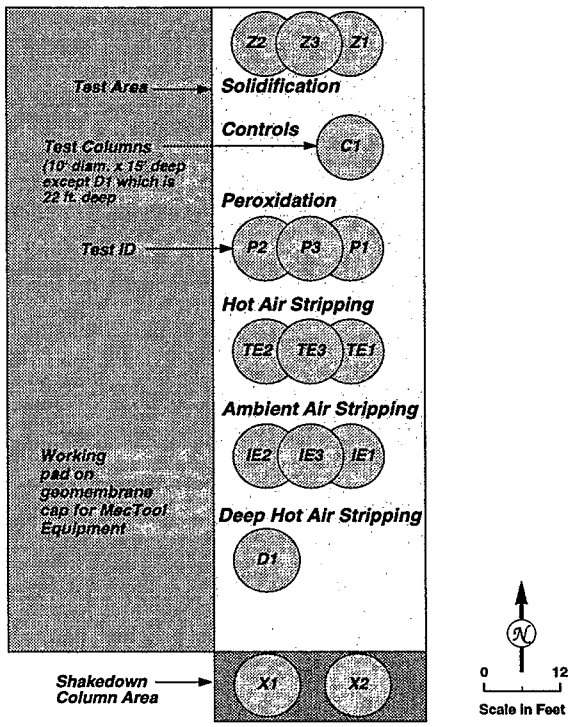
SECTION 2

TECHNOLOGY DESCRIPTION



Schematic of the test site layout for the full-scale field demonstration in the X-231B unit.

Overall Process Description

- A mechanical system was employed to mix unsaturated or saturated contaminated soils while simultaneously injecting treatment or stabilization agents. The main system components include the following:

  - ◊ a crane-mounted soil mixing auger,
  - ◊ a treatment agent delivery system,
  - ◊ a treatment agent supply,
  - ◊ an off-gas collection and treatment system.

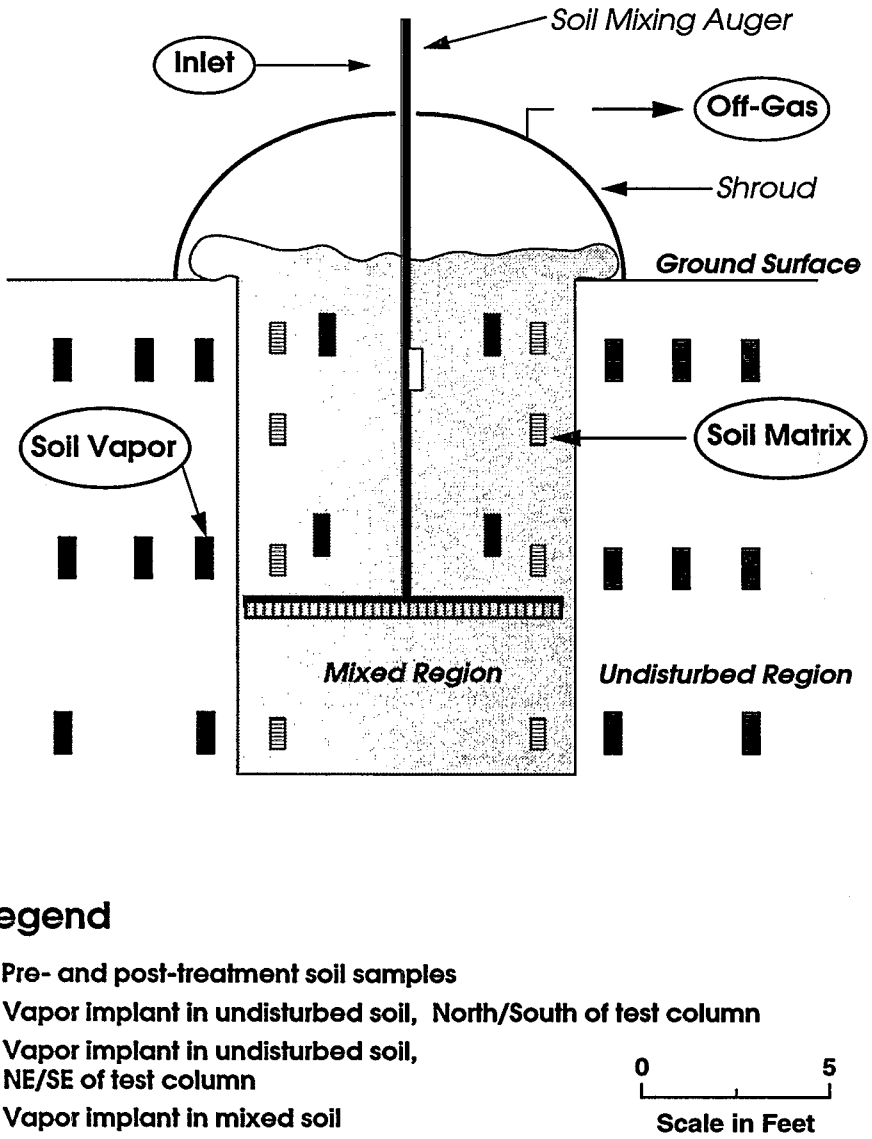
- The mixing system used in the demonstration was manufactured and operated by Millgard Environmental Corporation, Livonia, MI. It is comprised of a track-mounted crane with a hollow, kelly bar attached to a drilling tool, known as the MecTool™, consisting of one or two, 3- to 5-ft. long horizontal blades attached to a hollow vertical shaft, yielding an effective mixing diameter of 6 to 10 feet. Depths of 40 feet can be achieved with this equipment. The 10-foot mixing diameter was used for this demonstration.

- Treatment agents were injected through a vertical, hollow shaft and out into the soil through 0.25 or 0.50 in. diameter orifices in the back side of the soil mixing blades. Treatment is achieved in butted or overlapped soil columns. Chemical Waste Management conducted the solidification/stabilization portion of the demonstration working in concert with Millgard Environmental Corporation.

- The ground surface above the mixed region was covered by a 14-ft. diameter shroud under a low vacuum to contain any air emissions and direct them to an off-gas treatment process. The off-gas treatment system consisted of activated carbon filters followed by a HEPA filter.

- Removal of VOCs was enhanced by moving the mixing auger up and down from 2 to 15 ft below ground surface during vapor stripping.

- For the demonstration, a total of 14 soil columns, each 10 ft in diameter, were treated.
  - ◊ Each of the four treatment processes were demonstrated in three soil columns, each 15 ft. deep. Two of each set of three columns were located in an undisturbed area, while a third, central column was placed to overlap the outer two by approximately 40%.
  - ◊ One column was treated by the hot air stripping to a depth of 22 ft.
  - ◊ A single column, 15 ft. deep, was used for a tracer study.
  - ◊ The operating conditions for the demonstrations are summarized in Appendix B.



Profile view of a treated soil region and associated monitoring points.

- For the X-231B closure, a total of 628 soil columns with a depth of 22 feet were treated. The closure was completed by Geo-Con, using similar equipment.

SECTION 3

PERFORMANCE

Demonstration Plan

- The goal of the ISESM technology demonstration was reduction in the target VOCs in the treatment zone of at least 70%, to meet Ohio EPA performance standards.

- Primary monitoring and measurement activities included:

  ◊ Pre-treatment and post-treatment soil sampling
    - temperature
    - VOCs
    - particle-bound radioactivity

  ◊ In situ soil gas
    - temperature
    - pressure
    - VOCs

  ◊ Operations data
    - treatment depth
    - processing times
    - flow rate
    - resource consumption

Treatment Performance

- A table of general observations of treatment performance for each of the four technologies is presented in Appendix B.

Hot Air Vapor Stripping

- Treatment performance for a 15-ft. soil column:

VOC Removal Efficiency (%)	Minutes of Operation
50	90
85	120-150
95-98	225

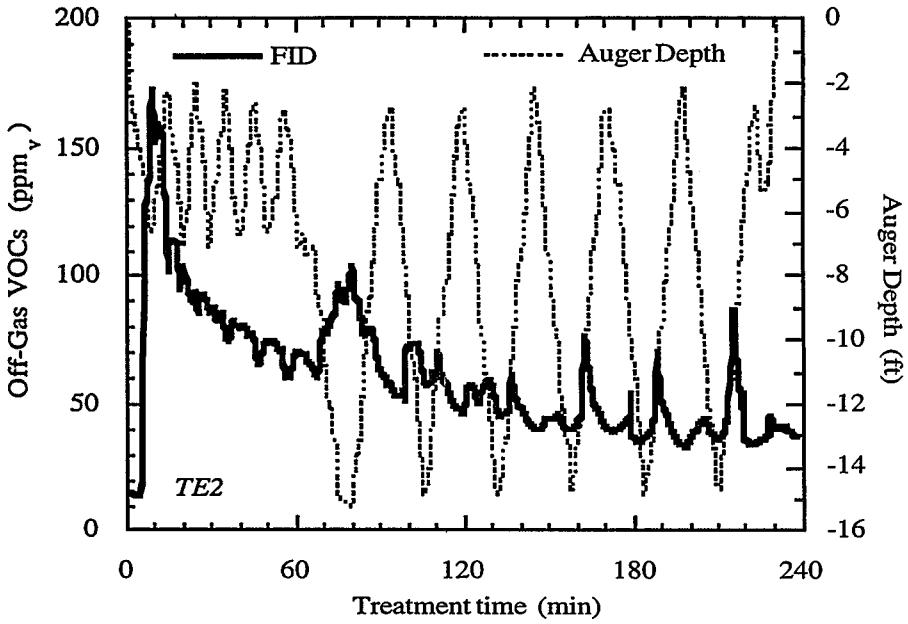
- VOC removal efficiency for the 22-ft. soil column was approximately 88%.

- The mass of VOCs removed as estimated by off-gas sampling generally was consistent with the reduction in soil VOCs estimated from pre-treatment and post-treatment sampling. These data indicated that VOCs were removed from the soil, rather than being forced into surrounding undisturbed soil. This assessment was confirmed by the absence of significant pressure or temperature effects on the unmixed region surrounding the treated columns.

- Off-gas temperatures increased from ~25 to ~40°C after 225 minutes of treatment. Warming of the soil matrix was demonstrated by using thermocouples. Seventy hours after completion of hot air injection, soil matrix temperatures were 34°C and 37°C at depths of 3.5 and 9 feet, respectively. After 140 hours, temperatures remained elevated above background.

- Mixing created a berm of soil of approximately 15% of the treated region above the treated volume for both vapor stripping and peroxidation.

- The figure below, illustrates the relationship between the position of the auger and the concentration of VOCs in the off-gas. The general decline in VOC concentrations with intermittent spikes suggested that VOCs were advectively removed from the gas-filled voids surrounding soil matrix clods while the auger passed through. Diffusion of VOCs from the soil matrix then replenished the gas-filled voids, which were later stripped during a subsequent pass of the auger.



Auger position and off-gas VOC concentration for hot air column TE2.

Ambient Air Vapor Stripping

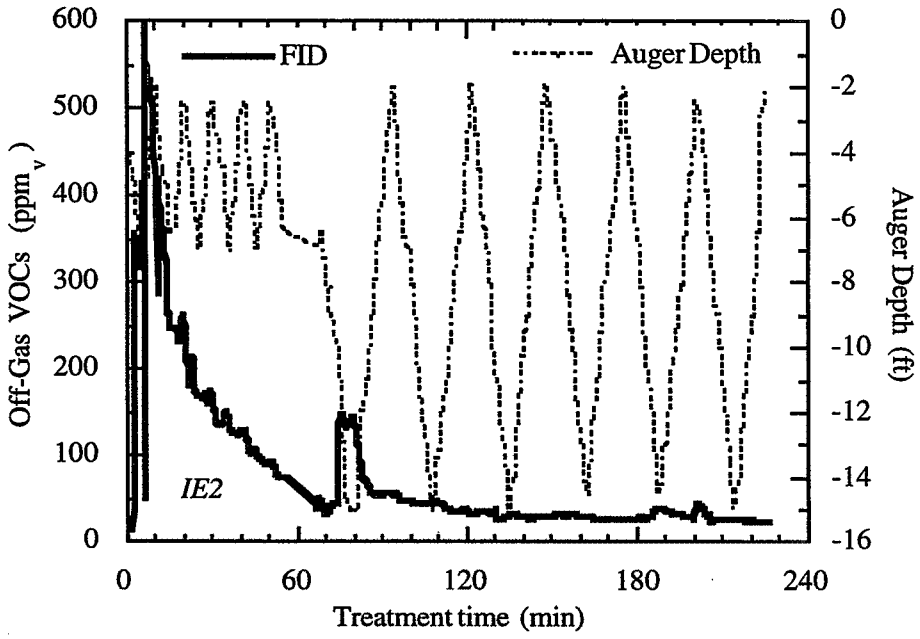
- The treatment performance achieved with ambient air injection was similar but slightly lower than that achieved with hot air. VOC removal efficiency for a 15-ft. soil column:

VOC Removal Efficiency (%)	Minutes of Operation
50	90
85	140-180
92	225

- Temperature of the off-gas increased gradually from 15°C. initially to 30°C. after 225 minutes of treatment. This gradual increase in off-gas temperature is believed to be due to warming of the soil matrix. Thermocouples placed in the soil revealed elevated temperatures of as much as 37°C. Elevated temperatures persisted for more than 94 hours after treatment.

- The mass of VOCs removed as estimated by off-gas sampling generally was consistent with the reduction in soil VOCs estimated from pre-treatment and post-treatment sampling. These data indicate that VOCs were removed from the soil, rather than being forced into surrounding undisturbed soil.

- The figure below illustrates the relationship between the position of the auger and the concentration of VOCs in the off-gas.



Auger position and off-gas VOC concentration for ambient air column IE2.

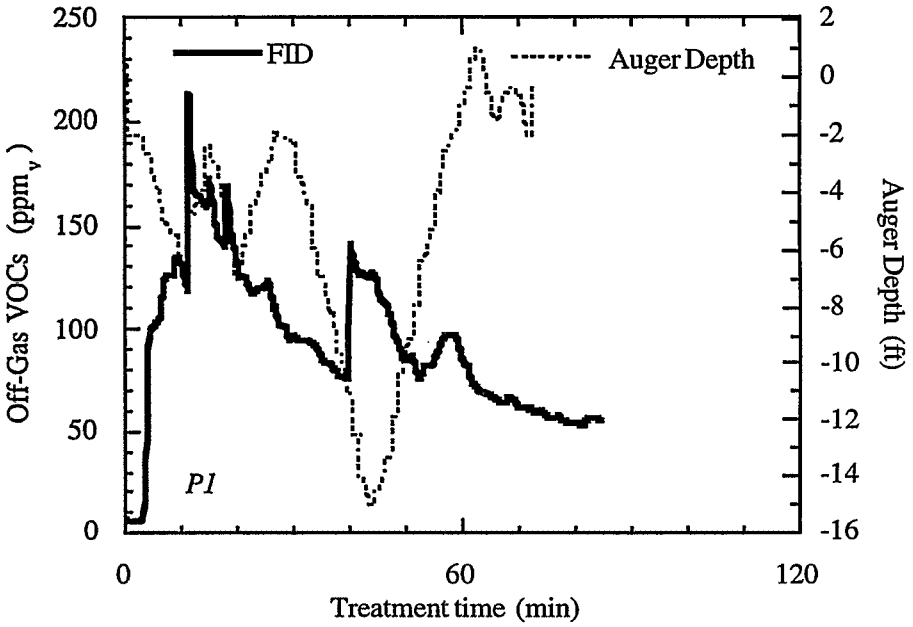
Peroxidation Destruction

- VOC removal efficiency for a 15-ft. soil column averaged approximately 72% after 75 minutes of operation. This removal efficiency is faster than that shown for vapor extraction.

- The apparent VOC treatment efficiency (total % removed) with peroxidation was below that achieved with both vapor extraction processes. This could have been due to:

  ◊ pre-treatment VOC concentrations were relatively low.
  ◊ in situ mixing only occurred for a short period of time (i.e., 60 min.).
  ◊ off-gas collection system capacity was too low during the peroxidation test (system dysfunctioned).

- The figure below illustrates the relationship between the position of the auger and the concentration of VOCs in the off-gas.



Auger position and off-gas VOC concentration for peroxidation column P1.

- During the peroxidation test, the off-gas collection system malfunctioned yielding a flow rate of roughly 30% of the air injection rate. This could have adversely affected the VOC treatment efficiency by altering the extraction of VOCs as well as the distribution of the peroxide mist.

Solidification/Stabilization

- During in situ mixing and grout injection, the concentrations of VOCs in the off-gas were at least an order of magnitude less than that obtained from the columns treated by vapor extraction/air injection. Because grout was applied before soil mixing was initiated and because the grout application rate was rapid, little volatization of VOCs is believed to have occurred as mixing proceeded.

- Total VOC concentrations in untreated soil ranged from 0.1 to over 500 mg/kg. Total VOCs in the uncured grout/soil mixture were markedly lower than in untreated soil when compared by depth. Analytical problems with measurement of VOCs in grout may be responsible for the uncertainty in the mass balance for the VOCs.

- Toxicity Concentration Leaching Procedure (TCLP) concentrations for regulated constituents were either not detected or were well below EPA's regulatory limits. A few examples of the data collected are provided in Table 3, Appendix B.

- A comparison of physicochemical properties of untreated and solidified soil are provided in Appendix B.

  ◊ The average bulk density of untreated soil (1.95 g/cm^3) was greater than that of the soil/grout specimens (1.78 g/cm^3). The decrease in bulk density after solidification may be due to the initial high bulk density of a clay-rich sample, which is reduced as a result of mixing. Also, the reduction in bulk density may be a result of entrapment/entrainment of air in the grout during mixing.

  ◊ The compressive strength values ranged from 390 to 5200 kPa (56 to 750 psig) and were inversely proportional to depth. Samples from the upper part of the core appeared to be highly grouted, while the deepest sample (13-14 ft.) appeared very fragile with a relatively small amount of grout material present. All values obtained, however, were greater than the currently accepted guideline of at least 340 kPa (50 psig).

◊ The hydraulic conductivity (K_{sat}) of cured grout/soil samples was two orders of magnitude greater than that of the untreated soil. This is probably due to disruption of the dense clay deposit as a result of mixing and increased porosity within the grout/soil mixture due to incomplete filling of the pores with grout.

◊ The pH of the grout/soil mixture (10.3-11.5) was significantly higher than that of the untreated soil (5.3-7.5), presumably due to the high alkalinity of the cement-based grout. The stabilized soil/grout mixture should be more stable to acid attack.

◊ Total volatile solids analyses revealed values ranging from 1.2 to 8.0 wt% throughout the solidified soil, with the values often lower than the corresponding value of the untreated soil column.

- The strengths and hydraulic conductivities measured are probably in error due to the sampling technique. Other projects using grout injection have demonstrated lower hydraulic conductivities and higher strengths.

- As a result of mixing the dense clay soil and injecting grout, an above-ground berm was created above each solidified column (approximately 1 meter high and equivalent to 30% v/v of the mixed region. The berms were eventually leveled out and compacted with vibratory equipment.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- In situ soil mixing is commonly used in the construction industry. In situ soil mixing for stabilization has been commonly used at sites with soil contaminated with organics, but is also recognized as appropriate for metals-contaminated soils.
- ISESM with injection of hot air, ambient air, or hydrogen peroxide has been demonstrated to effectively remediate clay-rich soils contaminated with VOCs in the unsaturated zone.
- ISESM is attractive for contaminated sites that contain low permeability soils that cannot be remediated using other technologies, such as in situ bioremediation. However, it can also be used in more permeable materials.
- ISESM is attractive for relatively small sites.
- ISESM requires surface access at all locations where soils are contaminated.

Competing Technologies

- ISESM as applied to sites like the X-231B site at Portsmouth competes with the following baseline technologies:
  - ◊ excavation followed by on-site or off-site storage and/or treatment,
  - ◊ in-place containment by capping and slurry wall emplacement.

Other technologies that were considered for demonstration at the X-231B site are listed below..

Soil treatment technology	Technology description
In situ immobilization	Soil mixing by auger or jet system with addition of solidification/immobilization agent to solidify soil mass and immobilize VOCs and other contaminants in place.
In situ hot-air and/or steam stripping	Soil mixing by dual auger system with injection of hot air and/or steam to raise soil temperature and volatilize VOCs.
In site electrokinetics	Application of electrical energy to the soil mass in situ with induced mobility of water and ions toward a capture electrode system.
In situ jet mixing and slurry reactor	In situ jet mixing with air or water to create an in-place slurry reactor that could be manipulated to achieve physical, chemical, or biological processes for removal/degradation of VOCs.
In situ EM/RF heating	In situ application of electromagnetic or radiofrequency energy to heat the soil mass in place and volatilize VOCs.
In site (ex situ) hydrogen peroxide	Injection of hydrogen peroxide during soil mixing by a dual auger system or by jetting, or application ex situ. VOCs are chemically oxidized, physically stripped, and/or destroyed.
Ex situ thermal treatment	Excavated soil is processed by thermal treatment during which VOCs are volatilized, captured, and/or destroyed.
Ex situ immobilization	Similar to in situ process, except excavated soil is treated above ground in a tank or container.

Technology Maturity

- The 1992 technology demonstration brought together existing technologies into new configurations or systems so that they could be applied in situ in low permeable media.
  - For example, peroxidation destruction is commercially available for ex situ applications, however in situ treatment of soils is novel.
  - Solidification/stabilization is well established for inorganics, but some questions remained for its effectiveness on organics.

SECTION 5

COST

Introduction

- Information in this section was prepared from data provided in various project reports from the actual demonstration and from one of the vendors (Geo-Con). An independent cost analysis has not been performed.

Capital Costs

ISESM Actual Demonstration Costs (Jolley et al., 1991)

Task Description	Estimated Cost
Project Management	199,500
Technical Task Plan Preparation	15,750
Permits and Plans	42,000
Procurement	31,500
Treatability Studies	31,500
Performance Monitoring	73,500
Site Preparation and Equipment Installation	42,000
Data Evaluation and Document Preparation	42,000
Labor	481,000
Travel (for equipment installation and monitoring by the ORNL team	50,000
Supplies	16,000
Materials and Subcontracts	40,000
Treatability Studies	150,000
On-Site Demonstration	
Plans and Permits	40,000
Site Preparation and Equipment Set-up (included building a road to the site)	100,000
Demonstration (approximately 2 weeks of soil mixing and treatment)	150,000
Demobilization and Site Restoration (included recapping the site)	60,000
Vendor Subcontracts	500,000
Miscellaneous and Computer Support	124,000
Analytical Support, QA, Waste Management	150,000
Other (including G&A and GPS)	595,000
Total Actual Demonstration Costs	**1,956,000**

Demonstration Cost Analysis

- Costs for equipment operation during demonstration treatment of three regions to a depth of up to 15 ft. are estimated at ~$20K/day.
- ISESM with a smaller auger blade would reduce equipment mobilization and demobilization costs.
- For the demonstration, soil mixing costs were the same for each treatment process with minor cost variation between processes based on required materials and equipment ($150 to $200/cy). Updated 1996 costs are estimated at $120-175/cy or less. Further development of the technologies has shown that solidification is less costly than hot air injection.
  - ◊ Hot air vapor extraction costs were approximately 5% higher than for ambient air due to equipment; however, the process obtained similar performance goals faster. Treatment times (drilling/injection time only) for hot air stripping, deep hot air stripping and ambient air stripping were comparable and approximately 3 times slower than peroxidation and 5 to 7 times slower than in situ immobilization.
  - ◊ Additional costs are associated with required materials for peroxide destruction and solidification/stabilization, but both of these processes achieved treatment goals rapidly.
  - ◊ A technology selection table for the X-231B Site is located in Appendix C.

Vendor Cost Analysis

- Preliminary cost information is based on clean up of a contaminated site with the following characteristics:
  - Area to be Treated: ~29,000 sq. ft (~0.8 acres) [460-10ft or 720-8ft columns]
  - Depth of Contamination: from ground surface to 25 ft deep
  - Target Contaminants: VOCs
  - Target Clean-up Goal: 90% destruction/removal/immobilization (total soil VOC concentration of less than 1 mg/kg)
- Other assumptions include:
  - Mixing with stabilization assumes use of Portland cement 15% by weight. Ten columns per day are grouted. No offgas treatment is necessary for this application.
  - Hot air injection assumes 5 columns per day. Each column is mixed for one hour.
  - Jet mixing is calculated assuming using three-foot spacing on the columns. 3720 columns are required for treating the area. Eight columns per day are completed. Cement must be added at 25% by weight. Two single stem rigs are used for this application.
  - No estimate for air monitoring, sampling, and testing is included.
  - Security, utilities, grading, etc. are not included. Level D protective equipment is required and included.
  - Cost for work at a government facility may be 10 to 50% higher.
  - Costs are estimated by Geo-Con as of 1996. If the contract is written as performance based, additional mixing time should be priced on an hourly or cost-plus basis.

Technique	Schedule (Production Weeks)		Mobilization ($)	Unit Costs ($/cy)	
	8 ft.	10 ft.		8 ft.	10 ft.
Hot Air Injection	28.8	18.4	250,000	75	60
Stabilization	14.4	9.2	150,000	55	45
Jet Mixing	55.8		70,000	170	

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- Early and continuous communication with the regulatory community is essential when assessing and determining the application of unproven or innovative technologies.

  - At the Portsmouth Gaseous Diffusion Plant, the regulators were brought in to work with the site managers to select options for closure of the X-231B site. This early involvement streamlined the process for regulatory approval of the technology demonstration and also the later closure of the facility.

  - Regulators in charge of ground water, surface water, RCRA, and the consent decree were all involved in the process.

- The technology demonstration was conducted by modifying the closure plan for the X-231B facility. No RD&D Permit was required.

- The closure of the X-231B facility was approved by Ohio EPA, requiring a performance standard of 70% mass removal. Actual mass removal was greater than 87% for the closure. A RCRA cap was placed on the surface.

- Specific permits for this technology must be worked out with the appropriate regulators.

  - Some type of air permit may be required because of the off-gas capture and treatment part of the system.

  - An underground injection permit might be required if the treatment is occurring below the water table.

  - CERCLA or RCRA permitting may be required.

  - At federal facilities a NEPA review may be required.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Potential worker safety risks for all the processes include those associated with standard drilling operations and potential exposure to VOCs and particulates in off-gas.

- Peroxide Injection: The hydrogen peroxide concentrations utilized were sufficiently low that it was not considered a hazardous material and its handling was of limited health and safety concern. While hydrogen peroxide at 5% by weight concentration is relatively harmless, it does require precautions in handling.

Community Safety

- ISESM with an operational off-gas treatment system does not produce any significant routine release of contaminants.

- No unusual or significant safety concerns are associated with transport of equipment, samples, waste, or other materials associated with ISESM.

Environmental Impacts

- ISESM disturbs the ground surface during operations. But because the site is remediated rapidly, long term effects are minimal.

- Operation of the equipment creates moderate noise in the immediate vicinity.

Socioeconomic Impacts and Community Perception

- ISESM has a minimal economic or labor force impact.

- The general public has limited familiarity with ISESM.

SECTION 7

LESSONS LEARNED

Design Issues

- The equipment utilized for all process components was commercially available. However, the equipment may need to be specially modified for a particular application.

- More recent experience suggests that an 8-ft. diameter auger may be optimum for this type of application.

- Hot Air Injection:
  - The orifices in the 2-arm, 10-ft. diameter tool were reduced to 0.25 in. from the ambient air size of 0.5 in. to increase the back pressure and enable maintenance of higher temperatures, thus encouraging further volatilization of contaminants.

  - A compressor operator was required to manually control system airflow, temperature, and pressure. However, the system has now been modified to be controlled automatically.

- Peroxidation:
  - Peroxide must be delivered by tank truck or rail car to meet required treatment processing.

- Solidification/Stabilization:
  - Laboratory treatability studies were performed to test the best grout formulation. The grout recommended contained 25% cement, 10% granular activated carbon, fly ash to increase fluidity and a retarder. Other more simple and less costly formulations have been successfully used at other locations.

Implementation Considerations

General observations regarding operation of each treatment process tested at the X-231B site.[a]

Technology	Soil treatment rate[b]	Operational simplicity and stability	Safety issues	Secondary waste generation
Hot air vapor stripping	~15 c.y. per hour.	Only requires an air compressor.	Heavy equipment operation; compressed hot air.	Off-gas and decontamination fluids.
Ambient air vapor stripping	~15 c.y. per hour.	Only requires an air compressor.	Heavy equipment operation; compressed air.	Off-gas and decontamination fluids.
Peroxidation	~45 c.y. per hour.	Requires chemical injection system	Heavy equipment operation; H_2O_2; compressed air.	Off-gas, excess H_2O_2, and decontamination fluids.
Solidification	~45 c.y. per hour.	Requires grout injection system.	Heavy equipment operation; grout handling equipment.	Off-gas, excess grout, and decontamination fluids.

a The information shown is preliminary and intended for general comparison only.
b Soil treatment rates (per equipment operating) were estimated assuming a process treatment efficiency of 70 to 95%.

- Injection of grout for solidification/stabilization required adjustments, including those made in the field. The grout formulation was adjusted by:
  - changing from powdered to granular activated carbon,
  - adding fly ash to increase the consistency and fluidity of the grout,
  - adding a retarder to provide a working time of 2 hours,
  - adding water to the grout at the site to further increase workability.

- In situ solidification of contaminated soil materials was more complicated than originally anticipated. This was due in part to the difficulty in effectively mixing the dense clay soils in situ and to delivering the proper volume of grout of the appropriate formulation. There are likely to be infield adjustments to the grout formulation and injection volume after working knowledge of the grout delivery system and the site conditions are acquired. Field experience since the demonstration has improved the process to make it more effective and efficient.

- Generation of secondary liquid wastes, namely waste grout from the delivery trucks and from rinsing out the mixing equipment, could be appreciable in the solidification process operation. An improved "grout-on-demand" system has been developed to minimize waste.

Technology Limitations/ Needs for Future Development

- Potential enhancements to the ISESM approach include:
  - ◊ more mobile and scaled down mixing equipment
  - ◊ more efficient coupling of treatment processes

- Other technologies may be coupled to the ISESM process as a post-soil mixing enhancement:
  - ◊ passive treatment processes for in situ treatment
  - ◊ soil vapor extraction
  - ◊ bioremediation

- Other reagent additives should be examined as alternatives:
  - ◊ other oxidants (e.g., permanganate, ozone)
  - ◊ reductants (e.g., zero-valence metals)
  - ◊ sorbents (e.g., peat or zeolites).

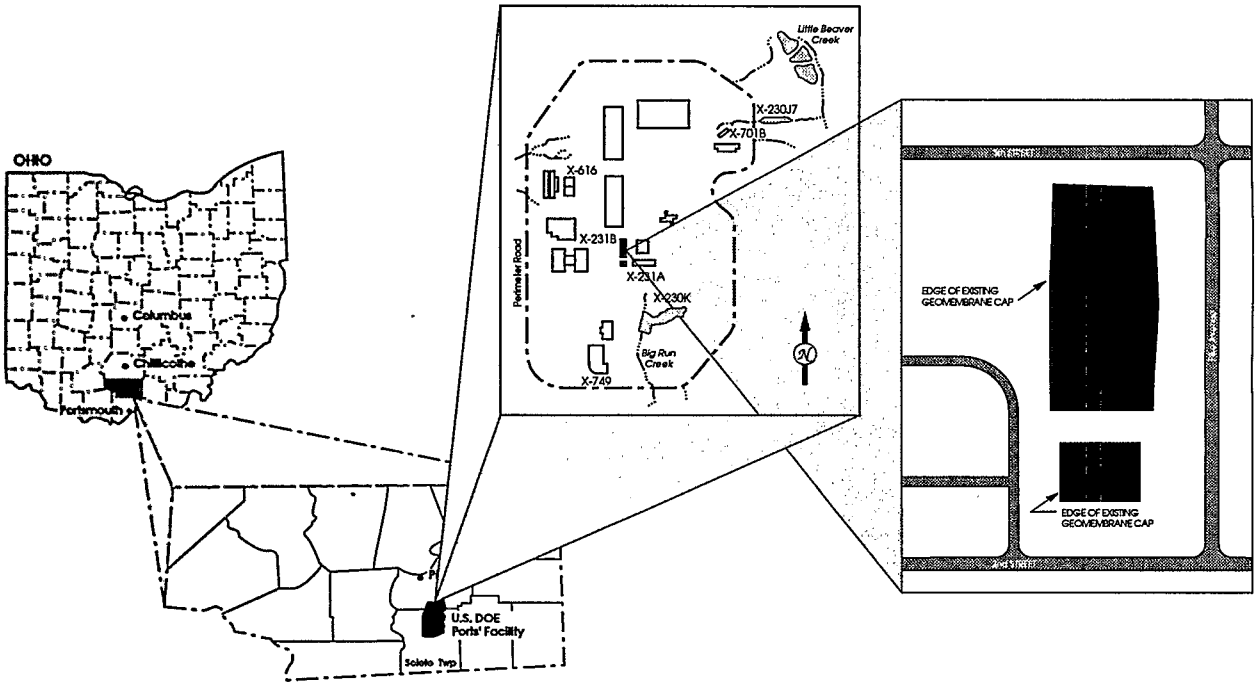
- Improvements in equipment and experience will eventually reduce costs further.

APPENDIX A

DEMONSTRATION SITE CHARACTERISTICS

Background

- The DOE Portsmouth Gaseous Diffusion Plant is located approximately 70 miles south of Columbus in southern Ohio.



Location of the DOE Portsmouth Gaseous Diffusion Plant and the X-231B Unit

- The X-231B waste management unit consists of two adjacent waste oil biodegradation areas. The X-231B Unit encompasses about 0.8 acres and was reportedly used from 1976 to 1983 for the treatment and disposal of waste oils and degreasing solvents, some containing uranium-235 (^{235}U) and technetium-99 (^{99}Tc). TCE and other VOCs remained in the soil and spread into the shallow ground water.

Site Characterization

- Physical, chemical and biological properties of subsurface soil at the X-231B site as measured in samples collected in 1990.

	Nominal depth and boring location					
	Shallow (7-ft depth)			Deep (17-ft depth)		
Characteristic[a]	**SB01**	**SB02**	**SB03**	**SB01**	**SB02**	**SB03**
Depth, ft	7.2	6.2	6.2	17.2	17.2	17.2
Particle size distribution:						
Clay: <0.002 mm, wt%	22.5	na	25.0	14.0	12.0	15.0
Silt: 0.002-0.05 mm, wt%	65.5	na	67.0	64.0	55.0	39.0
Sand: 0.05-2.0 mm, wt%	12.0	na	8.0	22.0	33.0	46.0
Water content, dry wt %	17.6	na	19.0	23.5	23.5	22.0
Percent solids, wt%	86.6	na	81.0	81.8	81.0	81.2
pH	5.32	na	5.96	7.40	6.16	7.01
Total organic carbon, mg/kg	579	na	1190	245	184	472
Kjeldahl nitrogen, mg/kg	<500	na	<500	<500	<500	<500
Total phosphorus, mg/kg	66	na	66	66	73	108
Total sulfur, mg/kg	24	na	<10	23	30	<10
Exchangeable cations:[b]						
Calcium, mg/L	47	na	48	60	37	71
Magnesium, mg/L	42	na	31	28	25	34
Sodium, mg/L	9.4	na	6.0	10.6	3.1	15.1
Potassium, mg/L	6.3	na	4.5	6.0	4.0	5.0
Percent moisture[c], wt%	17.9	18.7	20.1	23.0	23.5	23.4
Liquid limit[c], wt%	na	na	na	25.30	25.55	25.73
Plastic limit[c], wt%	na	na	na	22.19	22.63	20.56
Plasticity index[c], wt%	na	na	na	3.11	2.92	5.17
Total bacteria, CFU/g	2.26E04	2.37E05	1.02E04	<1E02	<1E02	<1E02
Methanotrophs,	Detected	Detected	Detected	Not Detected	Not Detected	Not Detected

na Indicates analyses not performed.
[a] Results of analyses are expressed on a field moist soil weight basis unless otherwise indicated.
[b] Averages of duplicate analyses; coefficient of variation for duplicates was <5%.
[c] Percent moisture (wet wt. %) analyses performed by Geraghty & Miller, Inc., Dublin, Ohio.

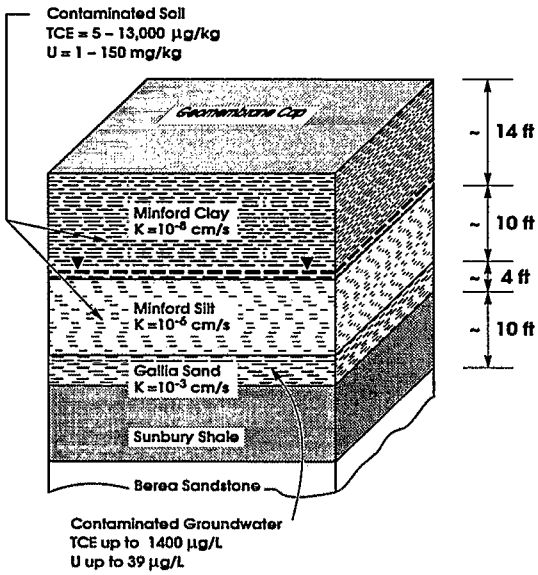
- Contaminants of Concern

◊ Soil
- Thirteen VOCs were identified with the following being most prevalent and at the highest concentrations (i.e., several hundred to several thousand micrograms per kilogram).
  trichloroethylene (TCE)
  1,1,1-trichloroethane (TCA)
  1,1-dichloroethylene (1,1-DCE)
  methylene chloride
- The highest concentrations were found in the unsaturated zone (~7-ft depth) near the center of the plot.
- Low levels of ^{235}U and ^{99}Tc are also present.

◊ Ground water
- The shallow ground water was also contaminated with some contaminants at levels well above drinking water standards.

Contaminant Locations and Hydrogeologic Profiles

- Ground water underneath the X-231B unit occurs in two aquifer systems: the Minford/Gallia Members and the Berea Sandstone. Existing site characterization data revealed that beneath the X-231B unit were fluvio-lacustrine silts and clays (Minford Member of the Teays Formation) underlain by silty sand and gravel (Gallia Member). The Gallia Member lies at a depth of approximately 25 ft and typically does not exceed 4 ft in thickness. Bedrock below the Gallia is the Mississippian age Sunbury Shale. The Sunbury Shale is 10 to 12 ft thick, slightly fractured, and has very low permeability. The water table in this area is approximately 10 to 14 ft below ground surface (bgs). Ground water flow occurs vertically through the Minford Member into the Gallia Member where flow is predominantly horizontal to the southeast toward a surface impoundment.



Subsurface characteristics beneath the X-231B Unit.

- Thirty-six groundwater monitoring wells have been installed in the vicinity of the X-231B unit. Twenty-five wells have been installed and screened within the Gallia deposit, but only three wells have been screened in the overlying Minford. Eight wells penetrate into the underlying bedrock (i.e., Sunbury or Berea).

- The hydraulic conductivities of all the shallow units are low. Laboratory measurements revealed a saturated hydraulic conductivity (K_{sat}) of only 0.00023 feet per day (ft/d) for the Minford clay and 0.0043 ft/d for the Minford silt. Field pumping tests yielded a substantially higher mean K_{sat} for the Gallia deposit of 7.1 ft/d. The lower portion of the Minford is in hydraulic continuity with the Gallia.

- The permeability of the Sunbury Shale is believed to be very low. Although thin and slightly fractured, the Sunbury may hydraulically isolate the underlying Berea from the overlying unconsolidated aquifer (i.e., Minford/Gallia).

- Several VOCs (e.g., TCE and 1,1,1-TCA) are present throughout the Minford Member under the X-231B site from the ground surface to approximately 25 ft bgs. These same contaminants are present in the shallow ground water underneath and up to 750 ft downgradient from the X-231B Unit boundaries. The primary soil and ground water contaminant is TCE, which is present in the ground water at levels above federal drinking water standards.

- The Minford deposit beneath the X-231B Unit extends from the ground surface to approximately 22- to 24-ft depth. The Minford is comprised of an upper zone (top 12 ft or so) that is finer textured than the lower zone. Intensive sampling and analysis of the Minford deposit was conducted to delineate the contaminant distribution throughout the deposit to enable development of the treatment locations for the field test. Analysis of the results of this work revealed that approximately 78% of the VOCs are located in the upper 12 ft, above the water table. As a result, the field test was designed to focus on treatment of the unsaturated portion of the Minford deposit (i.e. the upper 15 ft). In addition, a single test was conducted to a depth of approximately 22 ft to provide some operational information for treatment of the lower Minford deposit, located below the water table.

Summary of Operating Conditions

Operating Parameters	Units	Hot Air Stripping	Hot Air Stripping - Deep	Ambient Air Stripping	Peroxidation Destruction	Solidification Stabilization
Auger rotation speed	rpm	5 to 10	5 to 10	5 to 10	5 to 10	5 to 10
Auger vertical movement rate	fpm	1	1	1	1	1 to 3
Mixed region diameter	ft	10	10	10	10	10
Mixed region depth	ft	15	22	15	15	15
Mixed region volume	cf	1180	1730	1180	1180	-
Air delivery rate	cfm	1000-1400	1000-1400	1000-1400	800 initially, reduced to 300	0
Air exchange in soil column	RV/min	0.8 - 1.2	0.6 - 0.8	0.8 - 1.2	-	-
Air temperature at the source	°F	250	250	90	90	-
Air pressure at the source	psig	180	180	100	80	-
Shroud vacuum	in. H_2O	~ 5	~ 5	~ 5	-	~ 5
Peroxide injection rate	gpm	-	-	-	7.5	-
Peroxide injection volume	vol./vol.	-	-	-	ave. of 0.07	-
Peroxide concentration	wt%	-	-	-	5	-
Grout injection rate	vol.%	-	-	-	-	30
Off-gas flow rate	cfm	-	-	-	-	100-120
Treatment cycles						
0 to 7 ft zone	down/up	8	8	8	2	
7 to 15 ft zone	down/up	4	4	4	1	
0 to 15 ft zone	down/up					3 to 4
Treatment time per column	min	225	225	225	75	30 to 45

~	approximately	cf	cubic feet
cfm	cubic feet per minute	fpm	feet per minute
gpm	gallons per minute	°	degrees Fahrenheit
in H_2O	inches of water	min.	minutes
psig	pounds/square inch (gauge)	RV/min	reactor volumes/minute
vol%	per cent by volume	wt%	per cent by weight

Treatment Performance: General Observations

General Observations for Each Treatment Process Tested at the X-231B Site.

Technology and components	VOC treatment process	VOC removal efficiency	Effect on non-VOC contaminants	Effect on soil properties	Effect on unmixed adjacent soil
Hot Air Vapor Stripping. An air compressor to deliver ~1400 cfm of 250°F air through a hollow kelly bar via jets in a 10 ft. auger.	Mass transfer and advective removal for ex situ capture and destruction	>95% mass removal after 3.75 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Limited if any; stimulation of biological activity and possible degradation of SVOCs	Disrupts natural soil structure. Injection of hot air stimulated some increased biological activity.	Limited impact on soil gas concentrations or pressure.
Ambient Air Vapor Stripping. An air compressor to deliver ~1400 cfm of 90°F air through a hollow kelly bar via jets in a 10ft. auger.	Mass transfer and advective removal for ex situ capture and destruction	>90% mass removal after 3.75 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Limited if any; stimulation of biological activity and possible degradation of SVOCs	Disrupts natural soil structure. Injection of air stimulates markedly increased biological activity.	Limited impact on soil gas concentrations or pressure.
Peroxidation. An air compressor to deliver ~300 cfm of 90°F and 7% v/v addition of 5 wt% H_2O_2 in air through a hollow kelly bar via jets in a 10ft. auger.	H_2O_2 interacts with soil Fe to oxidize VOCs in situ. Limited VOCs in off-gas are captured for destruction	>70% mass removal after 1 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Increased binding of metals. Preoxidation of SVOCs for biodegradation.	Mixing disrupts natural soil structure. Injection of H_2O_2 does not "sterilize" soil. H_2O_2 can reduce soil permeability of clays.	Limited impact on soil gas concentrations or pressure.
Solidification. An injection system to deliver ~ 1.5 cfm of 30% v/v (20% wt/wt) grout through a hollow kelly bar via jets in a 10ft. auger.	Grout solidifies the soil and immobilizes the VOCs in situ. Limited VOCs in off-gas are captured for destruction by either carbon adsorption, catalytic oxidation, biotreatment, etc.	>90% apparent capture of VOCs in preset grout/soil mix after 1 hr of treatment in a 10 ft. diameter by 15 ft. deep column.	Encapsulation and stabilization of metals in grout.	Mixing disrupts natural soil structure. Injection of grout reduces permeability significantly.	Limited impact on soil gas concentrations or pressure.

Treatment Performance: Post-demonstration Soil Chemical Analyses

Results of selected TCLP analyses of grouted soil after in situ solidification.

Target analyte	Cores collected at 15 months (mg/L) [a]		Post-demonstration grout soil samples (mg/L) [b]		
	4-5 ft. depth	8-9 ft. depth	4-5 ft. depth	8-9 ft. depth	TCLP Limits (mg/L)
Carbon Tetrachloride	< 0.025	< 0.025	< 0.15	< 0.15	0.5
Benzene	< 0.025	< 0.025	< 0.09	< 0.09	0.5
1,2-Dichloroethane	< 0.025	< 0.025	< 0.10	< 0.10	0.5
Trichloroethylene	0.08	< 0.025	< 0.22	< 0.22	0.5
Barium	9.4	2.9	...	...	100.0
Lead	< 0.05	< 0.05	...	...	5.0
Uranium	< 0.0004	< 0.0004	...	...	...

a Samples collected 15 months after in situ solidification in August 1993 and analyzed at ORNL Analytical Chemistry Division.
b Samples collected immediately following in situ solidification in May 1992 and analyzed at the Clemson Technical Center, Clemson, South Carolina.

Treatment Performance: Physicochemical Properties of Soil, Pre-and Post-Demonstration

Physicochemical properties of the untreated and solidified X-231B soil.

Sample description	Sample depth (m)	Water content (wt%) [a]	Bulk density (g/cm³)	Compressive strength (kPa)	Hydraulic conductivity [b] (cm/sec)
Untreated	0.3-0.6	20.5 [c]			
control core	1.2-1.5	16.9 [c]	2.15	...	8.08×10^{-8}
	2.4-2.7	18.4 [c]	1.75	...	...
	3.9-4.2	16.5 [c]	...	...	8.09×10^{-8}
S/S core	0.3-0.6	19	1.73 [c]	5200 [d]	8.88×10^{-6}
	1.2-1.5	23.5	1.66 [c]	3500	...
	2.4-2.7	19	1.72	2600	...
	3.9-4.2	13.6	2.00 [c]	390	7.75×10^{-6}

[a] Analyses performed at 60°C.
[b] All values represent at a minimum, the average of 6 replicate analyses. Data reported at 25°C per ASTM D5084. Permeant fluid = 0.005M $CaSO_4$.
[c] Average of analyses of two samples.
[d] Sample taken at the 1-m depth.

APPENDIX C

TECHNOLOGY SELECTION DETAIL

Technology Selection

Selection of the most promising technologies for demonstration at X-231B was accomplished by a ration ranking process. The approach enabled rigorous evaluation of each technology and provided results regarding implementation, operation and maintenance, performance and cost. The following table summarizes key information from this process for comparison of technologies.

Technology	Estimated Time for Installation & Operation	Processing Rates	Minimization of Full-scale Remediation Costs[a]
In situ immobilization	1 month	1000 cy/d	54
In situ hot air/steam stripping	rapid	3 to 10 cy/hr	50
In situ electrokinetics	additional research required prior to VOC application	N/A[b]	38
In situ jet mixing and slurry reactor	1 month	N/A[b]	46
In situ electromagnetic or radiofrequency energy heating	5 months (3 mo. installation, 2 mo. operation)	20 cy/d for demo 200 tons/d full scale	39
In situ (ex situ) hydrogen peroxide	Installation about 1 week, operation about 1 month	100 cy/d	39
Ex situ thermal desorption	5 months to 2 years	100 to 200 tons/d full scale	34
Ex situ immobilization	1 months	10,000 to 20,000 cf/d	49

a Score listed is the result from the ranking process. The higher the score the greater the ability of the technology to minimize full-scale remediation costs.
b Not done to remove VOCs at the time of this demonstration.

APPENDIX D

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Flameless Thermal Oxidation at the M Area, Savannah River Site, Aiken, South Carolina, in Cooperation With the U.S. Department of Energy Oak Ridge Operations

Case Study Abstract

Flameless Thermal Oxidation at the M Area, Savannah River Site, Aiken, South Carolina, in Cooperation With the U.S. Department of Energy Oak Ridge Operations

Site Name:
U.S. Department of Energy (DOE), Savannah River Site, M Area Process Sewer/Integrated Demonstration Site

Location:
Aiken, South Carolina

Contaminants:
Chlorinated Aliphatics
- Trichloroethene (TCE), tetrachloroethene (PCE), and 1,1,1-trichloroethane (TCA)
- TCE concentrations in the off-gas ranged from 157 to 291 ppm, PCE from 243 to 737 ppm, and TCA from 12 to 21 ppm.

Period of Operation:
April to May 1995

Cleanup Type:
Field demonstration

Vendor:
Bob Wilbourn
Thermatrix, Inc.
(615) 539-9603

Technical Information:
Tim Jarosch, Prin. Inv., WSRC,
(803) 725-5189
Richard Machanoff, HAZWRAP,
(615) 435-3173

SIC Code:
9711 (National Security)
3355 (Aluminum Forming)
3471 (Metal Finishing)

Technology:
Post-Treatment (Air) - Flameless Thermal Oxidation
- Flameless Thermal Oxidizer (FTO) is a commercial technology available from Thermatrix, Inc.
- FTO uses a heated packed bed reactor typically filled with saddle- and spherical-shaped inert ceramic pieces to destroy chlorinated and non-chlorinated volatile organic compounds (VOCs) in vapors extracted by a Soil Vapor Extraction (SVE) system.
- Designed to oxidize off-gases without forming PICs or HAPs; not viewed as an incineration technology.

Cleanup Authority:
State: Air discharge permits for the Savannah River demonstration site are in place with the South Carolina Department of Health and Environmental Control (SCDHEC)

Point of Contact:
Jef Walker, DOE,
(301) 903-7966
Jim Wright, DOE,
(803) 725-5608

Waste Source:
Surface impoundment (unlined settling basin)

Purpose/Significance of Application:
FTO was demonstrated as an alternative technology for treatment of extracted vapors during an SVE application to oxidize off-gases without forming PICs or HAPs.

Type/Quantity of Media Treated:
Off-gases (extracted vapors)
- Information not provided on quantity treated

Regulatory Requirements/Cleanup Goals:
- The Savannah River site maintains air discharge permits for in situ remediation demonstrations associated with VOCs in non-arid soils and ground water.
- No specific regulatory requirements or cleanup goals were identified for the FTO demonstration.

Case Study Abstract

Flameless Thermal Oxidation at the M Area, Savannah River Site, Aiken, South Carolina in Cooperation With the U.S. Department of Energy Oak Ridge Operations (Continued)

Results:
This demonstration was evaluated in terms of destruction and removal efficiency (DRE) for specific VOCs and total chlorinated VOCs (CVOCs).
- The FTO unit achieved >99.995% DRE for PCE and >99.95% for TCE and total CVOCs during a 22-day continuous operation testing stage.
- The FTO unit achieved >99.995% DRE for total CVOCs during a 2.5 day testing period where the influent stream was spiked with 950 to 3060 ppm CVOC.

Cost Factors:
- Capital cost for the FTO unit used in the demonstration was $50,000 (for an electrically heated, 5 scfm unit without an integrated caustic scrubber).
- Total operating costs for FTO technology were estimated at $0.72 per pound of CVOC destroyed, including costs for capital recovery, energy, labor, and maintenance.
- No additional details provided on components of capital or operating costs; however, the authors report that FTO costs less per pound of CVOC destroyed than competing technologies such as thermal catalytic technologies.

Description:
From 1958 to 1985, Savannah River Area M conducted manufacturing operations including aluminum forming and metal finishing. Process wastewater from these operations containing solvents (TCE, PCE, and TCA) was discharged to an unlined settling basin at Savannah River, which lead to contamination of ground water and vadose zone soils. Treatment of vadose zone soils has been the subject of several demonstrations (e.g., in situ air stripping), including this investigation of the technical and economic performance of off-gas treatment technologies.

Flameless thermal oxidation (FTO) is a commercial technology used in a demonstration at Savannah River Area M to treat chlorinated VOCs in off-gasses extracted using a SVE system. FTO uses a heated packed bed reactor typically filled with saddle- and spherical-shaped inert ceramic pieces to destroy chlorinated and non-chlorinated VOCs in vapors extracted by a SVE system. The demonstration was based on pumping from one horizontal SVE well at a flow rate of 5 scfm, and the thermal reaction zone in the FTO was maintained at 1400 to 1700°F. A caustic scrubber was not included in this demonstration because of the relatively small quantity of HCl produced.

This demonstration was evaluated in terms of destruction and removal efficiency (DRE) for specific VOCs and total chlorinated VOCs (CVOCs). The FTO unit achieved >99.99% DRE for PCE, and >99.995% DRE for total CVOCs during a testing period where the influent stream was spiked with CVOC. During the continuous and spike testing phases, no PICs or HAPs were detected in the FTO effluent.

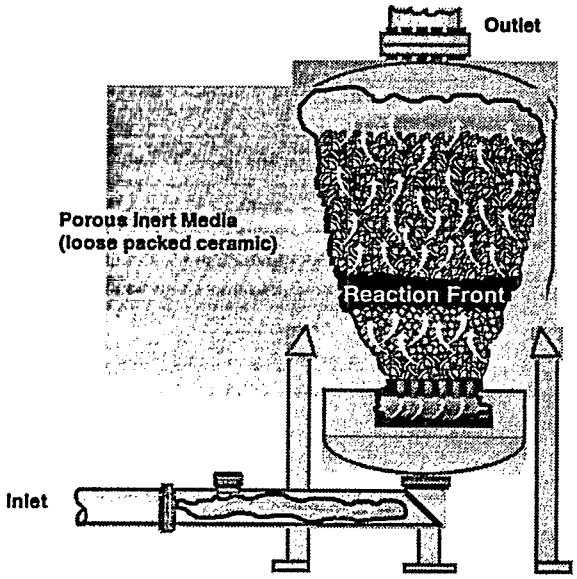
SECTION I

SUMMARY

Technology Description

The Flameless Thermal Oxidizer (FTO) is a commercial technology offered by Thermatrix, Inc. The FTO has been demonstrated to be an effective destructive technology for process and waste stream off-gas treatment of volatile organic compounds (VOCs), and in the treatment of VOC and chlorinated volatile organic compounds (CVOCs) off-gases generated during site remediation using either baseline or innovative in situ environmental technologies. The FTO process efficiently converts VOCs and CVOCs to carbon dioxide, water, and hydrogen chloride. When FTO is coupled with a baseline technology, such as soil vapor extraction (SVE), an efficient in situ soil remediation system is produced.

The innovation is in using a simple, reliable, scalable, and robust technology for the destruction of VOC and CVOC off-gases based on a design that generates a uniform thermal reaction zone that prevents flame propagation and efficiently oxidizes off-gases without forming products of incomplete combustion (PICs).



- The FTO provides destruction and removal efficiencies (DREs) in excess of 99.99% for hydrocarbons and CVOCs.
- The FTO unit yields extremely low NOx formation (typically < 2 ppmv) and extremely low CO formation (typically below the limits of detection) as measured from the effluent stream.
- The FTO can compensate for operations of low flow rates with low concentrations to high flow rates with high concentrations without affecting DRE.
- The FTO unit operates with a low pressure drop across the FTO reactor, typically < 3 inches of water.
- The FTO unit has been applied to gas flow rates ranging from 1 scfm to 6500 scfm.
- The Thermatrix FTO offers low capital and operating costs.
- The FTO is engineered to operate safely and includes the following safety design features:
  - operations below lower explosion limits,
  - inherent flame arrestor (ceramic matrix), and
  - large heat sink (ceramic matrix) to accommodate process fluctuations.
- The FTO has been permitted for many hazardous air pollutant (HAP) control applications.

Technology Status

A full-scale demonstration was conducted at the Savannah River Integrated Demonstration site where DOE has tested a number of off-gas treatment technologies.

U.S. Department of Energy
Savannah River Site
M Area Process Sewer/Integrated Demonstration Site
Aiken, South Carolina
April to May 1995

- The demonstration was conducted by the Savannah River Technology Center by a scientific team that had evaluated and analyzed technical and economic performance of other off-gas treatment technologies.

The demonstration site was located at one of the source areas within the 1-mile^2 VOC groundwater plume. Before the application of FTO coupled to SVE, the trichloroethylene (TCE), tetrachloroethylene (PCE), and 1,1,1-trichloroethane (TCA) concentrations in the off-gas ranged from 157 to 291 ppm, 243 to 737 ppm, and 12 to 21 ppm, respectively. The site conditions are described in more detail in Appendix A.

Key Results

- In 22 days of continuous operation treating DOE Savannah River Site wellhead SVE effluent, a total of 11.17 Kg of total CVOC was destroyed with no identifiable products of incomplete oxidation observed in any outlet sample.
- The Thermatrix unit successfully met and exceeded the 99.99% DRE for PCE at operating conditions of 1600°F and 5 scfm.
- All of the analyzed outlet samples were found to be below the analytical methodology detection limit with respect to any of the primary CVOCs in the inlet stream.
- The concentrations of TCE and TCA in the inlet feeding from the well were too low to enable a DRE measurement of > 99.99%; however, PCE is the major contaminant and typically the most difficult to destroy using thermal techniques and, therefore, the DRE for PCE is viewed as representative of the technology's true performance.
- In tests in which the feed stream was spiked with PCE, TCE, and TCA, the respective DREs were measured at > 99.995%, > 99.99%, and approaching 99.99%, respectively. These values represent the minimum DREs attained as all of the outlet samples were determined to be below the limit of detection of the analytical methodology with respect to PCE, TCE, and TCA.

The FTO is commercially available through Thermatrix, Inc.; more than 20 units have been placed in operation.

Contacts

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Applications
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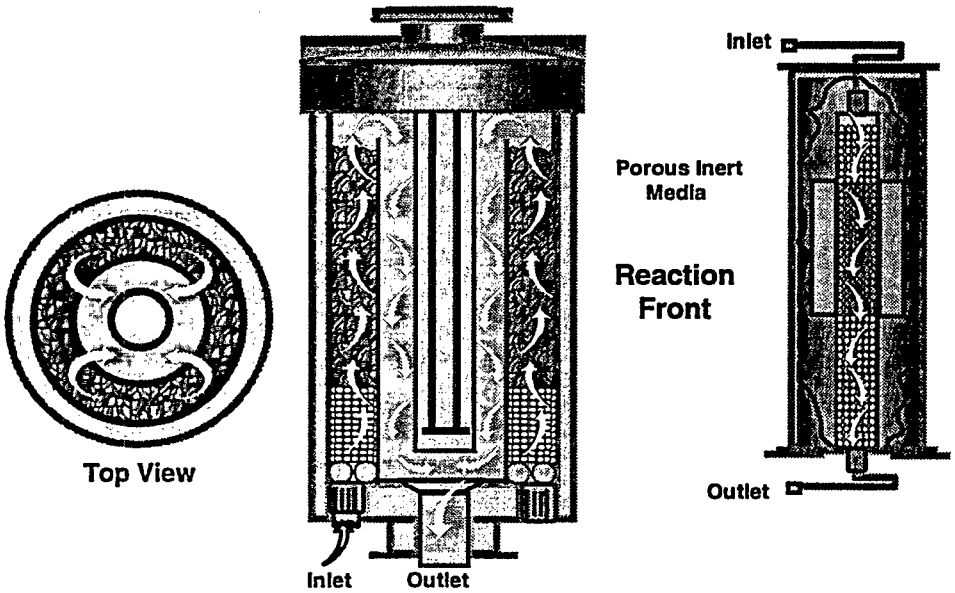
SECTION 2

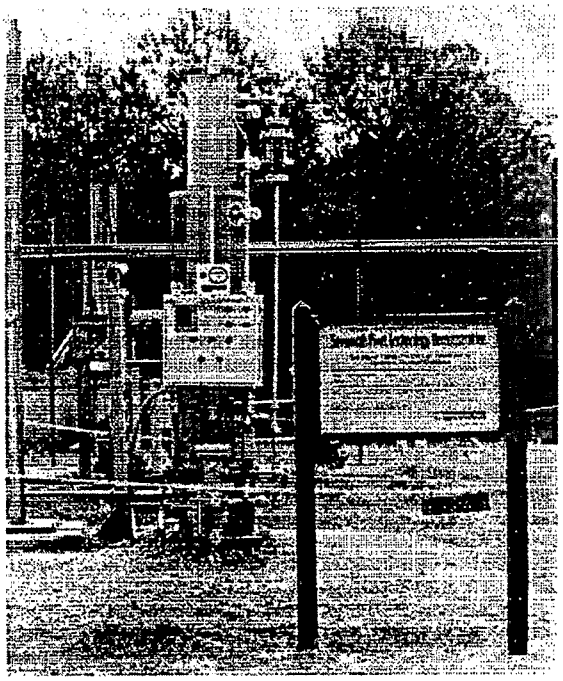
TECHNOLOGY DESCRIPTION

Overall Program Schematic

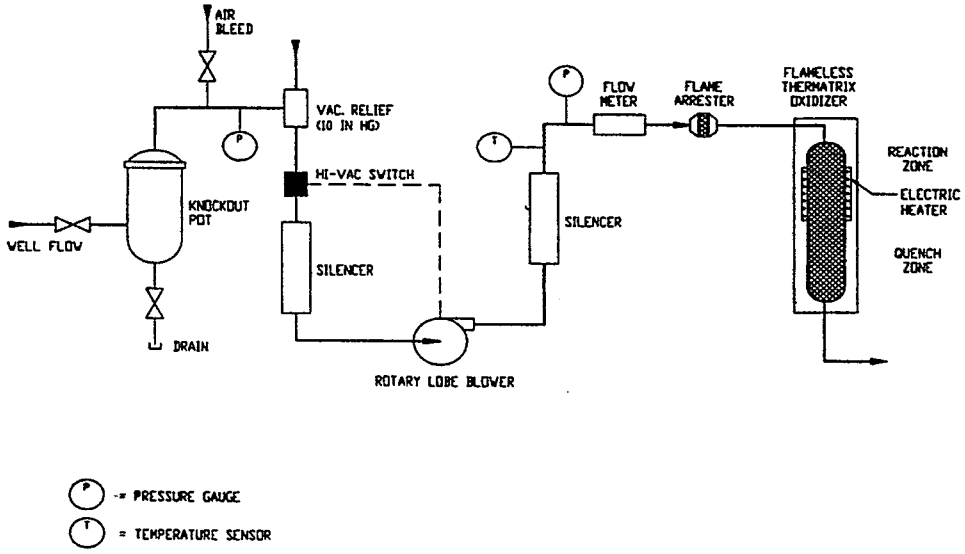


- The Thermatrix FTO technology achieves uniform thermal oxidation of CVOCs and VOCs using a heated packed-bed reactor typically filled with saddle- and spherical-shaped inert ceramic pieces.
- The oxidation of organic compounds occurs in a uniform thermal reaction zone contained in the packed bed of an inert ceramic matrix typically maintained at temperatures of 1600°-1850° F.
- The FTO design eliminates problems of temperature gradients, mixing, and resulting formation of PIC and HAP.
- The large thermal mass of the inert ceramic matrix enables it to store or release large amounts of heat without rapid changes in temperature and provides flame suppression within the FTO reactor.

Demonstration of Thermatrix Technology



Aboveground System



- The source of the air/CVOC feed gas used in this demonstration was well AMH-4, one of seven horizontal wells at the DOE SRS Demonstration Site.
- The well was pumped with a small SVE unit capable of providing up to 10 scfm of flow.
- The SVE system removed contaminant vapors and air from the subsurface; the vapors were passed through a knockout pot to remove any entrained moisture.

- The effluent from the SVE unit was fed directly to the inlet of a Thermatrix ES - 300H for treatment by FTO with the SVE pump providing the motive force for the FTO feed stream.
- CVOCs extracted from the soil by the SVE unit were oxidized in the Thermatrix oxidizer to form CO_2, H_2O, and HCl.
- The small scale of the demonstration permitted operation of the FTO without a caustic scrubber to remove the HCl produced. In large-scale operations, the FTO effluent stream would be coupled with a caustic scrubber.

SECTION 3

PERFORMANCE

Demonstration Plan

- Performance of the technology has been assessed using information from the demonstration at SRS.
- Three operational modes were tested during the demonstration:
  - Preliminary testing to determine optimal parameters for continuous operation (2.5 days)
  - Continuous operation testing stage (22 days)
  - Spike testing stage to increase the level of detection for determining DRE (2 days)

Treatment Performance

Summary

- The FTO successfully destroyed a CVOC air/gas mixture generated by SVE at the SRS Demonstration Site.
- The FTO unit achieved > 99.995% DRE for PCE and >99.95% DRE for TCE and total CVOC during the continuous testing phase of the 22-day demonstration.
- During the demonstration, concentrations of PCE, TCE, and total CVOC in the FTO influent decreased as a result of the continual removal of CVOCs from the subsurface by SVE. Lowered concentrations of the FTO influent limited the minimal concentrations of CVOC that could be detected in the FTO effluent.
- Over a 2.5-day period, the FTO influent stream was spiked with 950 to 3060 ppmv total CVOC in an effort to extend the detection limits of FTO effluent, and DREs were measured at >99.995% for total CVOC.
- Throughout the continuous testing stage and the spike test phase, no PICs or HAPs were detected in the FTO effluent.
- During the continuous testing stage and the spike test phase of the demonstration 11.27 and 1.5 kg total CVOC were destroyed, respectively.
- The only downtime experienced over the course of testing was to change the oil in the rotary pump of the mini-SVE every 10 days (approximately 1 hour per oil change).

Key System Parameters

- The FTO was operated in a continuous mode at 5 scfm and 1600° F for 22 days.
- The FTO operated with minimal attention and required no maintenance or repairs for the 6 weeks of the demonstration.
- CVOCs were extracted from the subsurface from a horizontal well by means of a mini-SVE unit and supplied to the FTO at 5 scfm.
- The FTO influent CVOC concentrations during the preliminary and continuous demonstration operation varied from 400 to 1000 ppmv with typical equilibrium concentrations of 400 to 600 ppmv.

- The FTO was electrically heated, though methane or propane would be the heat source for large-scale remediation with a >100 scfm throughput.

- The demonstration site air permit did not require caustic scrubbing of the HCl released from the treatment of CVOCs by the FTO technology, but a caustic scrubber would be required during full-scale site remediation.

Amount of VOCs Destroyed

- During the preliminary testing stage of the demonstration, the optimal operating conditions for the FTO were verified at 5 scfm and 1600°F and >1.5 Kg total CVOC were destroyed during this phase of the demonstration. The parameters tested are described in the table below.

- During 22 days of continuous operation, the FTO destroyed 11.17 Kg of CVOCs.

- The vapor contaminants consisted primarily of PCE (70.5%), TCE (28.2%), and 1,1,1-trichloroethane (TCA = 1.2%).

- The FTO successfully destroyed the targeted chlorinated organics with a DRE >99.99% at its design conditions of 5 scfm and 1600° F.

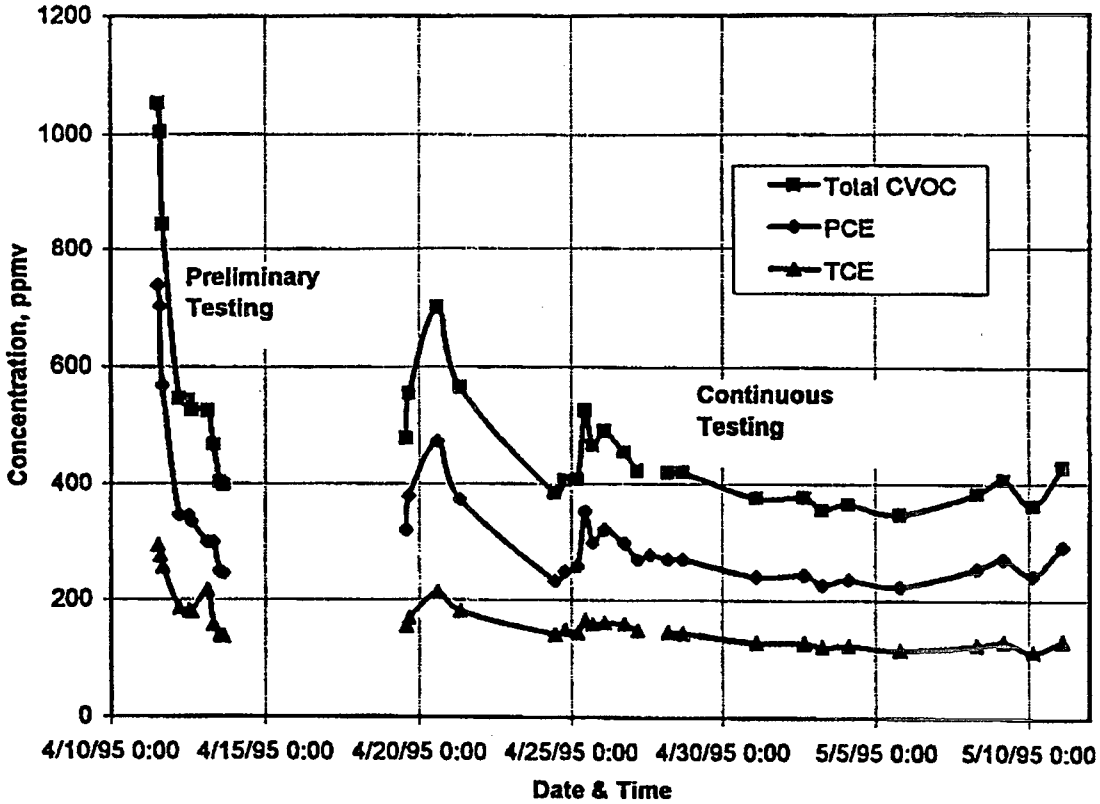
- The spike testing stage of the demonstration confirmed that the FTO could accommodate high CVOC concentration gas streams and >1.5 Kg total CVOC were destroyed during this stage of the demonstration at DRE > 99.995%.

Calculated Destruction Removal Efficiencies (DREs) During Preliminary Testing

Operating Conditions (time on stream[a])	PCE DRE	CVOC DRE
1600°F & 5 scfm (30 min)	9.99932E-01[b]	9.99382E-01
1600°F & 5 scfm (2.5 hrs)	9.99929E-01[b]	9.99352E-01
1600°F & 7 scfm (1 hr 15 min)	9.99700E-01	9.99087E-01
1500°F & 5 scfm (12 hrs)	9.87157E-01	9.90782E-01
1700°F & 5 scfm (1 hr 15 min)	9.99971E-01[c]	9.99705E-01
1400°F & 5 scfm (2 hrs)	9.98467E-01	9.98754E-01
1400°F & 5 scfm (14 hrs)	9.91007E-01	9.93651E-01
1400°F & 5 scfm (19 hrs)	5.29836E-01	6.16475E-01
1500°F & 3.5 cfm (1 hr 15 min)	9.99797E-01[d]	9.98387E-01
1500°F & 3.5 cfm (3 hrs)	9.99794E-01[b]	9.98363E-01

a = time on stream from establishment of current operating parameters
b = ND, normal split
c = < MDL, minimum split
d = < MDL, normal split

AMH-4 Well Concentrations (FTO Inlet) vs Time During Demonstration



Results of Spike Tests

	Conc'n (ppmv)				Calc. DRE[a]			
	PCE	TCE	TCA	Total CVOC	PCE	TCE	TCA	Total CVOC[b]
First Day No Sparge[c]	307	133		447	.999967	.999699		.999886
Sparge-1	448	242	125	954	NC	NC	NC	NC
Sparge-2	551	279	204	1126	.999982	.999856	.999804	.999913
Sparge-3	1037	607	456	2182	.999990	.999934	.999912	.999957
Second Day No Sparge	293	126		432	.999966	.999684		.9999881
Sparge-1	946	490	280	1742	.999989	.999918	.999857	.999948
Sparge-2[d]	1915	778	386	3087	.999995	.999949	.999896	.999971

NC = no outlet sample taken
a = outlet analysis for all primary constituents were nondetect. Reported DREs are minimum values (i.e., DRE>listed value).
b = total CVOC primary constituents listed in table.
c = sparge is the addition of concentrated CVOC to the FTO influent
d = well flow off, total flow is ambient air + sparge flow.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- FTO is an off-gas treatment technology that can be readily coupled with baseline or innovative remediation technologies or manufacturing processes where VOC and CVOC vapors are generated.

- FTO has been demonstrated to effectively destroy VOCs and CVOCs in off-gases from many sources, including:
  - CVOC off-gas from SVE of subsurface contaminated with PCE, TCE, and TCA;
  - VOC and petroleum vapors including the BTEX class of compounds from soil remediation, oil recycle, and manufacturing processes;
  - treatment of pulp plant noncondensable gases containing sulfur compounds;
  - treatment of methylene chloride emissions generated during pesticide production; and
  - treatment of wastewater from a chemical company containing butyl chloride, benzyl chloride, ethyl chloride, and toluene.

Competing Technologies

- Baseline technologies for treatment of CVOC and VOC off-gas from remediation processes include:
  - thermal oxidation,
  - catalytic thermal oxidation, and
  - adsorption/recovery.

- On a performance level, the flameless thermal oxidation technology can readily exceed destruction or removal efficiencies achieved by either thermal catalytic techniques or by adsorption/recovery systems.

Technology Maturity

- The FTO is a mature technology that has been successfully commercialized by Thermatrix, Inc.

- The FTO has been successfully installed and is currently operating more than 30 units in the private sector in 16 states, France, and the United Kingdom.

- The FTO technology can be scaled and tailored to site specific conditions and can be readily incorporated into existing treatment trains or manufacturing processes.

- Other innovative technologies are currently under development by DOE, including (1) activated carbon by steam reforming, (2) gas-phase bioreactor, (3) membrane separation; (4) high-energy corona, (5) silent discharge plasma, (6) xenon flashlamps, (7) pulsed combustion, and (8) solvent recycle.

- FTO is a destructive technology that differs from thermal oxidation by preventing formation of PIC and HAPs during the destruction process.

SECTION 5

COST

Introduction

- Information in this section was prepared from data provided to the Hazardous Waste Remedial Actions Program (HAZWRAP) by Thermatrix, Inc., and the Savannah River Technology Center (SRTC). HAZWRAP was tasked by the DOE Office of Technology Development to perform an independent cost analysis of the technology being demonstrated.
- The FTO provided by Thermatrix, Inc. for the demonstration was a small electrically heated 5 scfm unit without an integrated caustic scrubber.
- The site provided a low flow rate of contaminants during the demonstration, which the FTO handled with excellent technical performance.
- The FTO technology process is scalable, based on the experience of Thermatrix, and provides the basis for extrapolation of economic performance at higher flow rates.
- The conventional technologies of thermal oxidation, catalytic thermal oxidation, and adsorption/recovery technology were used as the baseline against which FTO was compared for the treatment of CVOC off-gas from SVE of the vadose zone at the demonstration site. The technologies were tested at the site with similar contaminant streams using comparable analytical methods. To compare the three technologies, a number of assumptions were made:
  - For the purposes of estimating economic performance, calculations were based on a gas recuperative style remediation grade Thermatrix FTO unit capable of treating 400 scfm of SVE well head/SVE gaseous effluent.
  - An SVE concentration of 400 ppmv (equivalent to 3.7 lb/hr CVOC) was used a basis for calculating economic performance.

Capital Costs

- Capital costs of the baseline and competing technologies of thermal oxidation, catalytic thermal oxidation, and adsorption/recovery technology are comparable with the FTO technology.
- The capital cost of the FTO used in this demonstration was $50,000.
- For the purposes of estimating economic performance, the capital cost of a 400-scfm, gas-heated FTO is $160,000.
- 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 the site.

Operating Costs

- The annual operating costs of the baseline, competing, and innovative technologies are comparable.
- However, the innovative technology FTO exceeds DRE (>99.99%) of competing technologies.
- Thermal catalytic techniques will typically achieve 98% to 99% destruction of PCE.
- Adsorption technologies, when operated at reasonable bed loadings, achieve similar removal efficiencies.
- Reliability and durability of the Thermatrix FTO are slightly higher than baseline or competing technologies.
- Thermal catalytic systems need periodic cleaning or replacement of the catalyst, the frequency of which is highly site dependent (typically, cleaning may be required yearly and replacement required every 3 years).
- The adsorption end of the recovery methods is simple and durable. The regeneration systems involve mechanical equipment subject to routine breakdown or replacement.
- Additional considerations in the evaluation of economic performance of the FTO technology include:
  - Total operating costs (including capital recovery, energy, labor, and maintenance) vary from $1 to $20 per pound of solvent treated for competing and baseline technologies, with the FTO estimated at $0.72/lb. (Thermal catalytic technologies typically cost $1.65–$2.35/lb CVOC destroyed.)

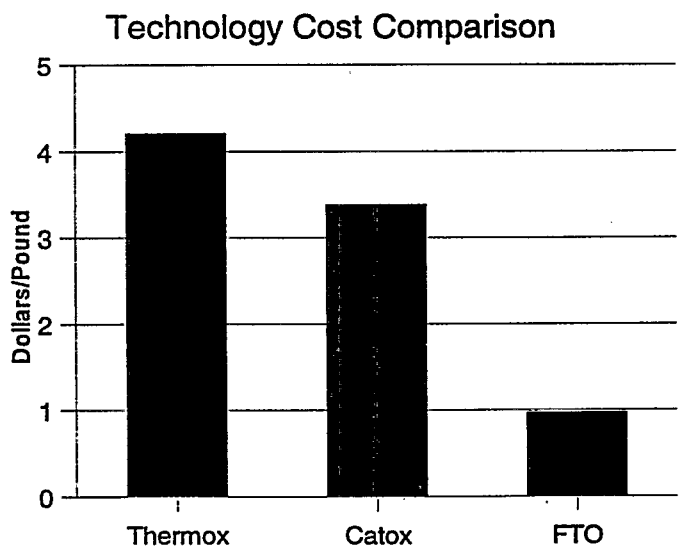
- The bulk of the total costs typically originate from capital recovery and labor, with the FTO technology requiring less maintenance than competing or baseline technologies.

- Energy costs are often viewed as an indicator of a technology's total costs, but typically comprise only 15–20% of the total operating costs.
  - Direct thermal destruction technologies will typically require about twice the energy input of thermal catalytic techniques.
  - Heat recapture systems coupled with thermal technologies decrease system energy requirements, but the savings due to heat recovery must be balanced against the added capital and maintenance costs of a heat exchanger and the need for corrosion protection from HCl generated from destruction of CVOC.
  - Solvent recovery methods will generally require 1/4 to 1/3 of the energy used for thermal techniques.

- Calculations based on the above assumptions put the cost of CVOC destruction at $0.72/lb ($1.58/Kg) CVOC destroyed.
- Common costs not evaluated because of use in all technology systems but that would be required are:
  - The destruction technologies demonstrated at SRS did not include acid scrubbers that would be necessary for full-scale continuous operations. Labor and maintenance costs for the scrubbers (including handling and disposition of the caustic solutions) would probably exceed that for the thermal units themselves.
  - Recovery systems carry an added cost for solvent handling and secondary waste stream disposition.
  - However, handling acid scrubber material and waste for thermal units should be on the order of costs for solvent recovery handling.

Cost Summary

- With this inlet feed concentration, the Thermatrix unit would also require ~315,000 Btu/hr supplemental fuel (natural gas), at a cost of $6,920/yr and minimal electricity at $525/yr.



SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- The SRS site was previously used for several in situ remediation demonstrations associated with the VOCs in Non-Arid Soils and Groundwater Integrated Demonstration (VNID) funded by the DOE Office of Technology Development. Air discharge permits for the demonstration site are in place, and a letter of intent to the South Carolina Department of Health and Environmental Control served as an amendment to the existing air permits.

- The small scale of the demonstration permitted operation of the FTO without a caustic scrubber to remove the HCl produced. In large-scale operations, the FTO effluent stream would be coupled with a caustic scrubber.

- The FTO has been permitted for operation in California and in New Jersey, which both have strict clean air standards and has been permitted in other states, in addition to 14 other states, France, and the United Kingdom.

- Permit requirements for future FTO applications are expected to include:

  - Air permit for discharge of treated vapor,
  - CERCLA and RCRA permitting depending on site-specific requirements,
  - NEPA review for federal projects, and
  - U.S. DOT certification if propane is transported to the site for operating a large-scale (100 scfm) FTO unit.

- Permit requirements will differ from state to state and for specific applications (e.g., CVOCs vs VOCs).

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Health and safety issues for the installation and operation of FTO are essentially equivalent to those for other thermal oxidative or thermal catalytic off-gas treatment technologies.
- FTO treatment of CVOCs produces HCl, which would require neutralization of the acid. Safety issues similar to those associated with wastes generated from baseline adsorption technologies like Granulated Activated Carbon would also apply to FTO caustic scrubber waste.
- The FTO contains safety interlocks that prevent potential worker exposure to contaminant vapors in the event of power or system failure.
- Level D personnel protection was used during the installation and operation of the FTO.

Community Safety

- The FTO does not produce any significant routine release of contaminants. No known hazardous by-products are produced.
- No unusual or significant safety concerns are associated with the transport of equipment, samples, or other materials associated with the FTO.
- FTO has no open flame, thus eliminating community concerns about incineration.

Environmental Impacts

- The FTO has a low profile and requires little space.
- Visual impacts are minor, and the FTO creates little noise or heat, even in close proximity.

Socioeconomic Impacts and Community Perception

- The FTO has minimal economic or labor force impact.

- The general public has little familiarity with the FTO; however, the technology has gained public acceptance.
- FTO is not viewed by the general public as an incineration technology because there are no open flames, and FTO has found acceptance as a "clean" technology.

SECTION 7

LESSONS LEARNED

Design Issues

- The FTO is designed to utilize heat provided by the thermal oxidative reaction.
- The FTO unit would have a lower energy requirement and concurrent lower operational cost when treating contaminated off-gases with a high heat of combustion (ca. 30 Btu/scf).
- CVOCs have a low heat of combustion (<2 Btu/scf at 1000 ppmv each of PCE and TCE) requiring resistance heating or addition of propane to maintain destruction performance.
- The design of the FTO is robust; the FTO required minimal maintenance throughout the demonstration.

Implementation Considerations

- Treatment of CVOC vapors using the FTO would require incorporating a caustic scrubber into the treatment system to neutralize HCl generated by the oxidation of CVOCs.
- Applications <100 scfm would require adequate power for resistance heating.
- Applications >100 scfm would require access to propane either by pipeline or by tanker.

Technology Limitations/Needs for Future Development

- The FTO is most energy efficient when treating compounds with a high heat of combustion (e.g., petroleum hydrocarbons) where heat recapture can boost operational efficiency.
- Moderate to high flow rates (>100 scfm) and contaminated vapor concentrations (>500 ppmv) improve the overall efficiency of operation and destruction of CVOCs by the FTO.

Technology Selection Considerations

- The FTO technology coupled with a baseline or innovative in situ remediation technology would be most effective during the early stages of remediation when contaminant concentrations tend to be high.
- The FTO has good application to manufacturing, process waste streams, and remediation processes when the flow rate and contaminant concentrations are moderate to high.
- The FTO technology has been demonstrated at SRS and in the private sector to be effective, efficient, reliable, and cost-effective in the destruction of VOC and CVOC vapors.
- The FTO technology is competitive in cost with, and achieves comparable or higher destruction efficiencies than, commercially available baseline technologies for off-gas treatment, including thermal oxidative techniques, thermal catalytic techniques, and adsorption/recovery technologies.

APPENDIX A

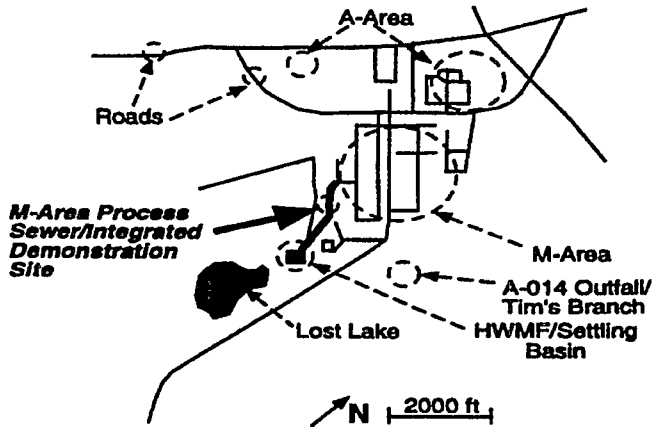
DEMONSTRATION SITE CHARACTERISTICS

Site History/Background

- The Savannah River Site's (SRS'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 mile^2 facility.

- The A and M Areas at Savannah River have been the sites of administrative buildings and manufacturing operations, respectively. The A/M-Area is approximately 1 mile inward from the northeast boundary of the 300-mile^2 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.

Site Layout



- 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. The remaining 1.3 million lbs were discharged from Outfall A-014 to Tim's Branch, a nearby stream, primarily from 1954 to 1982.

- 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 groundwater remediation system began operation in February 1983. Full-scale groundwater treatment began in September 1985.

Contaminants of Concern

Contaminants of greatest concern are 1,1,2-trichloroethylene (TCE), tetrachloroethylene (PCE), and 11,1,1-trichloroethylene (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				

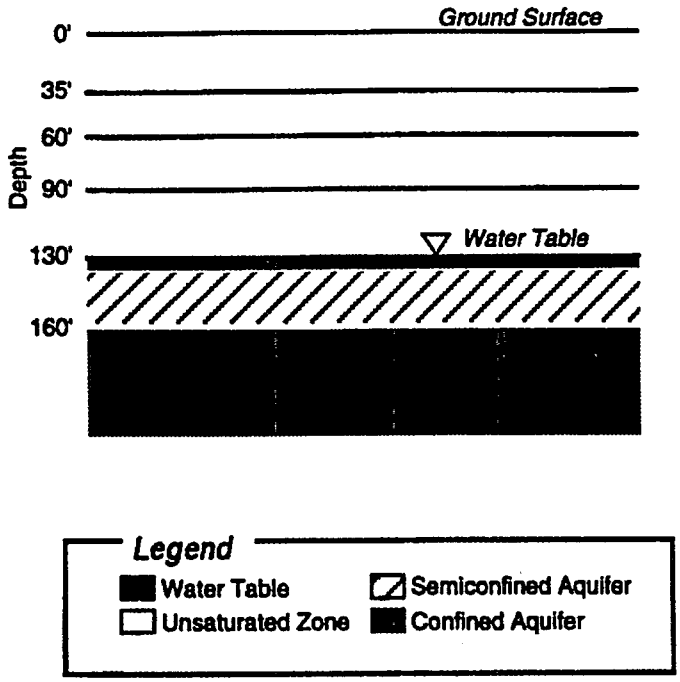
Nature and Extent of Contamination

- 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 groundwater 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 groundwater has an approximate thickness of 150 ft, covers about 1200 acres, and contains contaminant concentrations greater than 50,000 μg/L.
- Dense, nonaqueous-phase liquids 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 Areas at SRS.

Vadose Zone and Upper Aquifer Characteristics



Sediments are composed of sand, clay, and gravel.

Clay layers are relatively thin and discontinuous, with the exception of the clay layers at a 160-ft depth and a thicker zone of interbedded clay and sand found at a 90-ft depth.

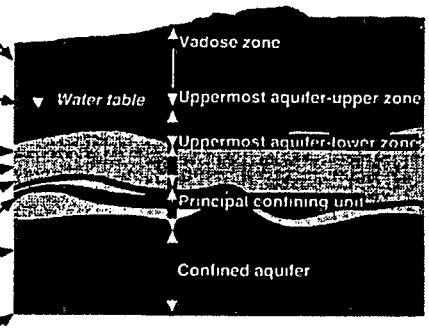
The water table is approximately 135 ft below grade.

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 groundwater plateau under most of the A/M-Area exists. Flow is approximately 15 to 100 ft/year.

Hydrogeologic Units

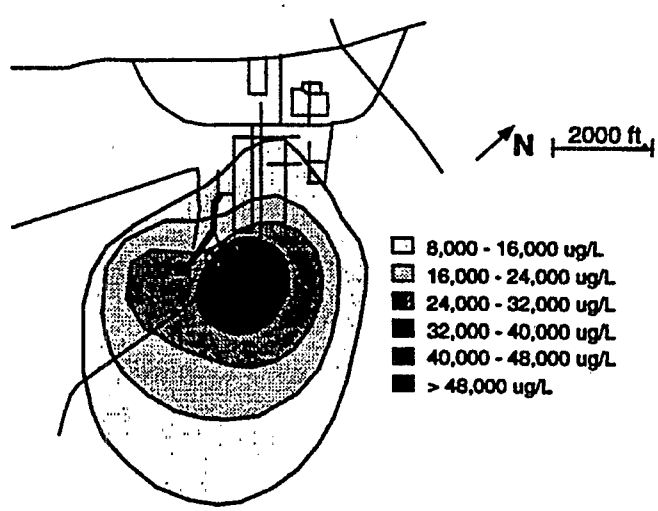
Aquifer Unit	Description	Thickness
Vadose Zone	Poorly sorted mix of sand, cobbles, silt and clay	~57 ft
	Moderate to well-sorted, fine to medium sand containing some pebbles; 13% silt and clay	0-97 ft
	Moderately to well-sorted medium sand; 18% silt and clay	30-55 ft
Water Table Unit	Moderate to well-sorted 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



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.

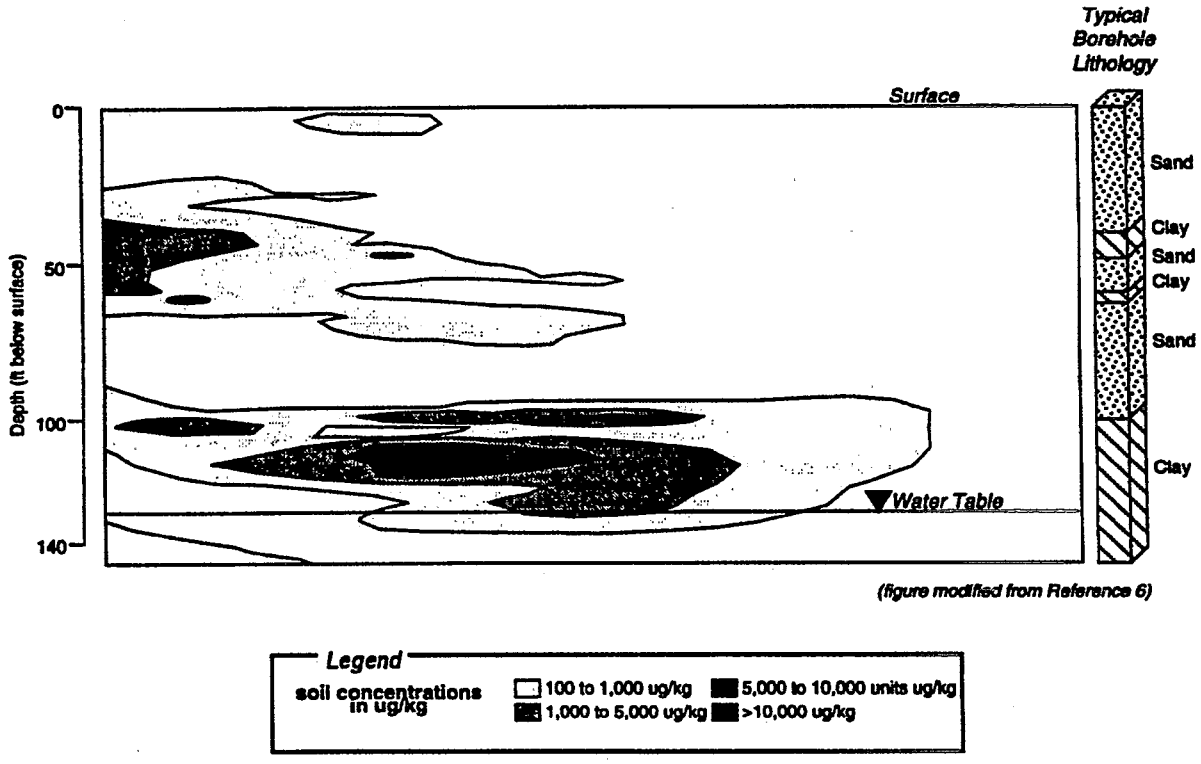
TCE Ground Water Plume (Top View)

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



TCE Concentrations in Soils (West-East Cross Section)

Concentrations and lithology data were acquired in 1991 along an approximately 200-ft cross section of the integrated demonstration site. Concentration contours of TCE in sediments are based on analysis of more than 1000 sediment samples. Highest concentrations of TCE occur in clay zones. These data were collected before the in situ air stripping demonstration was conducted and do not represent pretest conditions for the in situ bioremediation demonstration.



(figure modified from Reference 6)

APPENDIX B

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This report was prepared by:

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Six Phase Soil Heating at the U.S. Department of Energy, M Area, Savannah River Site, Aiken, South Carolina, and the 300-Area, Hanford Site, Richland, Washington

Case Study Abstract

Six Phase Soil Heating at the U.S. Department of Energy, M Area, Savannah River Site, Aiken, South Carolina, and the 300-Area, Hanford Site, Richland, Washington

Site Name:
U.S. Department of Energy (DOE), Savannah River Site (SRS), M Area Process Sewer/Integrated Demonstration Site
(for Hanford Site, see Results)

Contaminants:
Chlorinated Aliphatics
- Trichloroethene (TCE) and tetrachloroethene (PCE)
- TCE concentrations in the sediments ranged from 0 to 181 μg/kg (ppb), and PCE from 0 to 4,529 μg/kg.

Period of Operation:
October 1993 to January 1994

Location:
Aiken, South Carolina

Cleanup Type:
Field demonstration

Technical Information:
Theresa Bergsman, PNL, (509) 376-3638
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Bill Heath, (509) 376-0554
Harry Burkholder (Licensing), PNL, (509) 376-1867

Technology:
Six Phase Soil Heating (SPSH)
- SPSH splits conventional three-phase electricity into six separate electrical phases, with each phase delivered to a single electrode.
- The six electrodes are placed in a hexagonal pattern, with the vapor extraction well located in the center of the hexagon.
- At SRS, the diameter of the hexagon was 30 ft, and 1 to 2 gals/hr of water with 500 ppm NaCl was added at each electrode to maintain moisture. Electrical resistivity tomography (ERT) was used to monitor heating progress.

Cleanup Authority:
State: Air discharge and underground injection control (UIC) permits for the SRS are in place with the South Carolina Department of Health and Environmental Control (SCDHEC).

SIC Code:
9711 (National Security)
3355 (Aluminum Forming)
3471 (Metal Finishing)

Points of Contact:
Kurt Gerdes, DOE EM-50, (301) 903-7289
Dave Biancosino, DOE, (301) 903-7961
Jim Wright, DOE, (803) 725-5608

Waste Source:
Surface impoundment (unlined settling basin)

Purpose/Significance of Application:
SPSH was demonstrated as an alternative technology for enhancing removal of contaminants from clayey soils during an SVE application

Type/Quantity of Media Treated:
Soil and Sediment
The contaminated target zone was a ten-foot thick clay layer at a depth of approximately 40 feet, underlain by a thick section of relatively permeable sands with thin lenses of clayey sediments.

Regulatory Requirements/Cleanup Goals:
- The demonstration was covered by permits issued by the SCDHEC, including an air quality permit and a UIC permit (because of the addition of NaCl-bearing water to the electrodes).
- No specific regulatory requirements or cleanup goals were identified for the SPSH demonstration.

Case Study Abstract

Six Phase Soil Heating at the U.S. Department of Energy, M Area, Savannah River Site, Aiken, South Carolina, and the 300-Area, Hanford Site, Richland, Washington (Continued)

Results:
- Temperature in the clay zone increased to 100°C within 8 days and held at 100-110°C for 25-day demonstration.
- 19,000 gallons of water were removed from the soil as steam; approximately 5,000 gallons of water were added to maintain electrode conductivity.
- Median removal of PCE from the soil was 99.7%
- 180 kg of PCE and 23 kg of TCE were removed from the soil within the heated zone.
- SPSH at the Hanford site was conducted in 1993 on an uncontaminated area.
- Results from Hanford were used to improve process understanding, refine system design (e.g., of electrodes), and address scale-up issues.

Cost Factors:
- No data are provided on the capital or operating costs for the two demonstrations.
- An analysis of the capital and operating costs comparing SPSH and SVE technologies was made based on the following assumptions: a plume 100 ft in diameter; depth from 20 to 120 ft; energy demand 200 kW-hr per yd^3; target contaminants are VOCs and semi-VOCs.
- SPSH was shown to have a lower cost than SVE ($86/$yd^3$ compared with $576/$yd^3$) and to require less time for remediation (5 yrs compared with 50 yrs).

Description:
From 1958 to 1985, Savannah River Area M conducted manufacturing operations including aluminum forming and metal finishing. Process wastewater from these operations containing solvents (TCE, PCE, and TCA) was discharged to an unlined settling basin at Savannah River, which lead to contamination of ground water and vadose zone soils. Treatment of vadose zone soils has been the subject of several demonstrations (e.g., in situ air stripping), including this investigation of the technical and economic feasibility of six phase soil heating (SPSH) technology.

At SRS, SPSH was used to increase the removal efficiency of SVE for a clayey soil contaminated with TCE and PCE. At Hanford, SPSH was demonstrated on an uncontaminated site to improve process understanding, refine system design (e.g., of electrodes), and address scale-up issues. SPSH splits conventional three-phase electricity into six separate electrical phases, with each phase delivered to a single electrode. The six electrodes are placed in a hexagonal pattern, with the vapor extraction well located in the center of the hexagon.

Results from the SRS demonstration showed that SPSH increased the temperature in the clay zone to 100°C within 8 days and maintained it at 100-110°C for a 25 day demonstration. In addition, there were 19,000 gallons of water removed from the soil as steam, and approximately 5,000 gals of water added to maintain electrode conductivity. The median removal of PCE from the soil was 99.7%, with overall results showing that 180 kg of PCE and 23 kg of TCE were removed from the soil within the heated zone. Operating difficulties included drying out of the electrodes and shorting of the thermocouples. The system design was improved to overcome these difficulties.

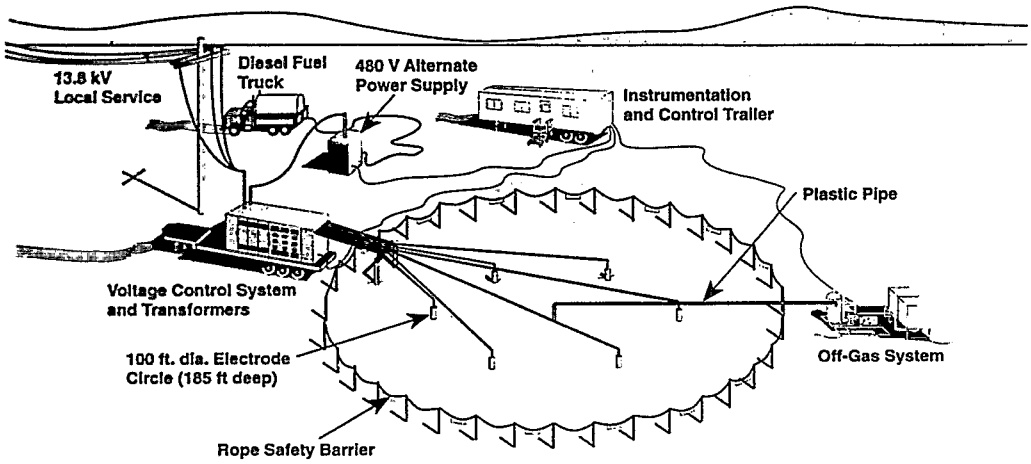
SECTION 1

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.



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- 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.

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	U.S. Department of Energy
Savannah River Site	Hanford Site
M Area Process Sewer/Integrated Demonstration Site	300 Area
Aiken, South Carolina	Richland, Washington
October 1993 to January 1994	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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Management

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Jim Wright, DOE Plumes Focus Area Implementation Team Manager, (803)725-5608.

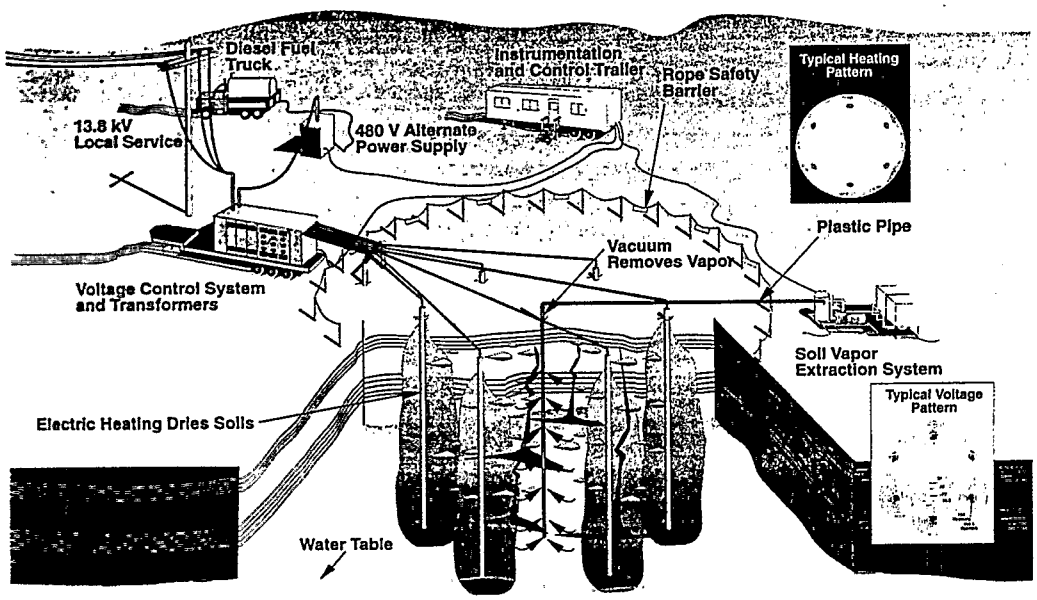
Licensing Information

Harry Burkholder, PNL, (509) 376-1867

SECTION 2

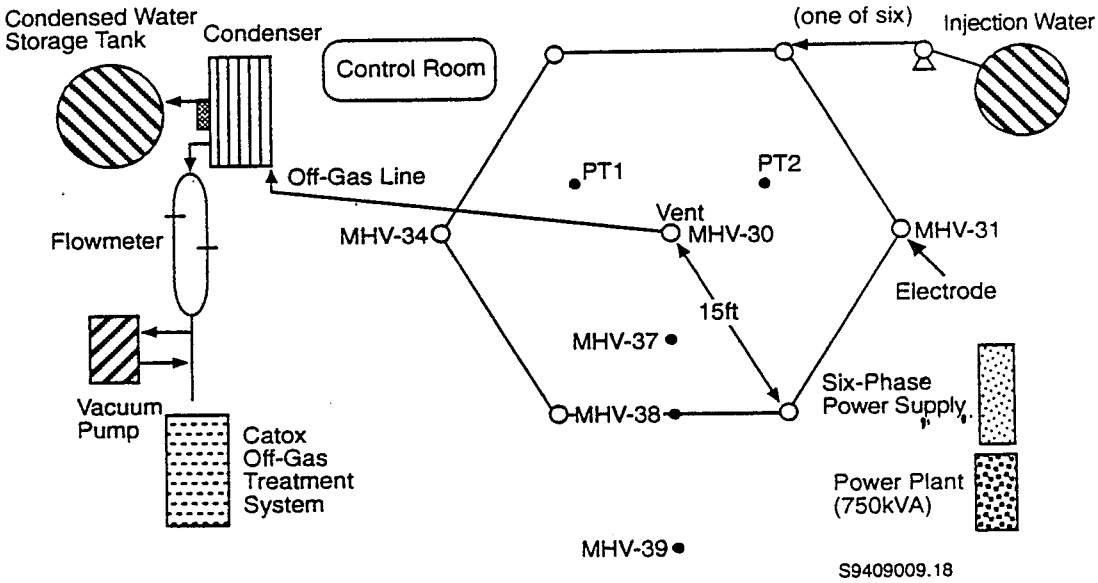
TECHNOLOGY DESCRIPTION

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.

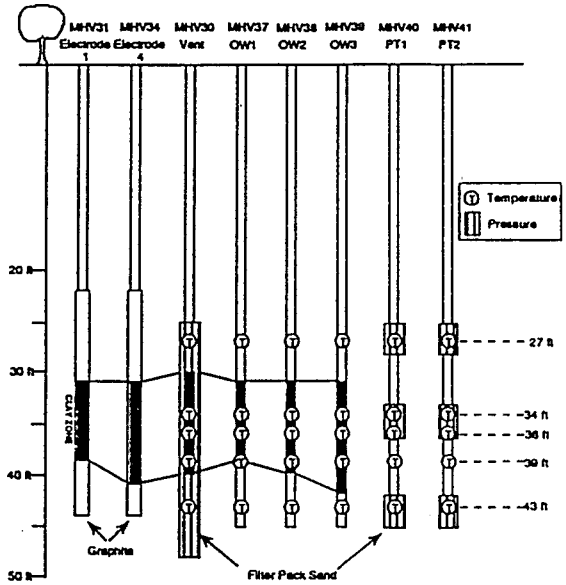
Above Ground System



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.

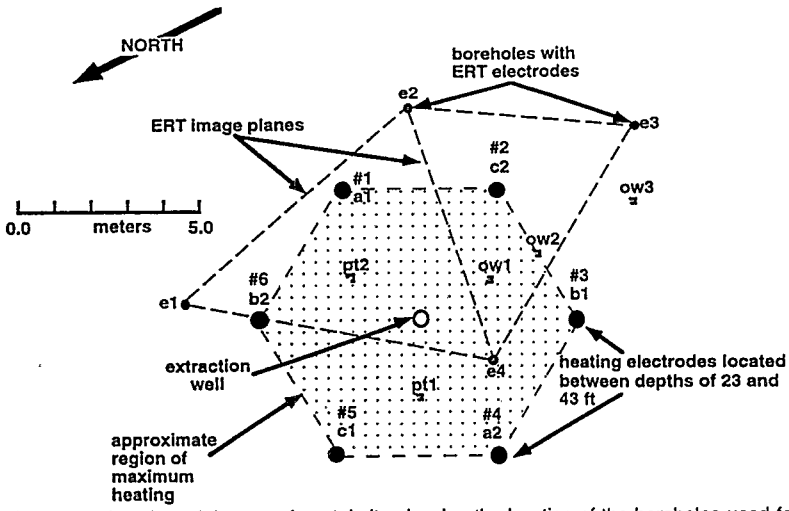


Figure 1. Plan view of the experimental site showing the location of the boreholes used for ERT (e1, e2, e3, e4), extraction well and the ohmic heating electrodes. The clay layer targeted for this demonstration is located between 9.14 to 12.5 m (30 and 41 ft) of depth

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.

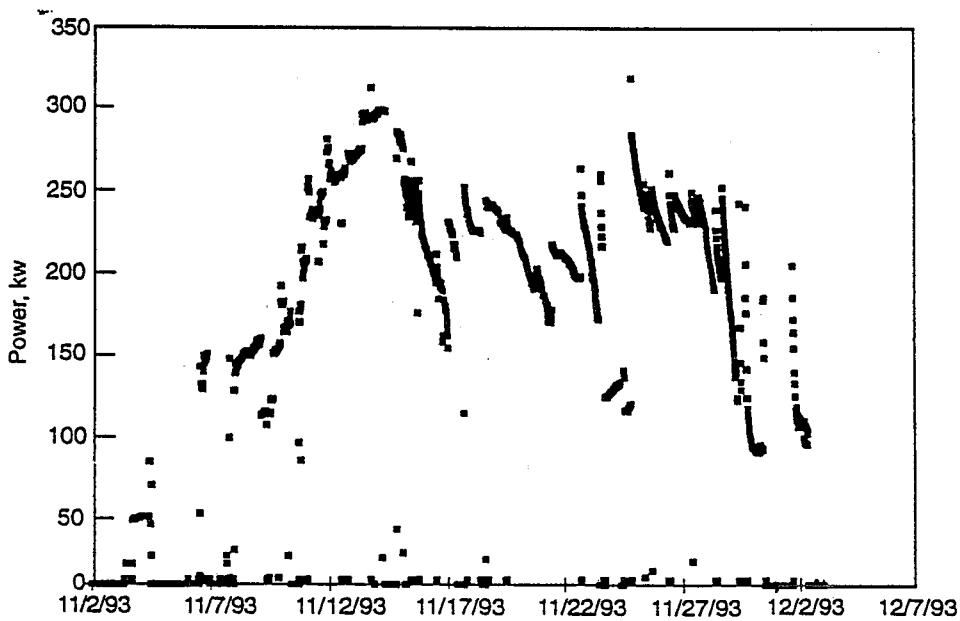
- Major objectives of the SRS demonstration included:
  - accelerated removal of TCE and PCE from clay soils at a depth of 30 to 40 feet
  - quantification of the areal and vertical distribution of heating (30-foot diameter circular array)
  - demonstration of functional electrode and extraction well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

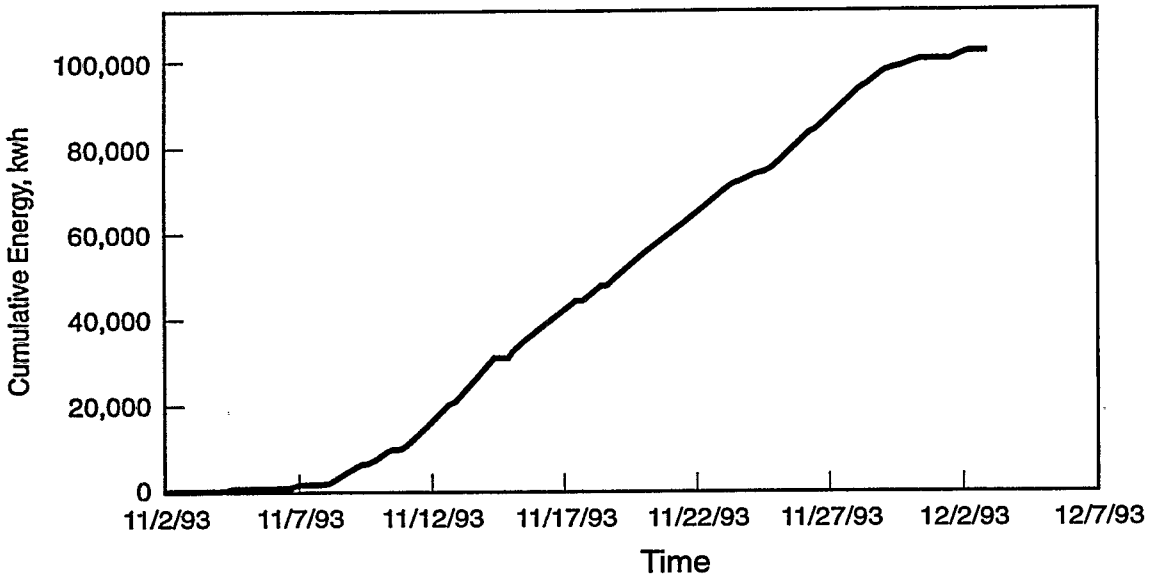
- Vacuum Applied
  - Air was extracted continuously during the demonstration.
- Power Applied
  - An average power of 200kW was applied to the electrode array. A total of 100,000kWh of energy was applied.
  - Mean voltage was 1000V. At the end of the heating period, voltage was increased to 2400V to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



Power Applied to SPSH Array

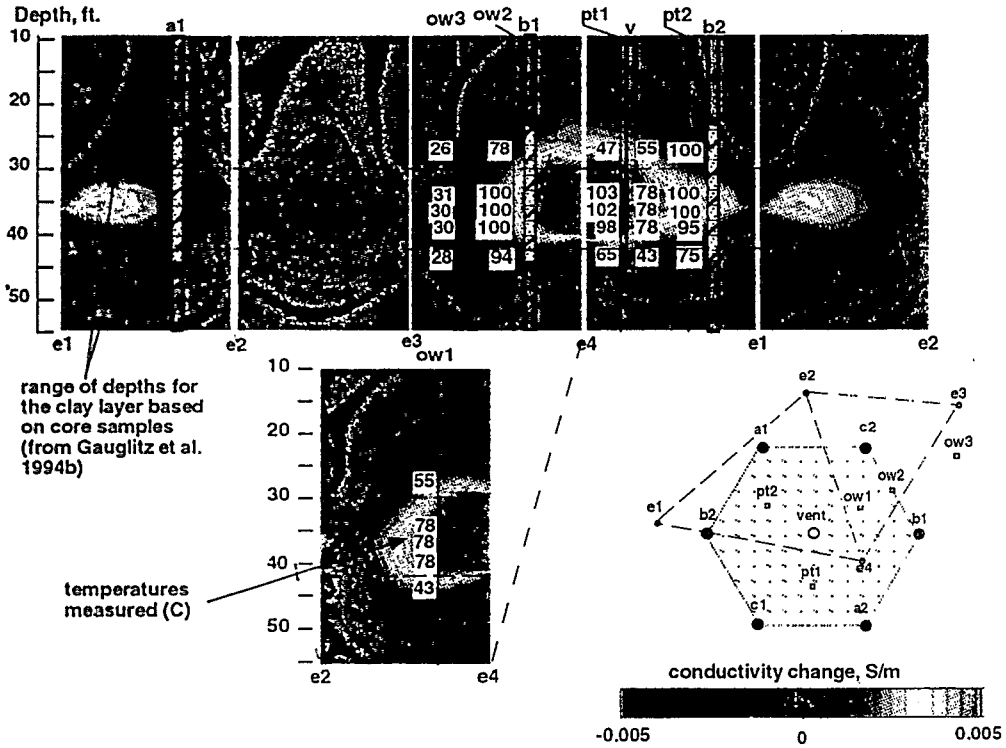
*Periods when power is zero, indicate times when the system was shutdown for maintenance or data gathering

Cumulative Energy Applied to the Soil



Zones of Influence

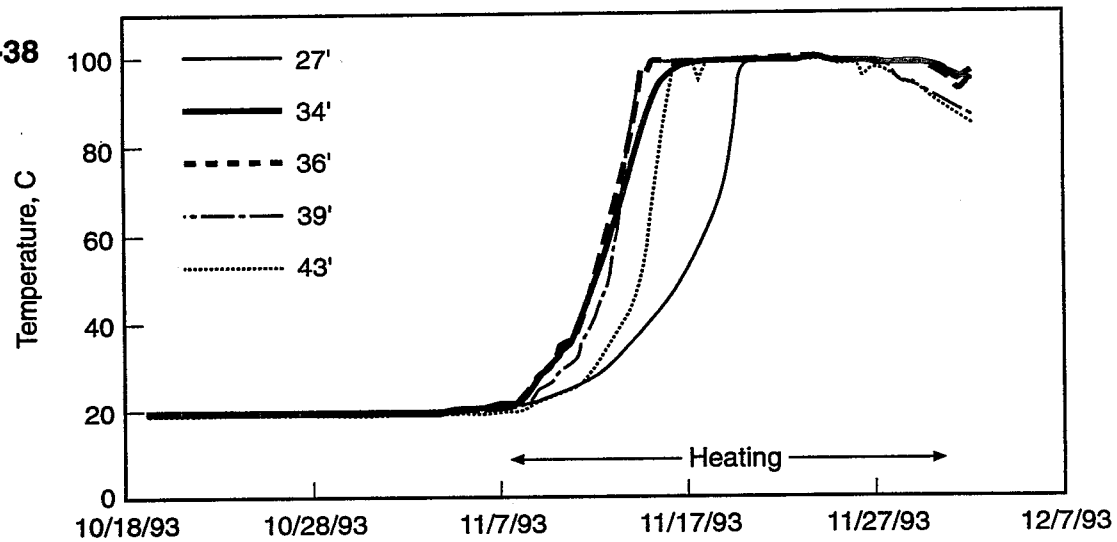
- Electrical resistance tomography (ERT) was used to map the zone of influence and effects of heating and drying on the soil.
  - A difference image representing the changes in electrical conductivity observed after two weeks of heating is shown below. The difference tomograph shows the combined effects 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%.



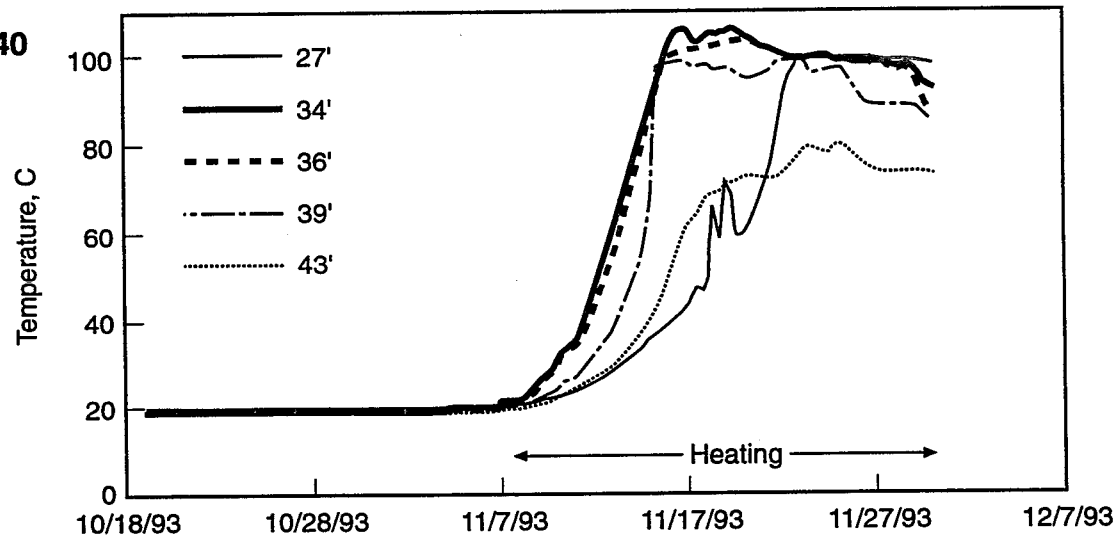
Thermal Performance

- 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



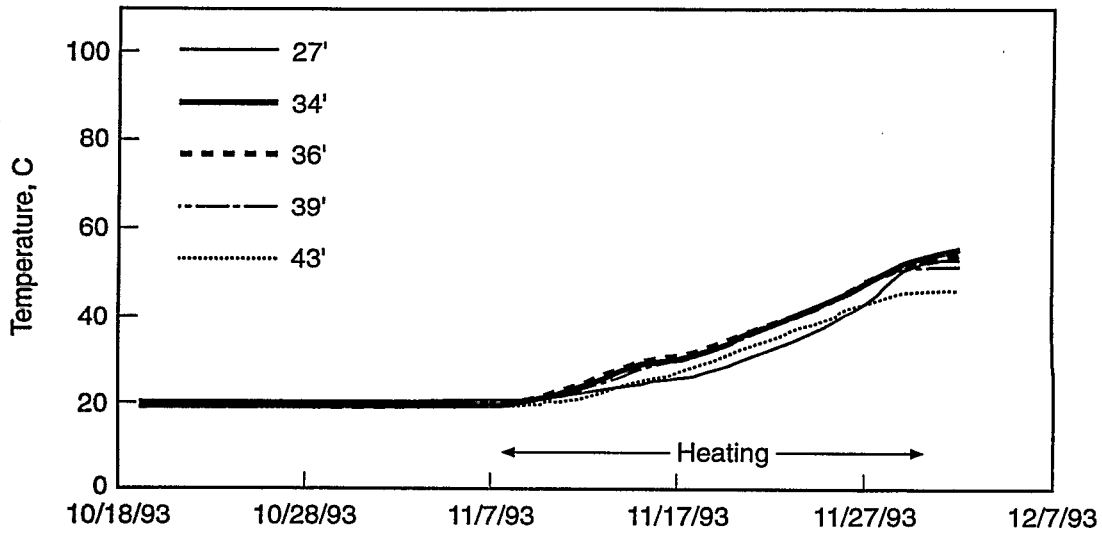
Well MHV-40



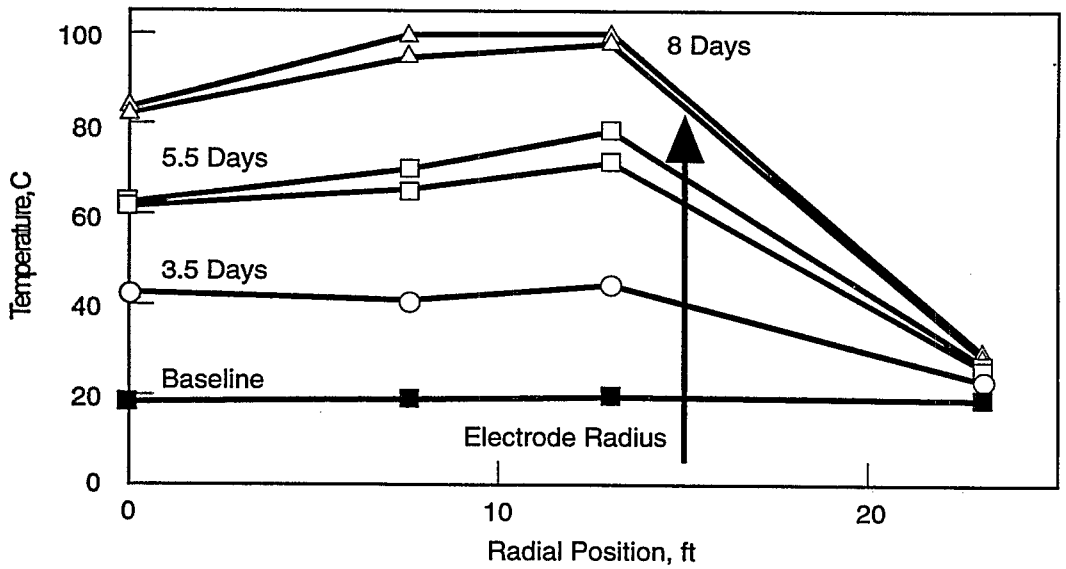
Note: MHV-38 was located midway between two electrodes.
Thermocouples at 27 and 43 feet represent sands above and below the target clay
Thermocouples at 34 and 36 feet are within the target clay, at 39 feet in the sand immediately adjacent to the clay.

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

Well MHV-39 (outside the array)

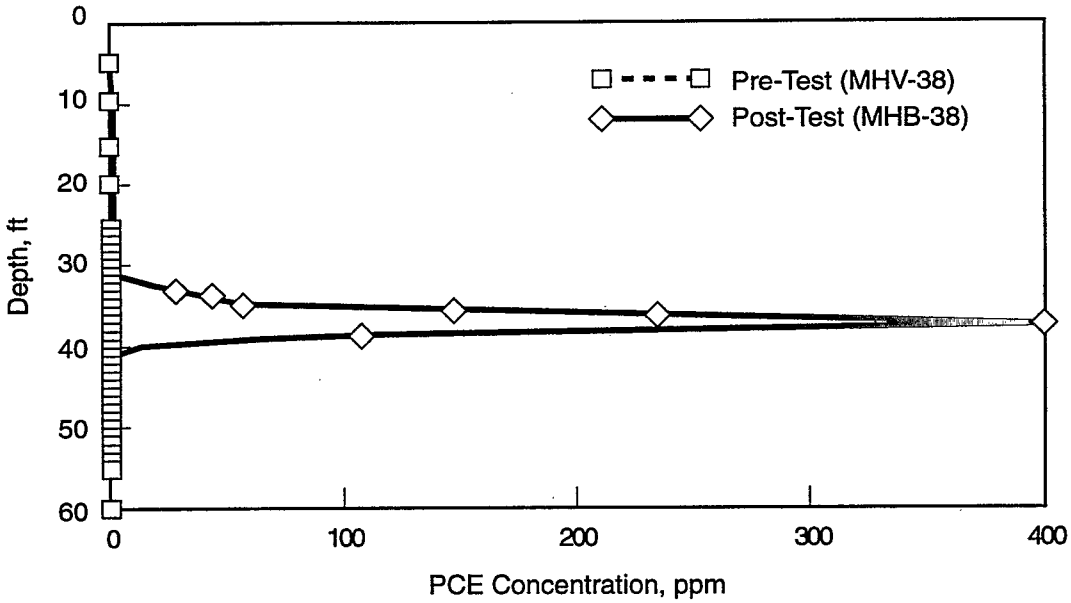


- Temperatures in the clay zone were quite uniform from the central extraction well to the electrodes and beyond (see below). Of course, temperatures outside the array are lower (see above).

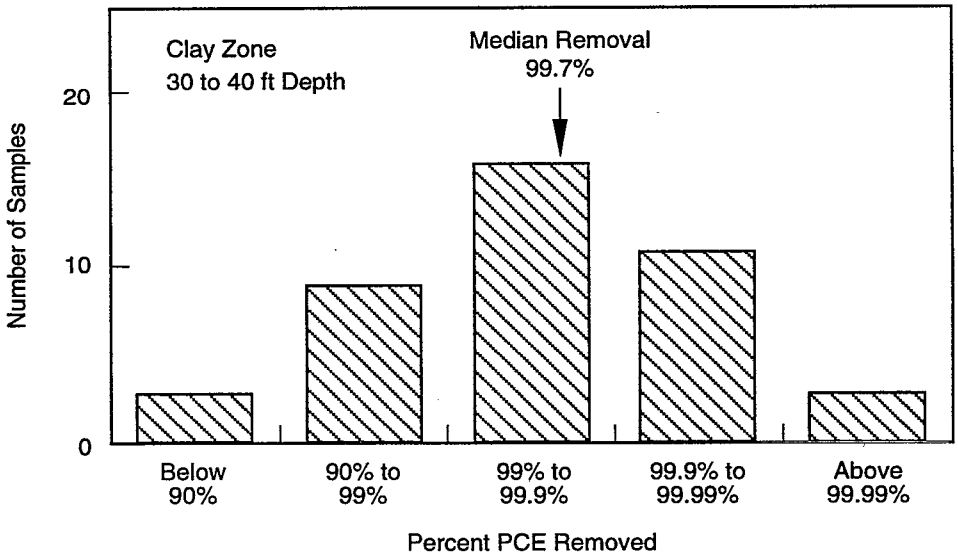


- Heating of the clays dried the soil and increased air permeability. However, core samples showed no evidence of fracturing. Permeabilities of the clays were still much less than the adjacent sands.
- As heating was initiated, the electrical resistance of the soil decreased as expected. However, as 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

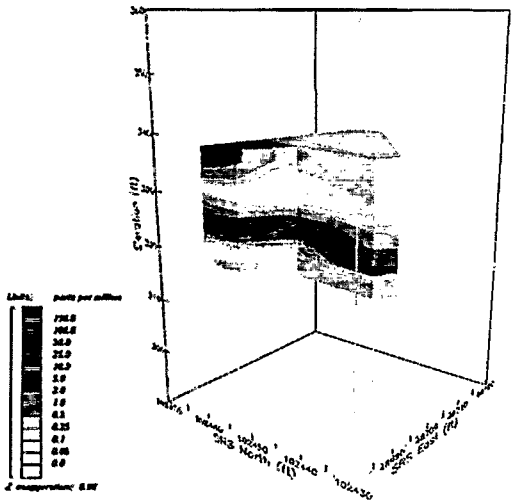


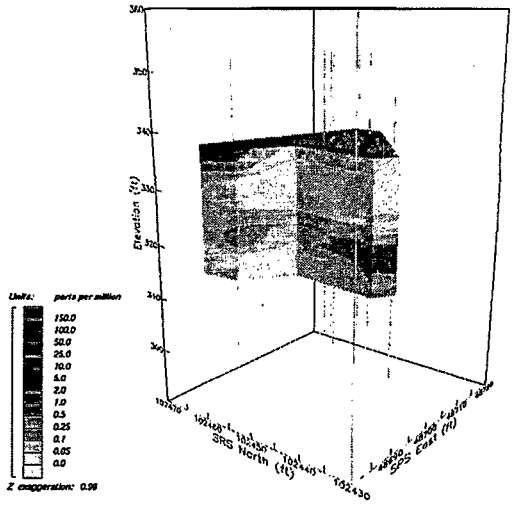
- Pre- and post-test soil samples show a tremendous difference in concentrations of PCE. Samples were collected from the same depth in adjacent boreholes. Samples collected from the borehole for monitoring well MHV-38 are shown above.



- 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.

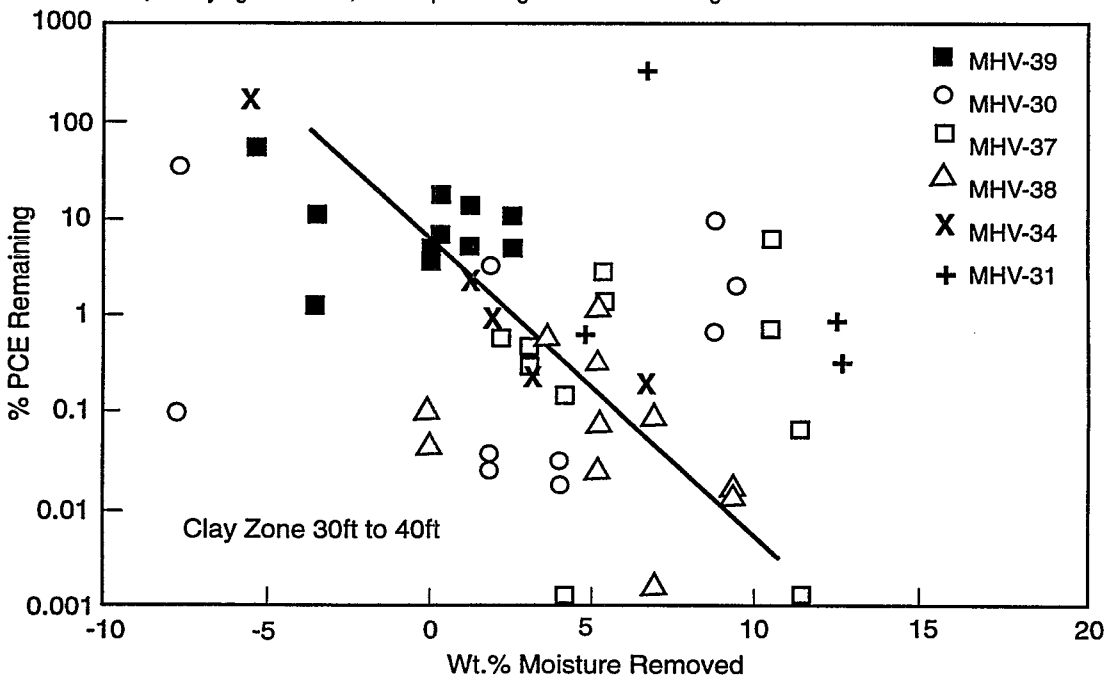




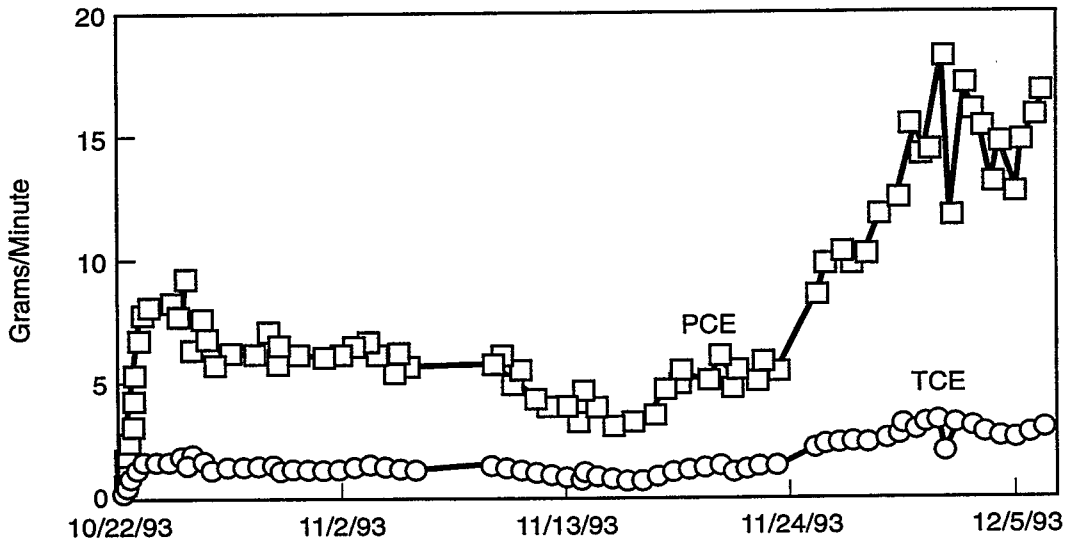
Post-test models show almost complete removal of VOCs from the heated zone.

- 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

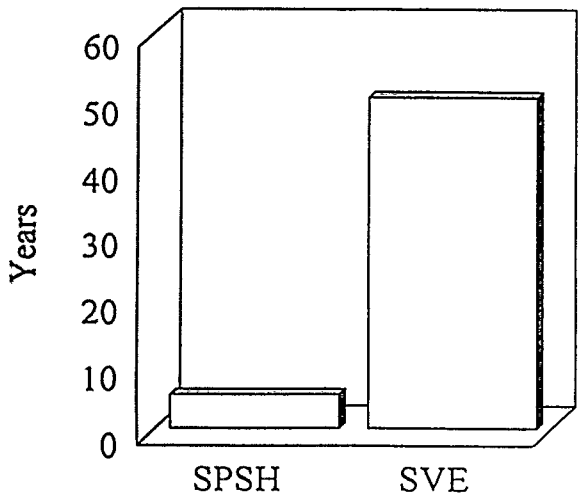
Operating Costs

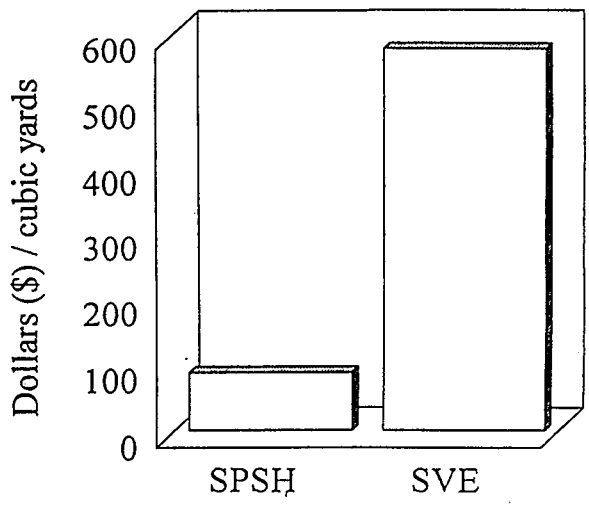
Cost Category	Description	Total ($/month)
Direct Cost	Field Monitoring	6,300
	Monitoring and Reporting	4,800
	System Operation and Maintenance	5,800
	Total O & M Costs	16,900

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

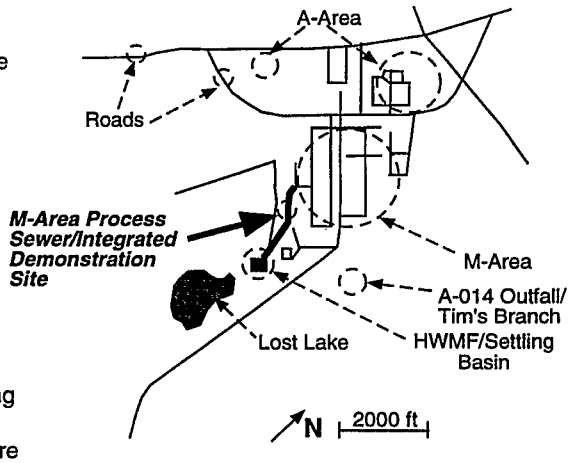
Site History/Background

- 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.

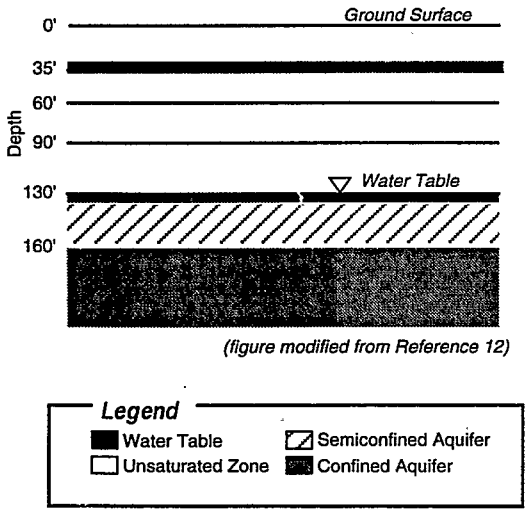
- DNAPLs found in 1991 present challenges for long-term remediation efforts.

- 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

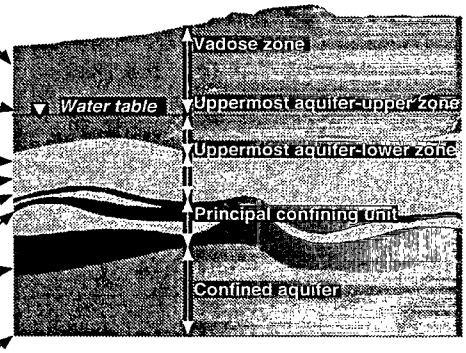


(figure modified from Reference 12)

- 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

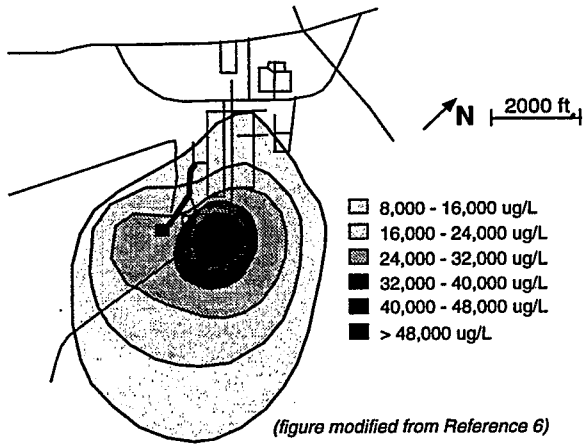


Contaminant Locations and Hydrogeologic Profiles (continued)

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)

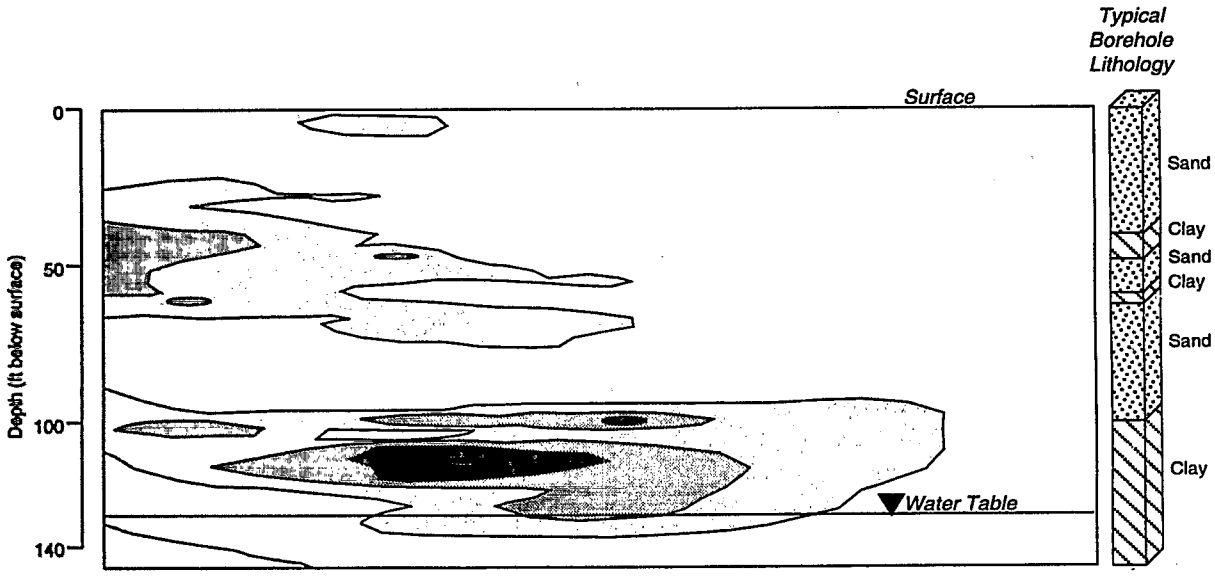
Data from 15 feet below water table in the third quarter of 1990.



(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
- 1,000 to 5,000 ug/kg
- 5,000 to 10,000 units ug/kg
- >10,000 ug/kg

APPENDIX B

PERFORMANCE DETAIL

Operational Performance

Maintainability and Reliability

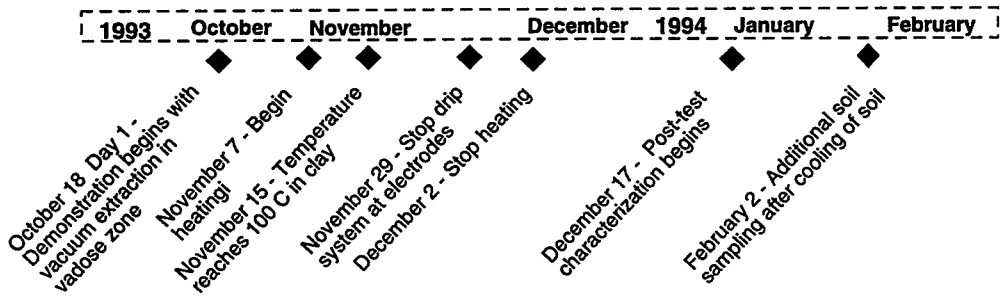
- No functional problems encountered during demonstration; system was operational approximately 90% of all available time.
- Operational performance over long periods (years) not yet available.

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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Assistance was provided by the
LAWRENCE LIVERMORE NATIONAL LABORATORY
ENVIRONMENTAL TECHNOLOGY PROGRAM
EARTH SCIENCES DIVISION
which supplied key information and reviewed report drafts.
Final editing and production was provided by the
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HAZWRAP
HAZARDOUS WASTE REMEDIAL ACTIONS PROGRAM

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Environmental Managment and Enrichment Facilities
Oak Ridge, Tennessee 37831-7606
managed by
MARTIN MARIETTA ENERGY SYSTEMS
for the
U.S. Department of Energy
under Contract DE-AC05-84OR-21400

950R-7400-001-008

OTHER IN SITU TECHNOLOGIES CASE STUDIES

Hydraulic and Pneumatic Fracturing, U.S. Department of Energy (Portsmouth Gaseous Diffusion Plant, Ohio), Department of Defense, and Commercial Sites

Case Study Abstract

Hydraulic and Pneumatic Fracturing, U.S. Department of Energy (Portsmouth Gaseous Diffusion Plant, Ohio), Department of Defense, and Commercial Sites

Site Name:
1. U.S. Department of Energy (DOE), Portsmouth Gaseous Diffusion Plant (PGDP)
2. DoD (e.g., Tinker AFB) and Commercial sites (various)

Location:
Piketon, Ohio (for PGDP)

Contaminants:
- Demonstrations conducted at sites contaminated with Volatile Organic Contaminants (VOCs) (including Trichloroethene (TCE)), Dense Nonaqueous Phase Liquids (DNAPLs), and at uncontaminated sites

Period of Operation:
July 1991 - August 1996 (multiple demos during this time period)

Cleanup Type:
Field demonstration

Technical Information:
Pneumatic: J. Liskowitz/T. Keffer, ARS, (908) 739-6444
John Schuring, NJIT, (201) 596-5849
Hydraulic: L. Murdoch, Univ. of Cinc., (513) 556-2519
W. Slack, FRX, (513) 556-2526
R. Siegrist, ORNL, Col. Sch. of Mines, (303) 273-3490

SIC Code:
9711 (National Security)
Others - information not provided

Technology:
Hydraulic and Pneumatic Fracturing
- Hydraulic fracturing equipment includes lance, notch tool, slurry mixer, and pump
- Gel-laden proppant is pumped into notch under 60 psig to create a fracture
- Pneumatic fracturing equipment includes high-pressure air source, pressure regulator, and receiver tank with inline flow meter and pressure gauge
- Air is injected at 72.5-290 psi for <30 seconds using a proprietary nozzle
- Design considerations include formation permeability, type, and structure; sand proppant; state of stress; site conditions; and depth
- Fracturing used in conjunction with other in situ technologies such as SVE, bioremediation, and pump and treat

Cleanup Authority:
Information not provided

Points of Contact:
Skip Chamberlain, DOE, (301) 903-7248
James Wright, DOE, (803) 725-5608

Waste Source:
Tinker - Underground Storage Tank
Others - Information not provided

Purpose/Significance of Application:
Demonstrations of technology used to increase hydraulic conductivity, contaminant mass recovery, and radius of influence (for example, in a SVE application)

Type/Quantity of Media Treated:
Soil and Ground Water
- Generally applicable in low permeability formations
- At PGDP, was used at uncontaminated site underlain by low permeability clays and silts to a depth of approximately 15-22 ft

Regulatory Requirements/Cleanup Goals:
- No special permits were required for use in the demonstrations
- Some states may be concerned about injection of fluids and other materials that may alter the pH of the subsurface

Hydraulic and Pneumatic Fracturing, U.S. Department of Energy (Portsmouth Gaseous Diffusion Plant, Ohio), Department of Defense, and Commercial Sites (Continued)

Results:
- Hydraulic fracturing demonstrations showed mass recovery increased from 2.8-50 times, and radius of influence from 25-30 times
- Pneumatic fracturing at Tinker Air Force Base increased product thickness in recovery well from 1.5 to 20.2 ft
- Pneumatic fracturing at PGDP doubled hydraulic conductivity, and increased radius of influence by 33% after one day of pumping

Cost Factors:
- Capital and annual costs not provided for demonstrations
- Hydraulic fracturing projected to cost $5,400 for one-time costs, and $5,700 for daily costs (corresponding to $950-1,425 per fracture, for 4-6 fractures)
- Pneumatic fracturing projected to be similar to those for hydraulic fracturing ($400-1,425 per fracture)
- Pneumatic fracturing at a SITE demonstration estimated at $140/lb of TCE removed; other estimates predict pneumatic fracturing cost of $8-17/yd^3 soil treated

Description:
Hydraulic and pneumatic fracturing are technologies that can enhance access to the subsurface for remediation of contaminants above and below the water table. Enhanced access is provided by creating new or enlarging existing fractures in the subsurface. These fractures enhance the performance of in situ remediation technologies such as SVE, bioremediation, and pump and treat by increasing the soil permeability; increasing the effective radius of recovery or injection wells; increasing potential contact area with contaminated soils; and intersecting natural features. Fracturing can also be used to improve delivery of materials to the subsurface (e.g., nutrients).

A number of demonstrations of hydraulic and pneumatic fracturing have been conducted to show technology applicability and performance in a variety of settings. Hydraulic fracturing demonstrations have showed mass recovery increases from 2.8-50 times, and radius of influence increases from 25-30 times. Pneumatic fracturing demonstrations have been conducted at Tinker Air Force Base and PGDP, with results provided in terms of increased product thickness in recovery wells and increases in hydraulic conductivity and radius of influence. Hydraulic fracturing is commercially available from several companies, while pneumatic fracturing has been patented by the New Jersey Institute of Technology (NJIT). The NJIT has licensed pneumatic fracturing to Accutech Remedial Services (ARS). While hydraulic fracturing produces larger apertures and can be performed at greater depths than pneumatic fracturing, the addition of water in hydraulic fracturing may create a larger volume of contaminated media possibly requiring remediation. Prior to proposing fracturing, sites should be analyzed for permeability. Sites with extensively fractured strata will have permeabilities that are high enough that fracturing may not be required.

SECTION 1

SUMMARY

Technology Description

Hydraulic and Pneumatic Fracturing are two technologies that can enhance access to the subsurface for remediation of contaminants both above and below the water table.

- Enhanced access is provided by creating new or enlarging existing fractures in the subsurface to improve fluid flow to encourage removal or treatment of contaminants.
- The innovation adapts a petroleum recovery technique to the environmental field. Fracturing can then be combined with other innovative technologies to provide an effective remediation system at difficult sites.

Induced fractures enhance the performance of in situ remediation technologies in low-permeability strata by

- increasing the permeability of the soil,
- increasing the effective radius of recovery or injection wells,
- increasing potential contact area with contaminated soils,
- intersecting natural fractures.

Better extraction of contaminants from or delivery of materials (gases, liquids, or solids) to the subsurface can produce a more effective in situ remediation. Examples of innovative materials that can be introduced through fractures include:

- ◊ Nutrients or slowly dissolving oxygen sources to improve bioremediation processes;
- ◊ Electrically conductive compounds (e.g., graphite) to improve electrokinetic processes;
- ◊ Reactant materials such as zero-valent iron or permanganate.

These technologies are particularly useful at contaminated sites with low-permeability soil and geologic media, such as clays, shales, and tight sandstones. However fracturing technology is not limited to low-permeability sites.

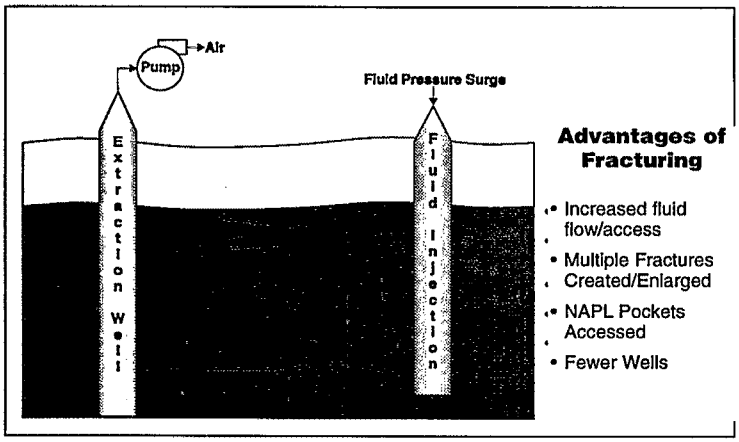

Figure 1. Fracturing of Low-Permeability Formation. Extraction/treatment can be accomplished either in the fluid injection borehole or in adjacent boreholes.

- Fractures are typically created in a horizontal or subhorizontal plane at specific horizons (<2 feet) by injecting a fluid (either liquid or gaseous) into a sealed borehole until the pressure exceeds a critical value, thus nucleating a fracture. After injection is complete, fractures are held open naturally or with an introduced proppant, a material injected to "prop" open the fractures. If a liquid (e.g. guar gum gel) is used to create the fracture, a granular proppant can be introduced to assist with maintenance of fracture openings.

- The direction of fracture propagation is controlled by the state of stress in the subsurface. Sites with horizontal stress greater than vertical stress will produce horizontal or subhorizontal fractures. These sites typically consist of overconsolidated fine-grained deposits (silts and clays). For Pneumatic Fracturing a directional nozzle can be used to control the direction of fracture propagation.

- Creation of fractures does not add significant up-front costs (up to a few percent) to an overall remediation system and it may provide significant reduction in the life-cycle costs to remediate a site because fewer wells may be required and cleanup may be accomplished more rapidly.

Technology Status

- Hydraulic Fracturing has been extensively researched and used in the petroleum industry for over 50 years. It has required modification for use in the environmental field. Since the early 1990's, research has been conducted on the viability of both Pneumatic and Hydraulic Fracturing for environmental applications.

- A number of demonstrations of Hydraulic and Pneumatic Fracturing have been conducted to show their applicability to the environmental field. Both technologies were demonstrated under the EPA SITE program in the early 1990's. Technology Evaluation and Applications Analysis Reports are available for both technologies (see references).

- Bench-scale tests, followed by pilot- and field-scale tests on both clean and contaminated sites, have been conducted by NJIT and ARS using Pneumatic Fracturing. Terra Vac, Malcolm Pirnie, and others have also participated in Pneumatic Fracturing projects. The U.S. Department of Energy (DOE) has supported several demonstrations of Pneumatic Fracturing, including one at Tinker Air Force Base and one at the DOE Portsmouth Gaseous Diffusion Plant. New Jersey Institute of Technology (NJIT) patented Pneumatic Fracturing for environmental applications. In 1992 they licensed the technology to Accutech Remedial Systems (ARS).

- FRX in cooperation with the University of Cincinnati has conducted pilot and field scale tests of hydraulic fracturing on both clean and contaminated sites in 9 states and Canada (TX, OH, ID, IL, CT, ME, MI, NJ, CO). Golder Associates has conducted bench, pilot and field scale tests concentrating on hydraulic fracturing. A hydraulic fracturing demonstration has been completed at the DOE Portsmouth Gaseous Diffusion Plant. Future development will include coupling of in situ mass transfer and destruction processes. Advanced applications such as injection of graphite, iron filings, oxidants and activated carbon were tested.

- ***Key Results***
  - Hydraulic and Pneumatic Fracturing at geologically appropriate sites have significantly improved recovery of contaminated fluids (~10 to >1000 times). These technologies typically have generated fractures that significantly increase the radius of influence for vertical recovery wells at the sites (10-fold).
    - ◊ Hydraulically developed fractures were demonstrated to be effective for a period of more than one year. Vapor flow rates were increased by 15 to 30 times that of unfractured wells. Water flow rates were increased by 25 to 40 times that of unfractured wells.

  - Hydraulic and Pneumatic Fracturing have been used in conjunction with soil vapor extraction, pump and treat, bioremediation, free product recovery, and in situ vitification at contaminated sites. Demonstrations of other applications, such as passive chemical barriers or electrokinetics, are underway.

  - Hydraulic Fracturing is commercially available from several companies: FRX, Inc., Golder Associates Ltd., Hayward Baker Environmental, Inc., and perhaps others. Larger scale, more costly applications are performed by several companies for oilfield applications. Pneumatic Fracturing is commercially available from ARS. ARS has used Pneumatic Fracturing at over 30 sites in North America. ARS has recently signed an agreement with DOWA Mining Company LTD of Japan to market Pneumatic Fracturing in Japan.

CONTACTS

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(Information in this report is based on technologies as implemented by ARS and FRX.)

Process Schematic

Hydraulic Fracturing

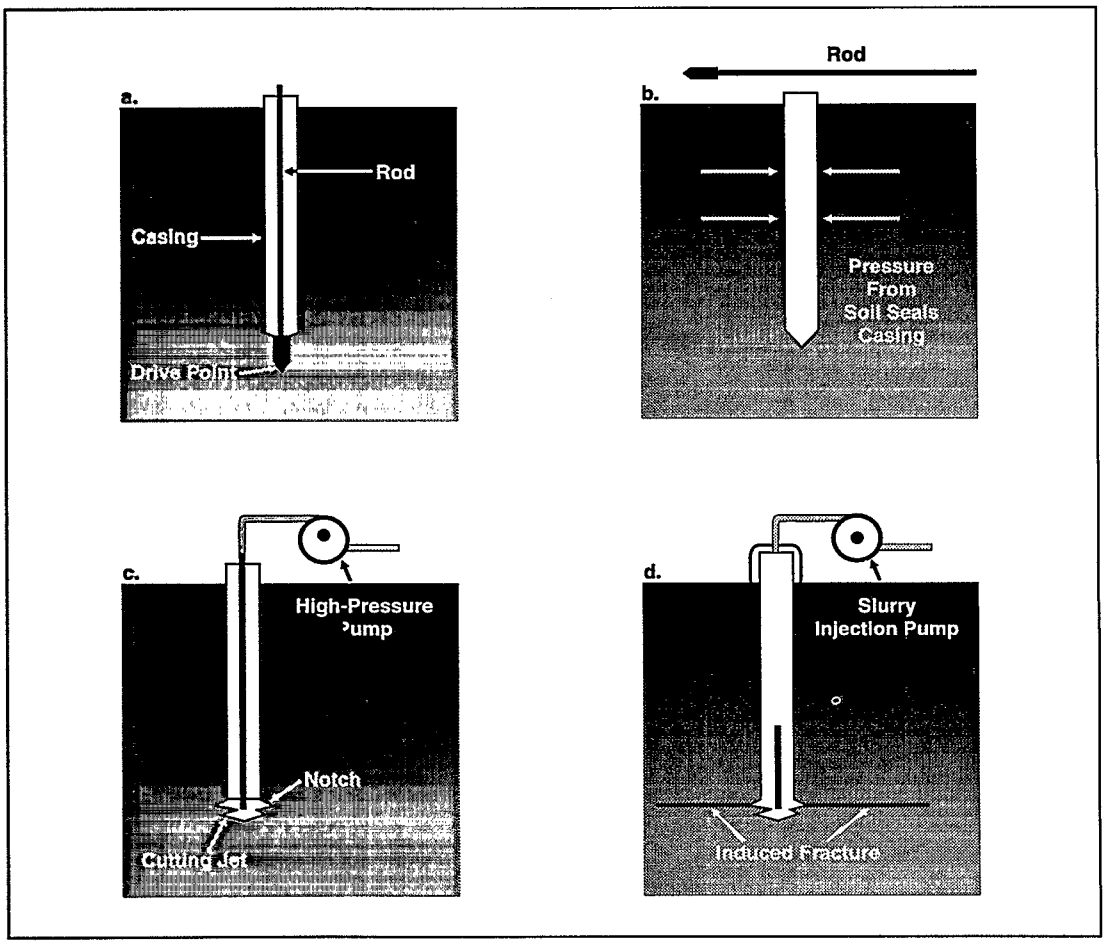

Figure 3. Hydraulic Fracturing Schematic (from U.S. EPA, 1994)

Equipment

- The fracturing equipment consists of a lance, a tool to create an initial notch, a continuous slurry mixer, a positive displacement pump mounted on a trailer, and the fracture mixture (fluid and proppant).

Process

- A well is drilled and cased down to the depth where fractures are desired in lithified sediments (in unlithified sediments a straddle-packer system is used). A rod with a cone-shaped end, the lance, is introduced into the bottom of the borehole and is driven to the depth at which the fracture is desired. The lance tip remains in the soil whereas the lance is later removed from the borehole.

- A water jet (steel tubing with a narrow orifice at one end) is inserted into the cone-shaped rod, water is pumped through the tubing to create a high-pressure water jet (pressure 3500 psi). The jet is rotated within the borehole to create a disc-shaped horizontal notch extending 4 to 6 inches from the borehole.

- The gel-laden proppant is then pumped into the notch under relatively low pressures (60 psig) to create a fracture. Lateral pressure from the soil on the outer wall of the casing effectively seals the casing and prevents leakage of the slurry. The fracture nucleates at the notch and grows radially up to about 20 feet from the borehole wall. The gel to sand ratio is adjusted from fracture to fracture, depending on depth and site-specific soil conditions.

Pneumatic Fracturing

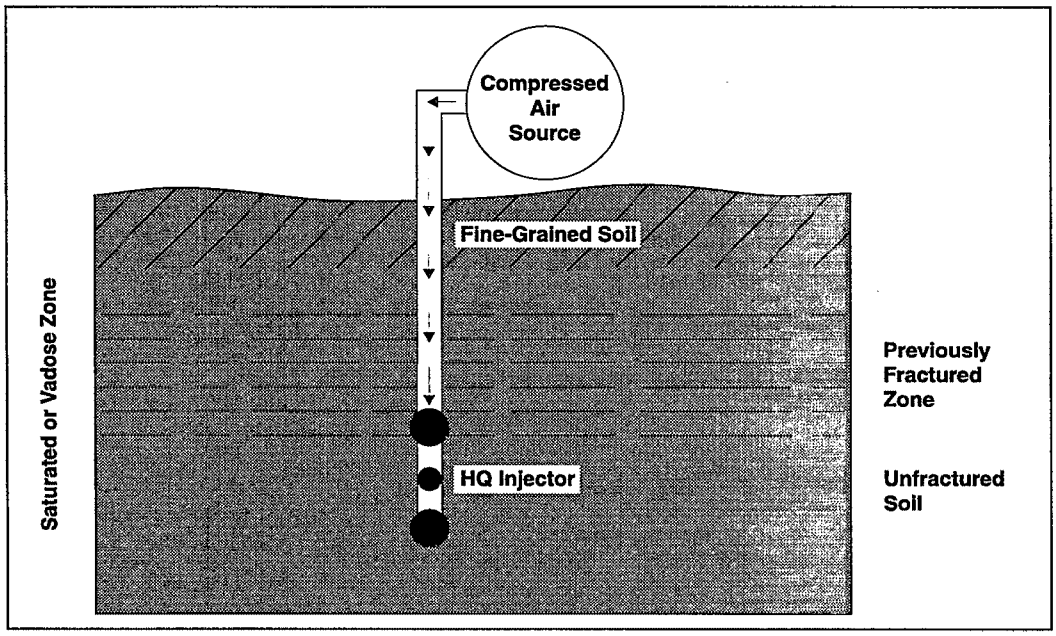

Figure 4. Schematic of Pneumatic Fracturing Process

Equipment

- The fracturing equipment consists of a high-pressure air source (e.g., compressed gas cylinders) with pressure regulator, and a receiver tank attached to a pipe with an inline flow meter and pressure gauge.

Process

- An uncased or cased well is drilled. A small vertical section of the well (up to two feet) is isolated, then high-pressure air is injected for short periods of time (< 30 seconds) using a proprietary nozzle. Air is injected at rates of 25 to 50 cubic meters (883 to 1,766 cubic feet) per minute at pressures of 0.5 to 2MPa (72.5 to 290 psi).

- The isolation and injection are repeated at the desired vertical intervals.

General Considerations

- The direction of fracture propagation will be perpendicular to the minimum principal stress in the subsurface at a particular site. Recent field data indicate that soil fabric or lithology may have a greater influence on fracture orientation than the in situ state of stress in the soil mass in some soil deposits.

- Injection pressure required to initiate a fracture generally increases with increasing depth, injection rate, and fluid viscosity.

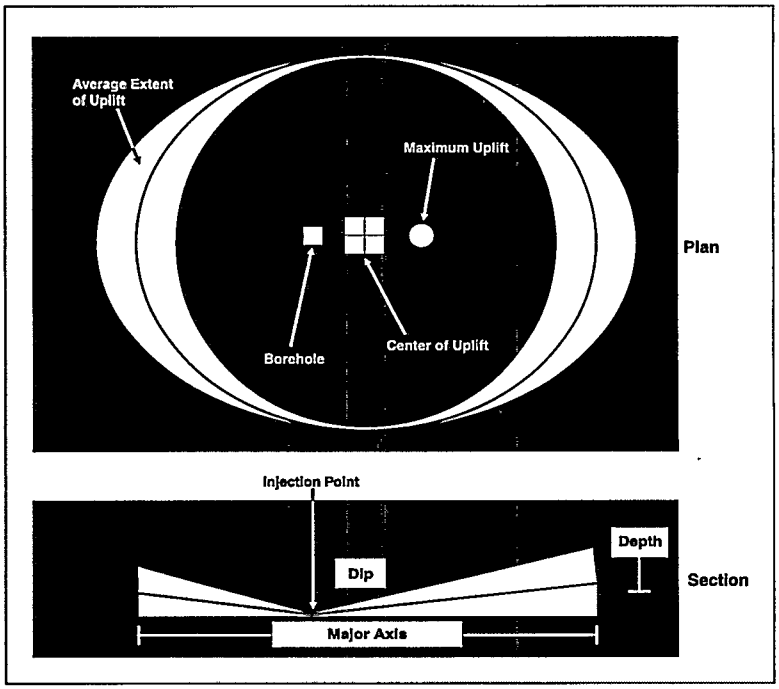

Figure 2. Plan and section of a typical hydraulic fracture created in overconsolidated silty clay. (modified from U.S. EPA, 1994).

Injection Fluids

- Guar gum gel is commonly used in hydraulic fracturing. The gel carries sand into the subsurface to prop the fractures open.
  - ◊ Guar gum is a food additive and when mixed with water forms a short-chain polymer with the consistency of molasses.
  - ◊ A crosslinker is added to lengthen the polymer chains and create a thick gel capable of suspending high concentrations of sand.
  - ◊ An enzyme is added to the gel that breaks down the polymer chains in a few hours to allow recovery of the thinned liquid.

- Pneumatic Fracturing (i.e., injection of air) typically uses no propping agents and is thus best applied at sites where the geology is conducive to maintaining open any dilated existing fractures or newly created fractures.

Leakoff

- Leakoff occurs when some of the injected fluid flows out through the walls of the fracture. The rate of fracture propagation decreases as the rate of leakoff increases, and propagation ceases entirely when the leakoff rate equals the rate of injection.

- Leakoff generally controls the size of the fractures. Leakoff is minimized by controlling amount and rate of injection.

Monitoring Fracture Location

- The most widely used method of monitoring fracture location is measuring the displacement of the ground surface, using either surveying of field staffs before and after or tiltmeters during fracture propagation. Pressure influence in surrounding monitoring wells can also be measured to determine fracture locations.

Design Considerations

The table below summarizes the factors that should be considered when deciding if a site is appropriate for fracturing and if so how to best design the project (modified from US EPA, 1994).

Factor	Favorable	Unfavorable
Formation permeability	Moderate to low($k < 10^{-6}$ cm^2)	Unnecessary in high permeability formations
Formation type	Rock or fine-grained sediment	Coarse-grained sediment
Formation structure	Horizontal bedding planes	Vertical structures
Sand proppant	Unlithified, saturated sediments	May be unnecessary in consolidated units
State of stress	Horizontal stress > vertical stress (overconsolidated)	Horizontal stress < vertical stress (normally consolidated)
Site conditions	Open ground over fracture/ no buried utilities	Structures sensitive to displacement over fracture/ buried utilities
Depth	One to eight meters	Surface or > eight meters

SECTION 3

PERFORMANCE

Demonstration Plan

Major elements of the demonstrations included:

- Initial flow rates and contaminant extraction levels from extraction and monitoring wells (monitoring wells sampled to determine whether fractures have established connections between the fracture well and the monitoring wells.)
- Final flow rates and contaminant extraction levels from extraction and monitoring wells;
- Pressures at both monitoring wells and extraction wells.

Specific examples of demonstrations for each of the technologies, with focus on those supported by DOE, are presented in this section.

Demonstration Summary

Hydraulic Fracturing

- Hydraulic fracturing was demonstrated under the EPA SITE program in July of 1991 at sites in Oak Brook Illinois and Dayton Ohio. Both sites contained low-permeability soils ($<10^{-7}$ cm/sec) that were contaminated with volatile organic compounds (VOCs). Fracturing was accomplished to a depth of 15 feet below ground surface.
  - ◊ In Illinois, contaminants removed by soil vapor extraction were increased by 7 to 14 times and the area of influence was 30 times greater after fracturing.
  - ◊ In Ohio flow of water into the fractured well was increased 25 to 40 times and bioremediation rate was increased by approximately 75%.

- Demonstrations have also been conducted at the DOE Portsmouth Gaseous Diffusion Plant (August 1996), the Laidlaw site near Sarnia, Ontario, Canada (cofunded by DOE), the Bristol Tennessee site, the Beaumont Texas site, and the Linemaster Switch Superfund Site in Woodstock Connecticut. At the DOE site, fractures were propped with sand, oxidants, and reductants; the site was then treated with hot air/steam enhanced air flushing and in situ chemical degradation.

Pneumatic Fracturing

- An EPA SITE demonstration was conducted at a site in Hillsborough, New Jersey in 1992. Fractures created during the demonstration significantly increased the effective radius of influence and increased the rate of mass removal about 675% over the rates measured before fracturing. By installing wells to be used as passive inlets/outlets, improvements in mass removal rates were as high as 2300%.

- DOE supported demonstration at the Tinker Air Force Base in Oklahoma and the Portsmouth Gaseous Diffusion Plant in Ohio.

Treatment Performance

Hydraulic Fracturing:

Site 1 - Laidlaw Site, Sarnia, Ontario

- The sheet-pile test cell was a clean site located adjacent to a major hazardous waste landfill. A synthetic gasoline blend with a tracer of trichloroethylene (TCE) was released into the cell in 1992. Soil vapor extraction was then initiated. Surface materials at this location are composed of clay-rich glacial till.

- In August of 1994, hydraulic fracturing was conducted. Fifteen fractures were emplaced at 9 locations outside of the sheet-pile cell at depths of 1.2 and 5.6 meters.
  - ◊ Minimum surface uplift from the fracturing was observed as 1 to 4.65 centimeters.
  - ◊ More symmetric fractures were created at shallow depths, while asymmetric fractures were created at depths greater than 2.5 meters. In addition, the dip of the fractures increased with the depth of the fracture, if greater than 2.5 meters.

Other Sites

- Performance of wells that have been hydraulically fractured generally increases by a factor of 1.5 to 10 but the range varies up to 100 or more.
- Several examples of demonstration performance are listed below.

Site Name	Contaminant/Geology	Mass Recovery Change	Radius of Influence Improvement
Oak Brook IL	VOCs in Silty Clay	7 to 14	30 times
Dayton OH	VOCs in Silty Clay	25 to 40	
Bristol TN	DNAPL/Fract. Bedrk.	2.8 to 6.2	30 times
Regina Saskatchewan	VOCs in Silty Clay		25
Calgary Alberta	VOCs in Silty Clay	10	
Linemaster, CT	Solvents in Till	4 to 6	
Beaumont TX	DNAPL in Silty Clay	50	~25

Pneumatic Fracturing:

Site 1- Fuel Oil In Sedimentary Strata : Tinker Air Force Base, Oklahoma

- Fuel oil had leaked from an underground storage tank into interbedded sedimentary strata. A pump and treat system was installed and recovered 155 gallons per month for 17 months.

- Four wells were installed at the site and pneumatically fractured.

- Key results were:
  - ◊ After installation of the first fractured well, fuel oil (as floating product) thickness in the nearby recovery well increased from 1.5 feet to 20.2 feet (see figure below) and oil recovery increased to approximately 435 gallons per month.
  - ◊ Other fracture wells improved performance from other recovery wells from 224 to 434%.
  - ◊ Oil production was increased in wells as far as 59 feet from the injection point.
  - ◊ Oil recovered as a percentage of total fluid pumped increased from 12 to 90%.

- Fracture wells were also installed at an adjacent site to enhance bioremediation in a clayey silt and sand formation. Air flows from vapor extraction increased 500 to 1700%.

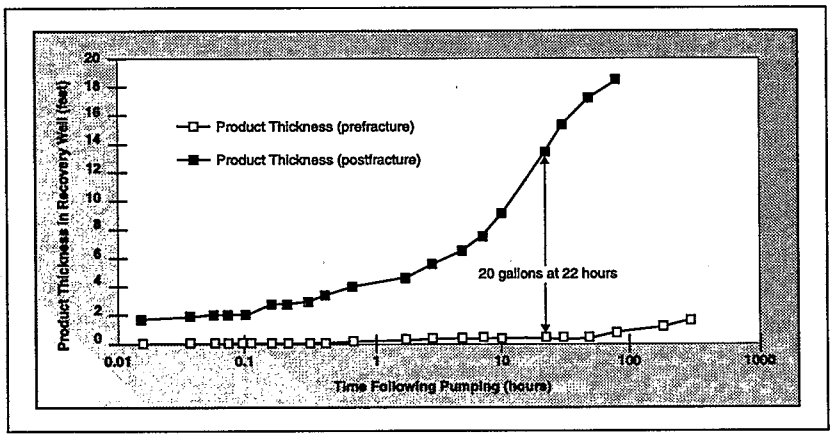

Figure 5. Floating Product (fuel oil) Thickness Data for Recovery Well 4

Site 2- VOCs and DNAPLs in silts and clays: DOE Portsmouth Gaseous Diffusion Plant, Ohio

- The Clean Test Site (CTS) is underlain by low-permeability clays and silts to a depth of approximately 15 to 22 feet. During the summer of 1994, two fracture wells were created. Post-fracture hydraulic conductivity was determined to be 1.0 feet/day, a two-fold increase with a radius of influence increasing by 33% from 200 to 300 feet after one day of pumping.

TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- Fracturing enhances current remediation technologies by increasing permeabilities and improving flow, recovery and destruction rates for:
  - ◊ vapor extraction,
  - ◊ ground water extraction,
  - ◊ bioremediation,
  - ◊ free product recovery (LNAPLs and DNAPLs),
  - ◊ possibly electrokinetics and other innovative in situ technologies, such as permeable barriers with chemical oxidants or reductants.

- Hydraulic and Pneumatic Fracturing for fluid recovery enhancement have been successfully demonstrated on the field scale in both the vadose and saturated zones.

- Hydraulic and Pneumatic Fracturing are well suited for sites with an assortment of underlying strata, especially such as low-permeability sandstones, clays, siltstones, and shales.

Competing Technologies

The baseline against which fracturing can be compared is remediation, such as soil vapor extraction, without fracturing. Improvements in recovery of contaminants after fracturing can then be used to compare to the baseline.

Hydraulic and Pneumatic Fracturing are competing technologies. A site being considered for fracturing must be evaluated to determine which technology would perform as required and be the most cost effective. A table comparing the two technologies is presented in Appendix B (from Keffer et al., 1996).

Another technology designed to enhance access to the subsurface is that of directionally drilled horizontal wells. Fracturing of geologic media and soils at low-permeability sites contaminated with VOCs also competes with soil heating technologies, designed to enhance contaminant removal by soil vapor extraction (see Six Phase Soil Heating ITSR report, DOE, 1995, as an example.) In situ enhanced soil mixing has been used to treat VOC-contaminated sites with low-permeability soils and geologic media (see ITSR In Situ Enhanced Soil Mixing, DOE, 1996). Other remediation technologies such as surfactant flushing and bioremediation do not compete directly as they do not enhance access to the subsurface.

Technology Maturity

Hydraulic Fracturing

- Hydraulic Fracturing has been used extensively for over fifty years in the petroleum industry. It has been demonstrated at a number of sites in North America for fluid recovery enhancement but not yet fully implemented for a site cleanup. Advanced applications of fracturing technology represent an earlier stage of development.

Pneumatic Fracturing

- Pneumatic Fracturing has been demonstrated at over thirty sites in North America and has been utilized for full implementation of site cleanup at six or more sites.

Hydraulic Fracturing

The EPA has reported the cost per single fracture ranging from $950-$1425, however the cost is highly dependent upon the number of fractures to be placed in each borehole. EPA also reported a daily cost of $5700 to create 4 to 6 fractures. Golder Associates Ltd. reports costs of $400-500 per fracture or $2000 to $6000 per well.

Type of Cost	Daily Cost ($)
Site Preparation	1,000
Permitting and Regulatory	5,000
Capital Equipment Rental	1,000
Startup	0
Labor	2,000
Supply and Consumables	1,000
Utilities	0
Effluent Treatment and Disposal	0
Residual and Waste Shipping and Handling	0
Analytical and Monitoring	700
Maintenance and Modifications	0
Demobilization	400
Total One-Time Costs	5,400
Total Daily Costs	5,700
Estimated Cost per Fracture	950-1425

Source: U.S. EPA 1993a.

Pneumatic Fracturing

Pneumatic Fracturing costs can be estimated to be similar to those of Hydraulic Fracturing reported above, $400-1425 per fracture. However, an alternative cost estimating method, based upon dollars per pound of contaminant removed, was completed by EPA. Costs calculated for the EPA SITE demonstration in New Jersey were estimated at $140/lb of TCE removed for a hypothetical remediation, assuming constant removal rate:

- site = 100 feet by 150 feet
- effective radius of influence 25 feet
- 15 wells required to get a 15-20% overlap
- one-year operating cycle with capital cost amortization.

Costs were extrapolated from a 4-hour postfracture test:

- labor 29%
- capital equipment 22%
- offgas treatment 19%
- site preparation 11%
- residuals disposal 10%

Other estimates predict Pneumatic Fracturing to cost $8 to $17 per cubic yard of soil treated. Fracturing can be completed using a weekly rate of $15,000 to $20,000.

REGULATORY/POLICY ISSUES

Regulatory Considerations

- To date, no special permits are required for the use of Pneumatic or Hydraulic Fracturing. Fracturing activities are considered under the requirements for the remediation of a particular site.
  - ◊ Gels used in Hydraulic Fracturing (usually guar gum) are biodegradable and non-toxic. Other additives, such as the proppants (usually sand of various grain sizes) and water, are naturally occurring and not a regulatory concern.
  - ◊ However, some state agencies are concerned about injection of fluids and materials that may alter the pH of the subsurface.

- A possible concern is the lack of control of fracture generation.
  - ◊ Behavior of a strata prior to fracture, such as the quantity, size and direction of the generated fractures, is not well-defined. Information on site geology/hydrology can be used to model the placement of fractures.
  - ◊ In a highly fractured system, further fracturing may drive contamination away from the pressure front, thus increasing the area of contamination.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Health and safety issues for fracturing technologies do not present significant hazards over conventional field remediation operations.
- Pressures used are high enough to require extreme caution. All equipment is checked regularly and contains safety features such as pressure relief valves. All workers are trained regularly in safe equipment operation and are required to take OSHA 40-hour training. An addendum to the Health and Safety Plan addressing pressure issues would typically be required.

Community Safety

- Fracturing technologies do not produce any routine release of contaminants.
- No unusual safety concerns are associated with the transport of equipment to and from the site.
- Careful monitoring of field operations assures safety to the workers and the public.

Environmental Impacts

- No additional impacts will be produced over that already underway as a result of the site remediation efforts. Equipment is transported to the site and then removed after the fractures are created.

Socioeconomic Impacts and Community Perception

- Fracturing has a minimal economic or labor force impact.
- The general public has limited familiarity with this technology.

Implementation Considerations

- The precise geometry (direction, length and size) of fractures cannot be determined prior to generation, but likely characteristics can be generalized by experienced practitioners based on site conditions and experience.

- Sites should be analyzed for permeability before fracturing is proposed. Extensively fractured strata will have permeabilities high enough such that they will not require fracturing and fracturing will not be optimal as the pressure required to fracture the strata further may be much larger than the operating range of the injection equipment (i.e too much leakoff occurs).

- Perched water may hamper measurement of the extent of fracturing or interfere with the remediation system performance for vadose-zone soil vapor extraction systems.

Technology Limitations and Need for Future Development

- Fracturing for ambient temperature fluid recovery has been demonstrated at many sites; existing and future development includes coupling of in situ mass transfer and destruction processes.

- The degree of post-emplacement healing of fractures (especially with unpropped fractures) and the degree of pore continuity disruption furing operation are not well documented at this time.

- Fracturing near foundations or utilities should include a risk analysis before the fracturing is initiated, as strata upheaval may weaken supports and crack foundations and utilities. The utilities or foundations may also act as preferential pathways, thus limiting fracture generation. However, many sites in the vicinity of utilities and foundations have been fractured without significant problems.

APPENDIX A

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APPENDIX B

Comparison of Pneumatic Fracturing and Hydraulic Fracturing

(Modified from Keffer et al., 1996)

PNEUMATIC FRACTURING	HYDRAULIC FRACTURING
Fracture apertures are small (usually measured after settling) on the order of 500 - 1,000 microns. The smaller openings create a lower cumulative heave, which could reduce or eliminate the long-term impact to structures.	Fracture apertures are large, usually on the order of 1 - 2 centimeters. The use of proppants in these fractures translates to a significant amount of cumulative heave, which can have a direct impact on nearby structures, but which also can further increase permeability.
The flow through these fractures is conductive and the lack of a proppant allows flow to be governed by the "cubic law," which states that the flow rate is proportional to the cube of the aperture opening allowing high flow rates through smaller openings.	The flow through the fractures is Darcian in nature. Thus a larger aperture opening is required to achieve equivalent flow rates.
The fluid used to fracture is air. This creates a cleaner operation where the volume of contaminated media is not increased, allows better control of fracture propagation and reduces the possibility of a hazardous waste spill due to back pressure venting through the fracture well. Air is also less expensive to produce.	The fluid used is usually water which can contact the waste product and dissolves into the water creating a larger volume of contaminated media. When the operation is complete, back pressures can eject hazardous waste to the surface making a dirty operation and possibly a reportable spill. Water introduced to a vadose zone needs to be removed.
The orientation of pneumatic fractures in soil formations is more consistently horizontal. Some upward migration occurs at the outer edges of shallow fractures.	Fracture orientation has been demonstrated to have a vertical component which often creates an angular fracture that intersects the surface.
Pneumatic fractures propagate between 20 and 50 feet outward. The farthest has been 70 feet.	Hydraulic fractures propagate between 15 and 50 feet outward.
Pneumatic fractures are best emplaced less than 75 feet. Below 75 feet the weight of the overburden decreases the effect of self-propping. Engineering adjustments also need to take place below this depth.	The depths at which hydraulic fractures can be emplaced are significantly higher than the depths Pneumatic Fractures can be emplaced.
Fracture density occurs as both a dense network of micro-fractures that impact a smaller area around the fracture point and a few major fractures which migrate outward into the formation. This density occurs in each interval of 2 – 3 feet.	Fracture density is typically limited to one or two major fractures per injection interval. The injection interval is larger varying between 5 and 20 feet.
Pneumatic Fracturing is faster. Injections typically last 20 seconds.	Hydraulic fracturing typically takes 5 to 10 minutes per fracture.

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Accutech Remedial Systems

Frozen Soil Barrier Technology at the SEG Facilities, Oak Ridge, Tennessee in Cooperation with U.S. Department of Energy Oak Ridge Operations

Case Study Abstract

Frozen Soil Barrier Technology at the SEG Facilities, Oak Ridge, Tennessee in Cooperation with U.S. Department of Energy Oak Ridge Operations

Site Name:
Scientific Ecology Group (SEG), Gallaher Road Facility

Location:
Oak Ridge, Tennessee

Contaminants:
None
- Surrogate solution (200 ppm Rhodamine-WT) were used to test the integrity characteristics of the barrier.

Period of Operation:
May 12 - October 10, 1994

Cleanup Type:
Field demonstration

Technical Information:
Rick Swatzell, Prin. Inv., Martin Marietta Energy Systems, Inc.
(615) 435-3126
Ray Peters, SEG
(615) 376-8194

Technology:
Frozen Soil Barrier
- Uses refrigeration to freeze soils and provide barrier/containment for hazardous and/or radioactive contaminants in soil and ground water.
- Demonstration facility was "V"-shaped, with dimensions of 56 by 56 feet outside and 33 by 33 feet inside; maximum depth was 28 feet;
- Refrigerant pipes were installed around circumference of facility in a double-rowed configuration with an ice wall allowed to grow together between the pipes and forming a barrier.

Cleanup Authority:
None - demonstration conducted at a nonhazardous site

SIC Code:
Not Applicable (not a contaminated site)

Management Information:
Jef Walker, DOE EM-50 Plumes Focus Area Program Manager, (303) 903-7966

Waste Source:
Not Applicable (not a contaminated site)

Purpose/Significance of Application:
Frozen soil barrier technology has been demonstrated for controlling waste migration in soils.

Type/Quantity of Media Treated:
Soil
- Subsurface soils consisted of 13 to 22 feet of fill soils overlying residual soils. Fill soils consisted of stiff to hard red-brown silty clay, with varying amounts of chert fragments. Residual soils consisted of stiff to soft red-brown to brown silty clay and clayey silt, with varying amounts of chert fragments.
- Soil density measured as 108.8 lb/ft^3.
- Average soil moisture content ranged from 26.5 to 33.9%.
- 8,175 cubic feet of soil contained by the frozen barrier.
- 35,694 cubic feet of soil composed frozen barrier.

Regulatory Requirements/Cleanup Goals:
No regulatory requirements or cleanup goals were identified for this demonstration because it was conducted at a nonhazardous site.

Results:
This demonstration was evaluated using the following four types of performance testing: 1) computer model validation; 2) soil movement testing, including heat grid tests; 3) barrier diffusion and leaking tank tests; and 4) barrier integrity testing. The barrier diffusion and leaking tank tests were used to demonstrate containment by the frozen barrier wall by releasing Rhodamine-WT from a tank inside the containment structure and measuring its potential diffusion across the barrier wall.
- Tests showed that Rhodamine was found only inside the barrier region, confirming barrier integrity.
- Tests showed that Rhodamine migrated approximately two feet in unfrozen soils, while essentially no Rhodamine was found below open-ended well casings within the freeze barrier.

Case Study Abstract

Frozen Soil Barrier Technology at the SEG Facilities, Oak Ridge, Tennessee in Cooperation with U.S. Department of Energy Oak Ridge Operations (Continued)

Cost Factors:
- Total capital costs for the SEG demonstration were $481,427.
- Maintenance costs for the demonstration were estimated as $40,000 per year ($3322 per month).
- No additional details provided on components of capital or maintenance costs.
- Unit costs identified for this technology ranged from $4 to $14 per cubic foot of iced formed, and are compared with unit costs for grout systems ranging from $1 to $37 per cubic foot.
- Report authors indicated that a more realistic cost (i.e., for an actual remedial activity) for this type of technology would be $332,754, assuming that extra sensors and test support were not needed, if equipment were leased instead of purchased, and barrier thickness was decreased (which would mean less drilling, energy consumption, etc.).

Description:
Frozen soil barrier technology was demonstrated under the sponsorship of the U.S. DOE In Situ Remediation Integrated Demonstration Program at a nonhazardous site on SEG property at the Gallaher Road Facility in Oak Ridge Tennessee. Frozen soil barrier technology has been used for a number of years in large-scale civil engineering projects to seal tunnels, mine shafts, and other subsurface structures against flooding, and to stabilize soils during excavation. Advantages of frozen soil barrier technology include: 1) it can provide complete containment; 2) it uses benign material (water/ice) as a containment medium; 3) frozen barriers can be removed by thawing; and 4) frozen barriers can be repaired in situ (by injecting water into the leaking area).

At the SEG demonstration, a "V"-shaped containment structure was constructed 56 feet long by 56 feet wide by 28 feet deep. Refrigerant piping was used to create an area of frozen soil ranging from 5 to 15 feet thick. Several types of performance testing were performed, including barrier diffusion and leaking tank tests, based on use of a surrogate solution containing 200 ppm of Rhodamine-WT. The barrier diffusion and leaking tank tests showed that Rhodamine was found only inside the barrier region, confirming barrier integrity, and that Rhodamine migrated approximately two feet in unfrozen soils, while essentially no Rhodamine was found below open-ended well casings within the freeze barrier.

Determining the suitability of this technology for applications for arid/sandy environments will require development of methods for homogeneously adding and retaining moisture in the soils. In addition, technology applications in fine-grained soils around structures may be limited because of soil movement.

SECTION 1

SUMMARY

Technology Description

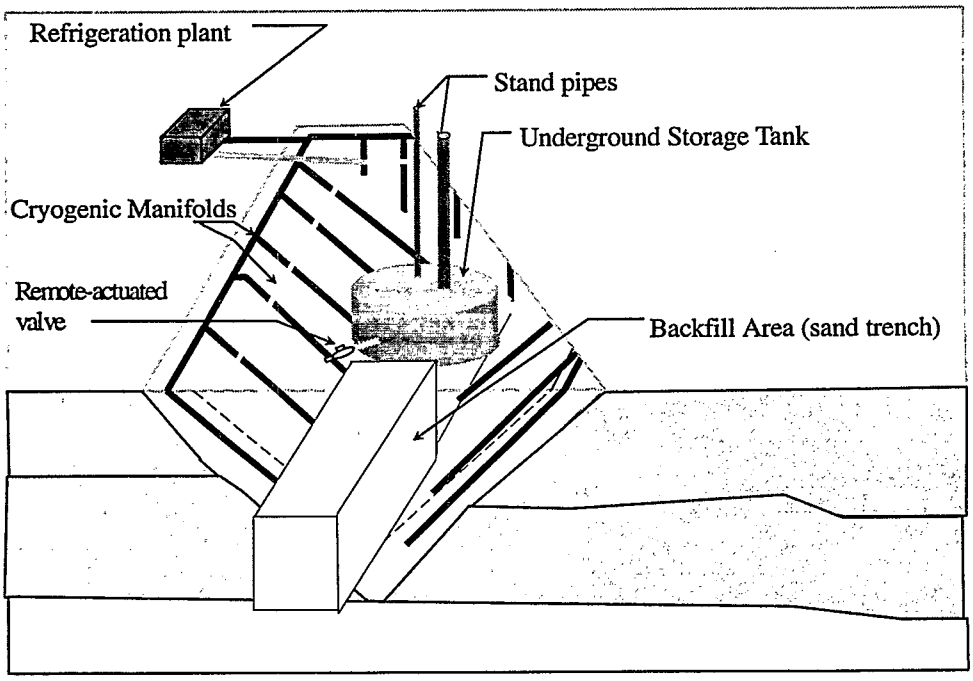
The technology of using refrigeration to freeze soils has been employed in large-scale engineering projects for a number of years. This technology bonds soils to give load-bearing strength during construction; to seal tunnels, mine shafts, and other subsurface structures against flooding from groundwater; and to stabilize soils during excavation. Examples of modern applications include several large subway, highway, and water supply tunnels.

Ground freezing to form subsurface frozen soil barriers is an innovative technology designed to contain hazardous and radioactive contaminants in soils and groundwater. Frozen soil barriers that provide complete containment ("V" configuration) are formed by drilling and installing refrigerant piping (on 8-ft centers) horizontally at approximately 45° angles for sides and vertically for ends and then recirculating an environmentally safe refrigerant solution through the piping to freeze the soil porewater. Freeze plants are used to keep the containment structure at subfreezing temperatures. Advantages for this technology include the following:

- It can provide complete containment.
- It uses benign material (water/ice) as a containment medium.
- Frozen barriers can be removed (by thawing).
- Frozen barriers can be repaired in situ (by injecting water into the leakage area).

Technology Status

A full-scale "V-shaped" containment structure (56 ft long x 56 ft wide x 28 ft deep) was demonstrated from May 12 to October 10, 1994, at a nonhazardous site on SEG property at the Gallaher Road Facility in Oak Ridge, Tennessee. The project was sponsored under the U.S. Department of Energy In-Situ Remediation Integrated Demonstration Program by the Office of Technology Development (EM-50). Surrogate solutions (200 ppm Rhodamine-WT) were used to test the integrity characteristics of the barrier.



Key Results

- Time-constrained laboratory studies showed that effective frozen soil barriers (hydraulic permeabilities < 4x10E-10 cm/sec) can be formed in saturated soils for chromate (4000 mg/kg) and trichloroethylene (TCE) (6000 mg/kg). Tests with cesium-137 showed no detectable diffusion through the barrier although sorption on the soil grains may have been responsible for the immobility.
- Soil movement can be predicted accurately for fine-grained soils based on past civil engineering practices.
- Computer modeling of heat transfer characteristics and soil temperature for fine-grained soils was validated.
- Costs associated with engineering, construction, operation, and maintenance of frozen soil barriers in fine-grained soils using full-scale equipment were established (for a nonhazardous site).
- Electropotential studies utilizing frozen soil's low electrical conductivity properties showed low ionic transport across the frozen soil barrier, indicating that the barrier is an effective deterrent to ionic transport.
- Excavation of the nonfrozen soil within the contained area and ground penetrating radar studies showed (1) the inner area to be in the predicted formation ("V" shape) and (2) the frozen wall thicknesses to be approximately 15 ft in the sand trench area and 5 to 9 ft in the clay-dominated areas.
- Diffusion studies (with Rhodamine-WT as the tracer) conducted by Los Alamos National Laboratory (LANL) confirmed barrier integrity.
- An in-place temperature-monitoring system provided soil temperature information confirming barrier formation.
- The Frozen Soil Barrier process is based upon U.S. Patent No. 4,860,544, issued to RKK Ltd. for CRYOCELL ground freezing technology.

Contacts

Technical

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Ray Peters, Scientific Ecology Group (SEG), 615-376-8194

Management

Jef Walker, DOE EM-50, DOE Plumes Focus Area Program Manager, 303-903-7966

SECTION 2

TECHNOLOGY DESCRIPTION

1.0 Purpose

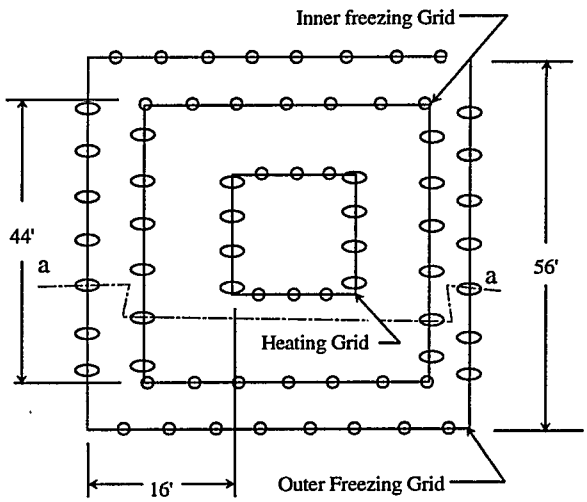
The purpose of this project was to provide the U.S. Department of Energy with an innovative technique for controlling waste migration in soils by demonstrating the use of frozen soil barriers. This project had the following goals and objectives:

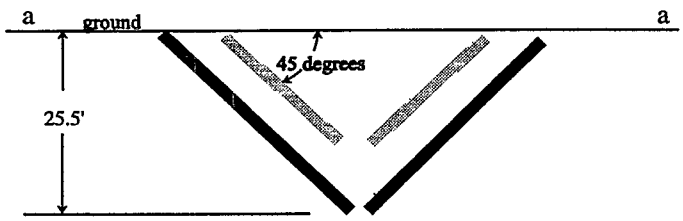
- Demonstrate in situ isolation of a simulated waste from the environment.
- Provide complete containment of the simulated waste.
- Construct a subsurface barrier without adding injectants or any barrier materials.
- Demonstrate long-term control of in situ waste.
- Conduct barrier monitoring and integrity testing.

2.0 Description of the Demonstration Facility

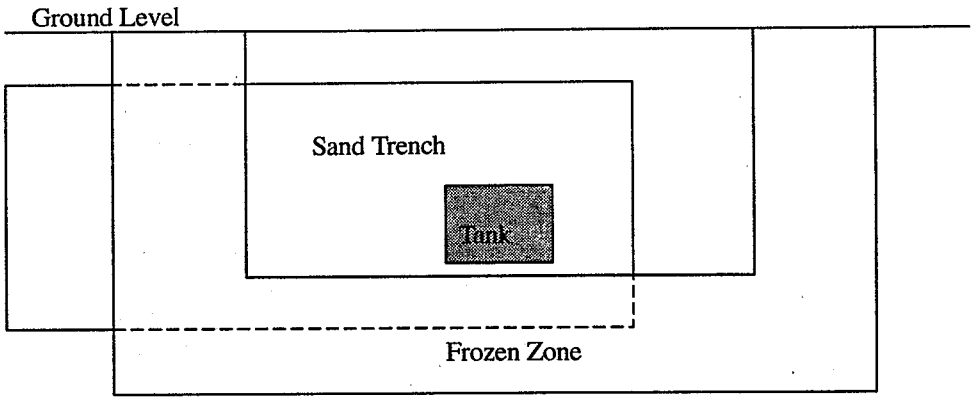
The dimensions of the frozen soil barrier region were 56 ft by 56 ft (outside) and 33 ft by 33 ft (inside) once the ice barrier was fully formed.

- Freeze pipes were installed in double-rowed configuration for overlap.
- Pipes were installed at a 45° angle to establish a bottom to the containment structure.
- Pipes were set on 8-ft centers with the two rows set at 4-ft centerlines, and the ice wall was allowed to grow together forming the barrier.
- An array of heating pipes was installed inside the freeze grid to allow some oil heave control.
- The piping material was 4-in. schedule 10 carbon steel for both freeze and heat grids.
- Monitoring was accomplished through additional pipes inserted around the site. Resistance temperature detectors (RTDs) were placed inside these pipes at 5-ft intervals.





A sand trench was built to cross the area that would be consumed by the frozen barrier to insure that the tracer material would have an adequate flow path. The native soil was determined to be clayey with low permeability. The trench was 8 ft below the surface and 6 ft thick with native soil packed over to backfill to grade.



A carbon steel tank measuring 52.5 in. high by 65 in. diameter was buried in the center of the sand trench. This tank was used as the distribution point for releasing the tracer during the barrier integrity testing phase of the project.
The site was covered with a plastic liner to prevent rain infiltration, insulate against surface warming, and allow the freeze front to reach the surface.

Ground freezing apparatus used for the demonstration project consisted of surface equipment (refrigeration unit, heat source, and piping) and subsurface equipment (freeze pipes, heat pipes, and monitoring wells).

Major surface components and/or characteristics of the freeze barrier demonstration are as follows:

• Refrigeration Capacity	Two 40-Ton Units
• Refrigerant	R-22
• Compressor	Rotary Screw
• Condenser	Evaporative
• Evaporators	Shell and Tube
• Evaporator Temperature	Approximately 35°C
• Coolant (calcium chloride brine)	1.28 specific gravity

Component	Horsepower
Compressor Motor	250
Condenser Fan Motor	20
Condenser Water Pump Motor	2
Lube Oil Pump	3
Brine Pump	40
Ancillary Pumps and Controls	5
Total	320

The following chart shows power requirements for the two 40-ton refrigeration units used on site:

SECTION 3

PERFORMANCE

Testing the frozen barrier consisted of looking at the physical aspects of soil freezing, the containment characteristics of the barrier, and the physical characteristics of the barrier once it was formed.

This evaluation was accomplished with four kinds of testing:

- computer model validation;
- soil movement testing, including heat grid tests;
- barrier diffusion and leaking tank tests; and
- barrier integrity testing.

Results obtained are discussed in the next section.

Computer Model Validation

Purpose

To compare predicted energy consumption and frozen barrier temperatures during formation and operation of the frozen barrier, to confirm the accuracy of ground freezing calculations, and to improve the parameters used in such calculations.

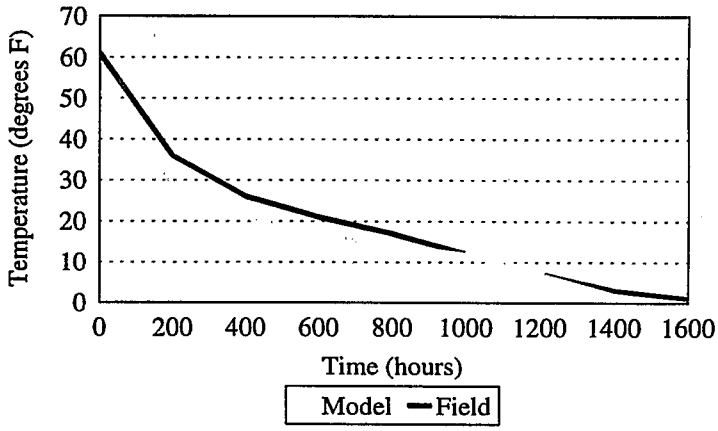
Test Equipment

Computer model, monitoring system (for both soil and brine temperature), flowmeters, and electrical meter.

Test Results

- The field data and calculated temperature data are in close agreement.
- Actual power consumption (420,000 kW-hours) showed good agreement with predicted values (380,000 kW-hours).
- To the extent that convective heat transfer coefficients can be quantified and the thermal properties of the soil can be characterized, this analysis provides an effective analytical tool for predicting how long it takes to develop the freeze barrier to the design thickness and the shape of the freeze wall. Finite element analysis can be a useful tool for developing freeze wall designs and selecting refrigeration equipment.

Temperature vs. Time - Comparison of Field Data and Modelling Results



Field data from monitoring well TPI-4A

Soil Movement Test

Purpose

This test measured soil movement and stresses on a tank buried in the center of the barrier test facility. Soil movement was expected because of the wet and fine-grained nature of the soil at the site, which is classified as "frost-susceptible" by the U.S. Army Corps of Engineers' Cold Regions Research and Engineering Laboratory (CRREL) according to their grain size criterion for silty and clayey soils. This test also determined the effect on soil movement when the heating grid was used.

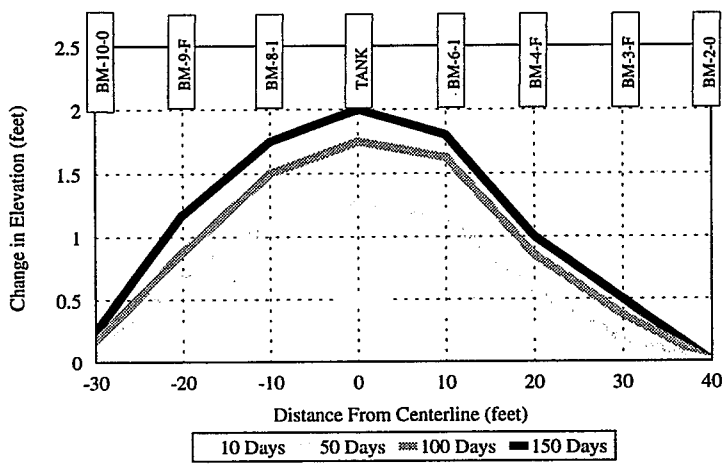
Test Equipment

Ten benchmarks, transit, strain gages, flowmeters, and temperature sensors were installed within the demonstration site. Benchmarks were constructed by drilling 3-ft-deep holes by hand with a post hole digger. Holes were backfilled with concrete, and 36-in. sections of iron rebar were inserted into the concrete. Approximately 10 to 12 in. of rebar was exposed at the marker surface. In addition, two benchmarks for the tank (the 2-in. and 4-in. risers) were measured.

Test Results

- The heat grid was effective in slowing the rate of increase in tank movement.
- The maximum stress calculated as part of the analysis was 4,000 psi. The allowable stress for carbon steel is 12,000 psi.
- Soil movement of 1.65 ft observed during first 70 days was in good agreement with predicted values (between 1.20 and 2.24 ft).
- Maximum lift of any monuments was 2.25 ft.
- The heat grid was effective in controlling inward growth of the barrier (ice).

Soil Movement Data BM-1-0 through BM-10-0



Barrier Diffusion and Leaking Tank Test

Purpose and Plan

The barrier diffusion and leaking tank testing were to provide quantitative measures of the effectiveness of the frozen soil barrier in preventing the passage of hazardous and radioactive wastes in the form of water-borne chemicals. Design of the tracer experiments had three phases: (1) hydraulic conductivity testing of the permeable sand trench crossing a segment of the then-unformed cryogenic barrier wall using fluorescein, (2) demonstration of containment by the cryogenic barrier wall following closure by releasing Rhodamine-WT from the tank inside the containment structure, and (3) comparison of tracer movement in the frozen native soil with that in unfrozen native soil at the demonstration site.

Test Equipment

Diffusion monitoring wells, tracers (200 ppm solutions of fluorescein, Rhodamine-WT), and fluorescence spectrometer.

Test Results

- Substantial hydraulic conductivity was shown through the sand trench by the appearance of fluorescein in recovery well WO-A (outside the planned barrier) in less than 4 hours (Figure 5).
- Rhodamine was found only inside the barrier region, showing barrier integrity (see Figure 6).
- Phase 3 tests showed that Rhodamine migrated approximately 2 feet in unfrozen soils, while essentially no Rhodamine tracer was found below open-ended well casings within the freeze barrier.

Barrier Integrity Testing

Purpose and Plan

Barrier integrity testing consisted of (1) measuring the electropotential of the soil to indicate reduced ionic transport properties (reduced electrical conductivity of frozen soil) through the frozen soil region and (2) performing ground penetrating radar studies of the barrier wall after the barrier-contained interior (unfrozen section) was excavated.

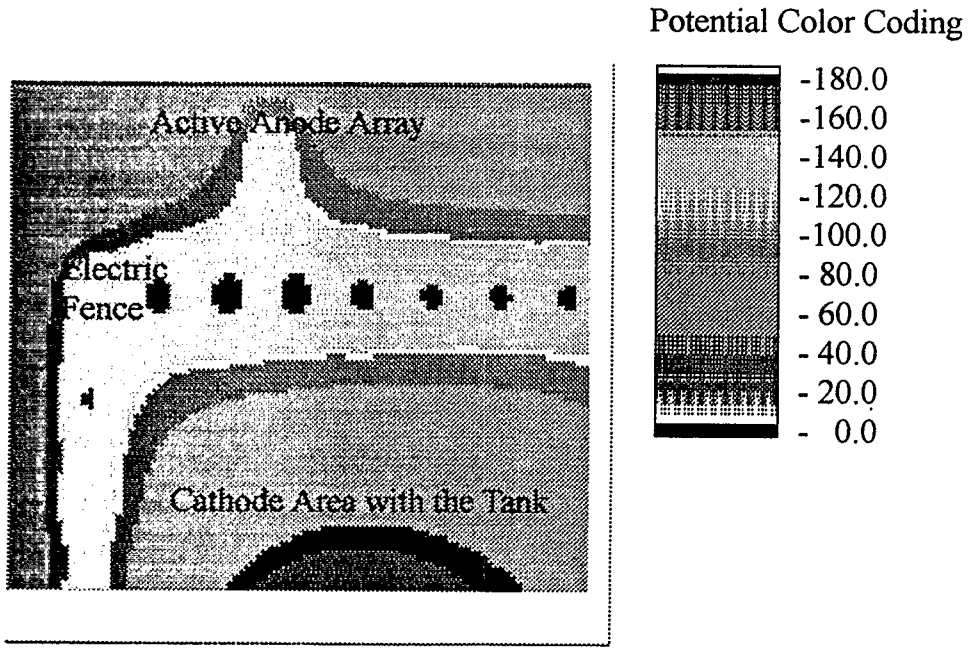
Test Equipment

Passive and active electrodes (for electropotential measurements), computer data collection and analysis system, and ground penetrating radar instrumentation.

Test Results

- Electropotential measurements showed low ionic transport across the frozen soil barrier walls.
- Excavation of the contained area within the frozen barrier confirmed the desired "V" configuration, and subsequent ground penetrating radar measurements showed the barrier wall to be approximately 12–15 ft thick within the sand trench area and approximately 5–9 ft thick within clay-dominated areas.

Uniform Electric Flux Field in the Southeast Corner of the "ICE BARRIER"



TECHNOLOGY APPLICABILITY AND ALTERNATIVE TECHNOLOGIES

Technology Applicability

- Radioactive, heavy metal, and organic contaminants can be contained by this technology.
- Laboratory studies have shown that frozen soil barriers with low hydraulic permeabilities (< 4x10E_10 cm/sec) can be formed in saturated soil conditions.
- Formation of frozen soil barriers in saturated, fine-grained soils has been demonstrated in the field.
- The formation of frozen soil barriers in arid conditions will require a suitable method of homogeneously adding moisture to the soils to achieve saturated conditions before the technology can be assessed for that application.
- Soil movement should be a factor to consider for applications in fine-grained soils around structures (buildings, submerged tanks and piping, etc.).
- Barriers should be such that they will not degrade upon contact with contaminant solutions.
- Formation of frozen soil barriers in areas where plumes of low-freezing-point contaminants (TCE, etc.) exist may require more expensive cryogenics (e.g., liquid nitrogen).

Competing Technologies

- Frozen soil barrier technology is competitive with other subsurface flow-control technologies such as liners, slurry walls, sheet pil ing, and grouting.
- Comparison with other technologies is difficult because of the unique aspects of ground freezing technology, including complete containment and removability. In addition, ground freezing incurs additional energy, operation, and maintenance costs over time that other containment technologies do not. However, it appears that this technology can be effectively applied in fine-grained, saturated soils for "complete" containment applications of relatively moderate durations where future remedial action of the contaminant source and subsequent barrier removal are desired.

Technology Maturity

- The technology of using refrigeration for the freezing of soils has been employed in large scale engineering projects for a number of years. It bonds soils to give load-bearing strength during construction; to seal tunnels, mine shafts, and other subsurface structures against flooding from groundwater; and to stabilize soils during excavation. Examples of modern applications include several large subway, highway, and water supply tunnels.
- Frozen soil barriers have not been demonstrated at an actual contaminated site.

SECTION 5

COST

The total capital cost for the SEG Demonstration was $481,427. It can be assumed that if demonstration costs such as those for the extra sensors and test support were deducted and if costs were reduced by purchasing (vs renting) equipment and by decreasing barrier thickness (which would mean less drilling, energy consumption, etc.), the real cost would be about $332,754. Engineering, health and safety, and permitting costs are not reflected in that figure. The maintenance cost for this frozen barrier was estimated to be $3322/month.

The contact area of the envelope created by the frozen barrier was 2223 ft2. The volume of frozen soil composing the frozen barrier was 35,694 ft3, and the volume of soil contained by the frozen barrier was 8175 ft3.

The cost shown below are for volume of ice formed. The results of the cost analysis are:

	Cost Attributes	First-Year Total	15-Year Average Maintenance Cost	15-Year Maintenance Cost Per Month
SEG Demon ($481,427)	Frozen Barrier Volume	14/ft^3	1.2/ft^3	0.09/ft^3
Actual Site ($332,754)	Frozen Barrier Volume	10/ft^3	1.12/ft^3	0.09/ft^3

	5.5 Months	Year 1 Total	Years 2-5	Years 6-10	Years 11-15
SEG Demon	13/ft^3	14/ft^3	4/ft^3	6/ft^3	6/ft^3
Actual Site	9/ft^3	10/ft^3	4/ft^3	6/ft^3	6/ft^3

In contrast with these calculations, if one of literally several hundred types of grout were used in place of a frozen barrier, costs could range from $1/ft3 to $37/ft3. These types of grout use a multiplicity of ingredients/recipes including Portland cement, bentonite, waxes, chemical components, and proprietary "magic dust." However, grout does not have the advantages of moderate-duration "complete" containment and removal capabilities as frozen soil barriers do.

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- No permit was required for this demonstration because the demonstration was performed on a nonhazardous site and a benign barrier material (water) was used. Regulatory participation was encouraged. If moisture additions were required (e.g., for arid site applications) in soils of high hydraulic conductivity (sandy soils), concerns about contaminant migration downward would have to be addressed. In addition, refrigerants of low toxicity (in cases of refrigerant pipe leakage) must be used and complete in situ barrier integrity must be confirmed by subsurface barrier verification techniques before regulatory acceptance can be gained.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Health and safety issues for installation (drilling, etc.) and operation are essentially equivalent to those for conventional environmental monitoring applications (monitoring well drilling, etc.).

Community Safety

- Frozen soil barrier systems do not produce contaminant releases because benign materials (water, nontoxic refrigerants, etc.) are used.
- No unusual or significant safety concerns are raised by the transport of equipment, samples, waste, or other materials associated with frozen soil barrier systems.

Environmental Impacts

- Drilling for refrigerant piping installation is required.
- Surface piping manifolds are required to supply refrigerant to the system.
- Compressor (refrigerant plant) noise is minimal.

SECTION 7

LESSONS LEARNED

Design Issues

- In situ temperature sensors installed within the refrigerant piping provided valuable information on barrier formation and refrigeration equipment operation.
- Typical refrigeration equipment (piping, refrigeration plants, etc.) can be used to form in situ frozen soil barriers. Single-row piping may be adequate to form barriers of sufficient thicknesses to contain contaminants. In addition, a single refrigeration plant (40 ton) can be employed to maintain barrier integrity (soil freezing conditions) after initial heat removal is acquired.
- Computer modeling for soil heat transfer characteristics can be used to predict barrier formation.
- Methods need to be designed for "injecting" moisture and lower-freezing-point refrigerants into barrier areas where leaks are detected (or where refrigerants have leaked because of pipe breakage).
- Soil movement can be predicted using experiences of past civil engineering practices and should be a consideration when designing a system for applications involving structures.
- Careful installation of the refrigerant piping is necessary to ensure "complete" barrier formation.
- For applications in humid and high ambient temperature regions, proper ground insulation and near-surface refrigerant piping may be required to ensure that surface to 1–2-ft depths are adequately frozen (if desired).
- In situ sensors (electrical conductivity, etc.) should be preinstalled in the soil to monitor barrier formation.
- Geophysical measurements of the barrier area should be performed before freezing to establish soil characteristics and heterogeneities.

Technology Limitations/Needs for Future Development

- Remote sites will require electrical power and utility installation.
- Technology applications for arid/sandy environments are undetermined until suitable methods are developed for homogeneously adding and retaining moisture in the soils.
- Technology applications in fine-grained soils around structures (submerged tanks, etc.) may be limited because of soil movement.
- Longer-duration applications at actual contaminated sites need to be studied to assess diffusion characteristics, costs, etc.
- In situ subsurface barrier verification technologies (enhanced ground penetrating radar, seismic, acoustics, electropotential, tracers, etc.) need to be developed that are capable of detecting barrier traverses as well as barrier infrastructure properties (voids, etc.).
- Additional laboratory diffusion studies may be required for various contaminants of differing concentrations. Contaminant solutions' effects on barrier degradation should be studied.

APPENDIX A

DEMONSTRATION SITE CHARACTERISTICS

Site History/Background

The site used for the demonstration project is located at the SEG Gallaher Road Facility in Oak Ridge, Tennessee.

The demonstration site is approximately 200 ft west of the access road entrance to the plateau area above Gallaher Road. The plateau area is a large, flat, unpaved area approximately the size of a football field. The plateau was constructed by "cutting and filling" with soil removed from a hillside (about 30 ft high) located along the southeastern side of the site about 25 years ago. The plateau was graded to its current contour and has not been used for any other known purpose.

Description of Soil Testing and Results

Soil testing was performed at the site on September 8 and September 9, 1993. The test report includes soil moisture contents, sieve analyses (hydrometer), and unit weight determination. A total of six test borings were drilled with augers to depths ranging from 25 to 46.3 ft.
Moisture content samples were taken in 5-ft intervals during penetration testing. The moist unit weight of the sample was obtained with a Shelby tube. The unit weight of the undrained soil at boring B-5 was 108.8 lb/ft3.
Subsurface soils encountered at the site at the time of our exploration generally consisted of 13 to 22 ft of fill soils that overlie residual soils. The fill soils were composed of stiff to hard red-brown silty clay, with varying amounts of chert fragments. The residual soils were composed of stiff to soft red-brown to brown silty clay and clayey silt, with varying amounts of chert fragments.
The soils were very fine as determined by hydrometer testing. The consistency of residual soil generally graded from stiff to soft with depth. The residual soils at the site are typical of the soils encountered overlying the dolomite of the Knox Group of the lower Ordovician System in the Oak Ridge area.

Moisture contents obtained from the soil samples show the following:

Boring Number	Number of Samples	High (%)	Low (%)	Average (%)
1	3	37.2	32.3	33.9
2	9	43.0	12.1	26.5
4	6	37.8	20.8	27.9
5	8	40.0	16.8	31.2

Fill currently at the site is not the result of placement of the soil from a remote location. As already discussed, the plateau was constructed about 25 years ago by a previous owner and was formed in a cut and fill fashion with soils from the adjacent hillside. All of the material observed during the soil analysis was homogenous and indigenous to the immediate area for each borehole. It is not known whether the fill was compacted when placed, but the soil is very stiff as shown by the penetration testing. The plateau is unpaved and flat (no slope), does not require grading, and supports a ground cover consisting of a few weeds (no grass or trees).

APPENDIX B

REFERENCES

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5. Law Engineering, Ground Freezing Project Facility, Gallaher Ferry Road Site, Law Report 382 93242 01, September 1993.

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ResonantSonic Drilling

Case Study Abstract

ResonantSonic Drilling

Site Name:
U.S. Department of Energy (DOE),
1. Hanford Site
2. Sandia National Laboratory

Contaminants:
Not used at contaminated sites

Period of Operation:
1992-1994 (see results)

Location:
1. Richland, Washington
2. Albuquerque, New Mexico

Cleanup Type:
Field demonstration

Technical Information/Vendor:
Information not provided

Technology:
ResonantSonic Drilling
- Used to access the subsurface for installation of monitoring and/or remediation wells and for collection of subsurface materials
- Uses a combination of mechanically generated vibrations and limited rotary power to penetrate soil
- Drill head consists of two counter rotating, out-of-balance rollers that cause the drill pipe to vibrate
- Transmits 50,000 to 280,000 lbs of force to the drill pipe; drills hole diameters up to 16 inches
- Newer designs also include drill head rotation capability

Cleanup Authority:
Not used at contaminated sites

SIC Code:
9711 (National Security)
Others - information not provided

Points of Contact:
Information not provided

Waste Source:
Not used at contaminated sites

Type/Quantity of Media Treated:
Soil and Sediment
- At Hanford, most drilling occurred in two facies: a coarse-grained sand and granule-to-boulder gravel; and a fine-to-coarse-grained sand and silt
- At Sandia, sediments are extremely heterogeneous, complexly-interlayered units consisting of sands, gravels, and cobbly units, with discontinuous low-permeability layers present

Purpose/Significance of Application:
ResonantSonic drilling, an alternative to traditional drilling technologies, was shown in some applications to be less costly and produce less drilling wastes than cable tool or mud rotary technologies.

Regulatory Requirements/Cleanup Goals:
- Not used at contaminated sites
- Does not require addition of fluids to a well, which in some states is restricted

Results:
- Initial Hanford demonstration averaged 23.9 ft drilled per day (8.9 ft/day, including downtime)
- Well depths ranged from 30 to 227 ft
- Provided intact lithologic samples
- Second Hanford demonstration included boreholes drilled at 45° angles, with wells up to 172 ft long
- Sandia demonstration included 3 different drill rigs, with 5-10% less down time than at Hanford

ResonantSonic Drilling (Continued)

Cost Factors:
- Capital and operating costs for the demonstrations are not provided in the report
- A comparison of cost ($/ft) for ResonantSonic, cable-tool, and mud-rotary drilling is provided based on a hypothetical scenario, for regular and difficult drilling
- ResonantSonic drilling ranged from $208-270/ft, cable-tool from $600-758/ft, and mud-rotary from $221-951/ft, depending on type of site and type of drilling

Description:
ResonantSonic drilling has been demonstrated at the U.S. DOE Hanford and Sandia sites as an alternative to cable tool and rotary-mud drilling. This technology is used for installation of monitoring and/or remediation wells, and for collection of subsurface materials for environmental restoration applications. Advantages of ResonantSonic drilling include: lower cost per foot for drilling, can provide relatively undisturbed continuous core samples; uses no drilling fluids and minimizes waste generation; and can be used to drill slant (angle) holes.

ResonantSonic drilling uses a combination of mechanically generated vibrations and limited rotary power to penetrate soil. The drill head consists of two counter-rotating, out-of-balance rollers that cause the drill pipe to vibrate, and transmit force to the drill pipe. From 1991 to 1994, this technology was used on uncontaminated soil in two demonstrations at Hanford and three at Sandia, with an additional demonstration planned at Hanford. These demonstrations included drilling hole diameters up to 16 inches.

Results from these demonstrations were used to improve system design and operation. For example, the initial Hanford demonstration had high percentages of downtime, while later demonstrations at Sandia resulted in much less downtime. These demonstrations included wells drilled up to 227 ft deep, and several wells drilled at 15-45° angles. Further, this technology shows significant waste minimization compared to mud rotary. However, heating core materials remains an issue where no fluid is used to cool the formation and under difficult drilling conditions. ResonantSonic generated core temperatures from 70°F to 140°F under difficult drilling conditions at Hanford. In addition, few drilling companies currently provide ResonantSonic drilling services. This should be considered in selecting this drilling alternative.

SECTION 1

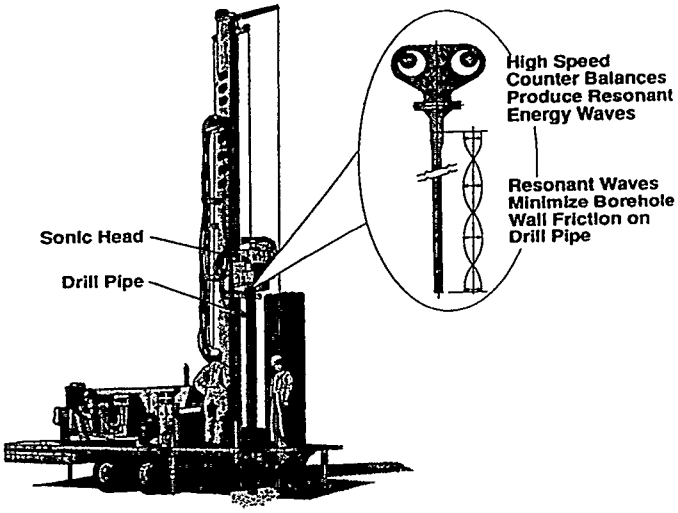
SUMMARY

Technology Description

ResonantSonic(SM) drilling has been demonstrated and deployed as an innovative tool to access the subsurface for installation of monitoring and/or remediation wells and for collection of subsurface materials for environmental restoration applications. The technology has been developed by industry with assistance from the U.S. Department of Energy (DOE) Office of Technology Development to ensure it meets the needs of the environmental restoration market.

The ResonantSonic drilling technology:

- can provide excellent quality, relatively undisturbed, continuous core samples that can be used for contaminated site characterization and for subsurface engineering design;
- uses no drilling fluids and minimizes generation of waste associated with the drilling operations (no cuttings);
- provides an alternative drilling method that at some locations is more cost effective than the baseline technology (e.g., at Hanford it can augment or replace cable tool drilling);
- can be used to drill slant holes;
- can be safer because worker exposure is minimized, because drilling is faster and waste generated is minimized; and
- can be used for retrieving core materials from the subsurface (i.e., sample collection), for installation of monitoring wells, and for providing subsurface access for collection of ground water samples.



- The ResonantSonic drilling system consists of two components: the drill head and the resonator (i.e., the drill pipe or rod).
- Three different mechanisms allow the bit to penetrate the formation: displacement, shearing, and fracturing. At any particular site, the mechanism is dependent upon the soil medium being drilled.
- ResonantSonic drilling has been used at many geologically different sites ranging from unconsolidated gravel-rich material to sandstone/shale sequences to clay-rich glacial till sites.
- Continuous cores have been obtained at depths as great as 550 feet.
- Drilling rates range up to 260 feet per day.
- Costs range from $70 to $300 per foot depending upon the drilling system used, the drilling approach, the site geology, etc.

(SM) "Registered Service Mark of Water Development Corporation"

Technology Status

- The original patent was developed by Albert Bodine in the early 1960s; the technology was used for pile driving and mineral exploration, especially in Canada. Several U.S. companies have purchased the Canadian equipment and licensed any existing patents to pursue a new market for this drilling technology.
- Water Development Corporation of California teamed with the Department of Energy via a Cooperative Research and Development Agreement (CRADA) to advance the application of this technology to the environmental business. The joint industry-government partnership mission was to develop and demonstrate improvements to the ResonantSonic technology so that it could be applied cost effectively to environmental restoration sites with special focus on difficult drilling sites such as the DOE Hanford Site.
- Field demonstrations of the ResonantSonic drilling technology were conducted at the DOE Hanford Site and at Sandia National Laboratory from 1991 through 1994. Refinements to the drilling system concentrated on improving the reliability of the equipment, developing new bit designs, pursuing automated tool handling and decontamination systems, and demonstrating angle drilling capabilities.
- Additional demonstrations have been conducted at the DOE Pantex Site in Amarillo, Texas and at a number of DOD military bases. Further, the technology has been implemented at the DOE Rocky Flats Site, at the Idaho National Engineering Laboratory, and at a number of private locations in California.
- Key results of the public-private partnership technology development program include the following:
  - In the initial demonstration at Hanford, penetration rates were twice that of the baseline technology; later results showed improvements as high as three to four times that of the baseline.
  - Equipment refinements included a new sonic head design, new drill pipe designs, an automated pipe handling system, and an extended-length split-tube sampler.
  - A method to maintain core temperatures, below 90 degrees Fahrenheit, to assure quality core recovery for VOC analysis was developed and tested.
  - A new rig that has multiple drilling technology capabilities (sonic, air rotary casing hammer, cable tool, percussion, and rotary) was designed and manufactured. The advantages of such a system include the ability to mix and match drilling technologies to the required objectives at each specific drilling location.
  - Angle-drilled wells have been installed at both Sandia National Laboratory and Hanford.

- The technology is commercially available. The number of companies that can provide such services is quite limited, however.

Contacts

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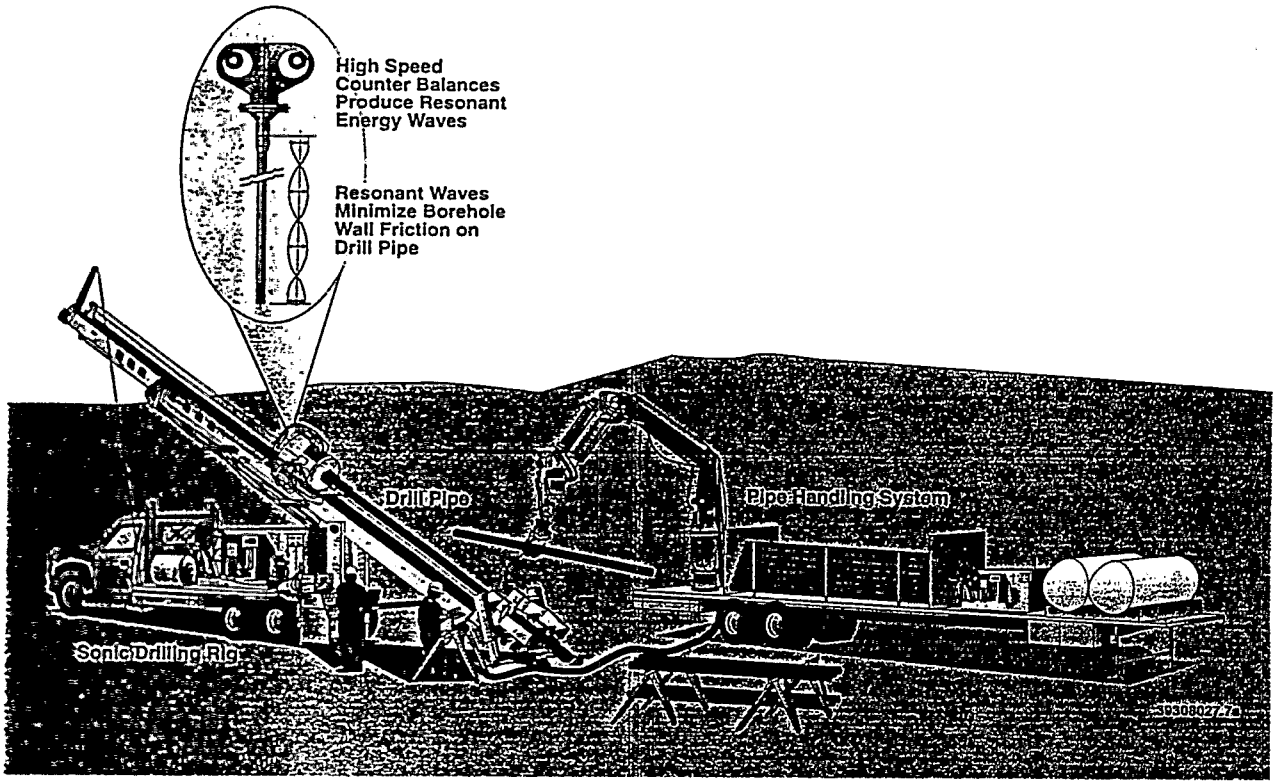
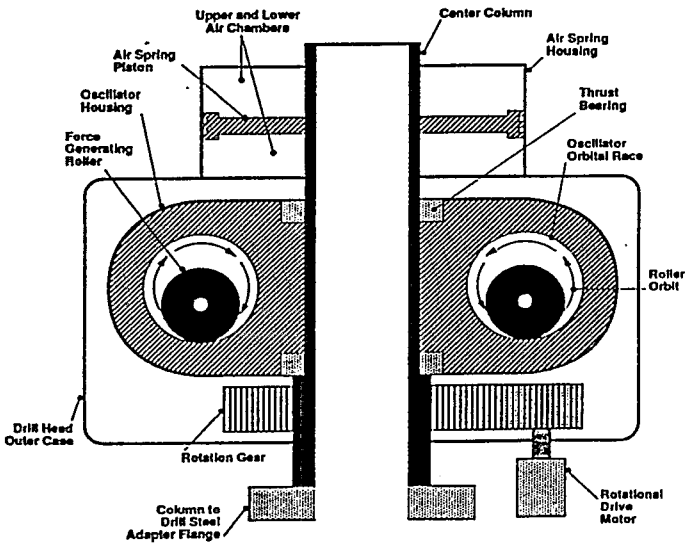
Overall Drilling Rig Schematic

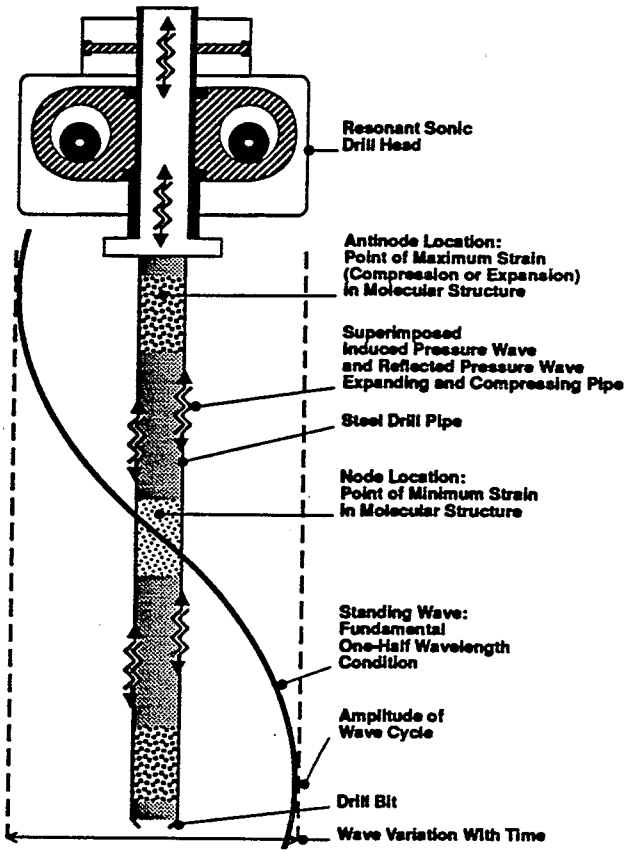
ResonantSonic℠ Drilling Method



- The ResonantSonic drilling rig uses a combination of mechanically generated vibrations and limited rotary power to penetrate the soil.
- The oscillator or drill head consists of two counter rotating, out-of-balance rollers that cause the drill pipe to vibrate. The rollers are synchronized with each other to ensure that the vertical force component is transmitted downward along the drill pipe or core barrel.



- The vibrations are isolated from the rig structure by the use of an air spring.
- Resonance occurs when the frequency of the vibrations is equal to the natural frequency of the drill pipe. In resonance, forces generated by the oscillator head can build up in the pipe from 50,000 to 280,000 pounds. The resonance and weight of the drill pipe along with the downward thrust of the drill head permit penetration of the formation.



- The newly designed ResonantSonic drill head also has rotation capability up to 8,500 foot pounds of torque to assist with penetration of the formation.
- Vibrations generated in the drill string range from 0 to greater than 150 Hertz and create up to 200,000 pounds of force. The drill pipe is advanced into the ground by weight applied hydraulically at the surface.

System Configuration and Operation

- There are two primary methods for retrieving core samples from the subsurface: the wireline method and the dual-rod method. Each method, of course, has advantages and disadvantages. The selection of a specific method must be tailored to the site-specific needs and conditions. The advantages and disadvantages of the two methods with a comparison to rotasonic drilling are discussed in Reference 5.
  - The **wireline method** uses an open-face core bit threaded to the bottom of the drill pipe. An inner core barrel rests on the shoulder of the bit and is kept in place during drilling by a downhole latch assembly or heavy weight. After drilling has proceeded far enough that the barrel is filled, the wireline retrieval system is attached to the core barrel so that it can be removed without pulling the drill pipe out of the hole.
  - The **dual-rod system** is similar to the wireline method, but the core barrel is attached to a small diameter steel inner rod, which then must be removed during core retrieval. This assures quality seating of the core barrel. Both drill rods can be resonated simultaneously or independently, depending upon formation conditions. Little if any rotation of the drill rods is used

with this system. Neither the wireline nor the dual rod method requires addition of fluids to the subsurface. They both can be used with the ResonantSonic system.

- Borehole integrity is maintained by the drill pipe that remains in the ground as the core barrel is retrieved and as the hole is advanced. Typical drill pipe diameter is 4.5 inches outer diameter (OD). Larger-size drill pipe ranging from 6 5/8 to 16 inch diameter can be used when telescoping pipe is required to seal a perched zone or confined aquifer or to make larger diameter monitoring or remediation wells.
- To install monitoring wells, the drill pipe acts as a temporary casing, inside of which the well materials can be placed for installation. It is quite easy to retrieve the temporary casing because it can be sonically vibrated to assist removal.
- Specifications of the six different drilling rigs used for the Hanford and Sandia demonstrations are shown below.

Sonic drilling rig	15-year-old rig used at Hanford	"Barber" rig used at Sandia	"Dresser" rig used at Sandia	"Angle" rig used at Sandia	"RSD300" rig used at Hanford	"RSD750" planned at Hanford
Resonant frequency	0 to 150 Hertz	0 to 15 0 Hertz	0 to 150 Hertz	0 to 15 0 Hertz	0 to 150 Hertz	0 to 15 0 Hertz
Rig Power	250 Hp	250 Hp	250 Hp	250 Hp	300 Hp	1200 Hp
Maximum force generated by the drill head	50,000 lbs.	50,000 lbs.	50,000 lbs.	50,000 lbs.	100,000 lbs.	200,000 lbs.
Maximum force transmitted due to hydraulic thrust alone	10,000 lbs.	15,000 llbs	15,000 lbs.	15,000 lbs.	30,000 lbs.	90,000 lbs.
Hole diameter that can be drilled	up to 7 in.	up to 6 5/8 in.	up to 6 5/8 in.	up to 6 5/8 in.	up to 10 3/4 in.	up to 16 in.

Operational Requirements

- ResonantSonic drilling requires one driller and one helper as a minimum for operation. Drilling at hazardous waste sites, of course, requires additional personnel. At a DOE hazardous waste site the field team could include a field team leader, a geologist, a site safety officer, a sampling scientist, a health physics technician, and two sampling technicians. The large number of personnel required significantly affects the cost of the drilling operation and maximizes the cost differential between different drilling technologies, because one technology is faster than the other.
- The ResonantSonic drill required about 2.5 hours of preventive maintenance per week during the first demonstration and less during subsequent demonstrations.
  - The Los Alamos National Laboratory (LANL) cost estimate uses a figure of $20,000 per year cost for preventive maintenance.
  - Stress on the drill pipe produced during resonance causes internal damages. Magnetic scanning of the drill pipe (magnafluxing) can be performed routinely to reveal microfractures. However, microfractures are not readily identified in all cases because the initial failure points occur within the body of the pipe.

SECTION 3

PERFORMANCE

Demonstration Overview

First demonstration with Harrison Western, Inc., 1991-1992

- The first demonstration of ResonantSonic drilling technology, which took place in 1991 at Hanford, was conducted jointly by DOE EM40 and EM50 to determine whether sonic drilling is a cost-effective alternative to the currently used cable-tool system for drilling and sampling at hazardous and radioactive waste sites at Hanford. Other requirements for the system include protection of human health and the environment and compliance with state and federal regulations.

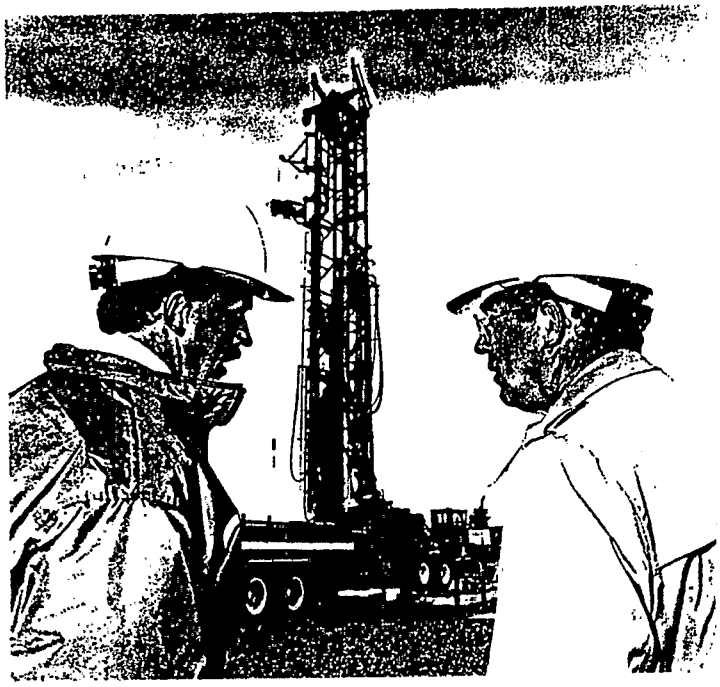
CRADA demonstrations with Water Development Corporation , 1993-1994

- Objectives of the 1993 demonstrations included the following:
  - Demonstrate the efficiency and reliability of the sonic drill head in penetrating variable geologic conditions.
  - Demonstrate angle drilling capabilities and determine areas for improvements.
  - Develop and install an instrumentation system to electronically record the resonant drilling process.
  - Correlate recorded drilling measurements with geology.
  - Test and evaluate sampling equipment and sample handling methods for both vertical and angle drilling.
  - Demonstrate that ResonantSonic drilling can meet safety standards and compliance with state regulations for well completions.
  - Demonstrate the ability to maintain contamination control and minimize generated waste.
  - Demonstrate ability to obtain high quality samples (including maintenance of an acceptable bit face temperature) and drill to required depths at required diameters.
  - Evaluate cost effectiveness of ResonantSonic versus cable tool drilling.
  - Determine the radial distance from the borehole of vibrations generated during drilling.
  - Demonstrate, evaluate, and select a preferred sonic drill rod.

Drilling Performance

First Hanford Demonstration, 1991-1992

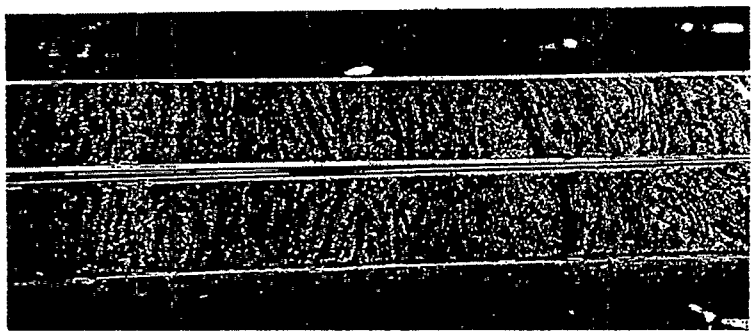
- The first demonstration at Hanford utilized a fifteen-year-old rig (Hawker-Siddely drill owned by Harrison Western Drilling, Inc.). This demonstration was plagued with high percentages of downtime due mostly to head and drill string failures related to the age of the equipment. This first demonstration laid the groundwork for future development work by demonstrating the technology's potential while demonstrating the need for more development.
- The ResonantSonic drill averaged 23.9 feet per day as compared with the average rate of 12.6 feet per day for cable tool (downtime excluded for both technologies). Including downtime, sonic averaged 8.9 feet per day and cable tool averaged 8.1 feet per day on a comparison of ten sonic drilled boreholes and 11 cable tool drilled boreholes. Average cable tool drilling rates at Hanford in 1991 ranged from 6.4 to 9.5 feet per day.
- Eight ground water monitoring wells, one ground water monitoring/extraction well, and two vadose zone characterization boreholes were completed during the demonstration. The borings ranged in depth from 30 to 227 feet and were located in several areas at the Hanford Site (100-D, 300, 3000, 200 East, and 200 West).
- The ResonantSonic drilling system provided intact lithologic samples that are not usually retrieved with the cable tool system. Sample quality for the sonic boreholes was at least equal to that of cable tool in sand and silt formations and was greater in hard formations unless large cobbles were encountered.
- The ResonantSonic drilling system protected human health and the environment by minimizing waste generation and easily containing cuttings.
- The ResonantSonic drilling method offers several advantages for well completion: temporary casing can be rotated and placed in resonance to prevent bridging of the completion material (this results in faster installation of the annular seal); rig hydraulics can be used to unscrew and handle the temporary casing; the same crew can be used for well installation (no additional crew mobilization is required).



Dr. Bill Schutte of the DOE Office of Technology Development watches the Hanford ResonantSonic drilling demonstration with Mr. Greg McLellan, principal investigator, Westinghouse Hanford Company.

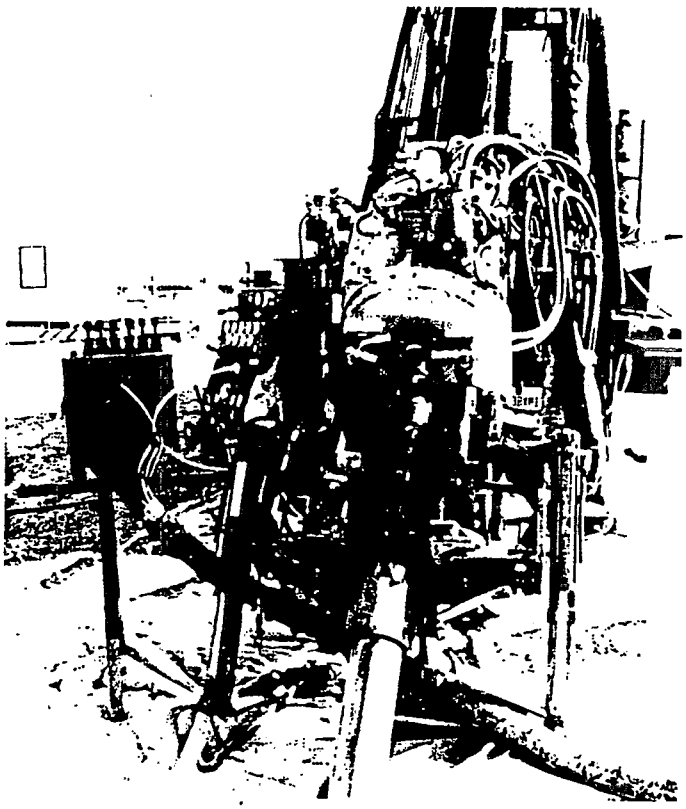
Hanford CRADA Demonstrations, 1993-1994

- During the first phase of this demonstration program, five boreholes were drilled, four of which were at 45 degree angles. The two deepest wells reached total lengths of 164 and 172 feet. Drilling rates averaged six feet per hour.
- Sampling equipment and methods investigated included core tray, split tube samplers, and core barrel liners.
- Concerns about sampling of core for analysis of VOCs due to heating of the core were examined and a new methodology was developed to minimize temperature elevation in the core. During the first demonstration at Sandia and Hanford, core samples were heated to temperatures unacceptable for chemical sampling.
  - An extended-length split-tube sampler was designed to be driven ahead of the drill string and filled to only 75% of its length to obtain samples for chemical analysis.
  - Other improvements include reductions in drilling frequencies and rotation rate as a result of real-time temperature monitoring, lining of the samplers with low thermal conductivity materials (Lexan), and pre-chilling the samplers with dry ice in special coolers.



An example of unsonsolidated core removed using the ResonantSonic system.

- The second phase included installation of a 45-degree-angle vapor-extraction borehole to a measured depth of 168 feet (118 feet vertical depth) with 3-inch stainless steel casing at a hazardous waste site under a parking lot in the 200 West Area.
  - New developments in the drilling system included the use of Lexan liners to collect superior quality core, core temperatures held to under 90 degrees Fahrenheit, and the use of a robotic arm to handle the drill pipe.
  - Downtime was less than five percent.



- Later phases of the CRADA demonstrations included drilling with larger-diameter drill pipe (up to 20 inches) and installation of deep wells (310 feet) with 4-inch stainless steel pipe.
- Drill pipe analysis showed that eddy currents could detect abnormal electric or magnetic features in the threaded fastener region, where pipe failure occurs most often. Failure analysis of the pipe itself demonstrated a difference between pipe that was threaded directly and in pipe that utilized threaded tool pieces.

DOE Sandia National Laboratory Demonstrations

- In 1993 three different ResonantSonic rigs were demonstrated at Sandia. All three were rigs newer than that used at the 1991-1992 Hanford demonstration.
  - Technological advances in both the drill head and drill string resulted in much less downtime (averaged 5-10%) during the Sandia demonstrations.
- Two 4-inch PVC slant wells (15 degrees from horizontal) were installed beneath the Chemical Waste Landfill to a depth of 150 feet.
  - During the drilling operations, dynamic drilling measurements were made to obtain information on pipe integrity. A new instrumented subassembly was designed and manufactured to be used for this demonstration. This was the first step toward development of diagnostic capabilities to enhance drilling performance through optimized control and improved hardware design.
- The boreholes did not deviate off linearity by more than one-half degree over the full length of the wells.

DOE Pantex Demonstration 1994

- Four continuous core boreholes were completed to average depths of 290 feet, where a continuous perched water interval overlying the Ogalalla Aquifer exists.
- Depth-discrete ground water sampling using the HydroPunch and geophysical logging were combined with the ResonantSonic drilling method to maximize the amount of information obtained from each of the boreholes.
- The amount of waste generated was 2% of that normally obtained using the baseline Pantex technology.

Marketplace Opportunities

- The optimum application of ResonantSonic drilling technology will be at sites where:
  1) high-quality core materials are required; the ResonantSonic drilling system provides intact core samples that demonstrate detailed lithological parameters such as thin layers (such as clays and chemical precipitates) and fragile structures (depositional and fossiliferous features) that are normally not observed in samples collected by other drilling methods;
  2) where there is a requirement to minimize the amount of hazardous waste generated; Land Disposal Restrictions (LDR) now require containment, storage, and ultimate treatment of investigative-derived wastes such as drill cuttings and drilling fluids;
  3) when regulators prefer the use of a drilling technology that does not add fluids to the subsurface; at many sites there may be concerns about the migration of contaminants being exacerbated by the addition of drilling fluids; and
  4) lithology is not conducive to conventional technology (e.g., karst).

Alternative Technologies

Rotasonic

- This technology, most closely related to the resonant sonic method, is a modification of the original Albert Bodine patent and is presently commercially available from a few companies in the United States.
- Rotasonic drilling uses a core barrel attached to a drill rod as an inner casing. The core barrel is advanced sonically until it has been filled. The core barrel is then overwashed with a fluidized outer rotational casing, which provides hole stability while the inner drill string is pulled to retrieve the core. Disadvantages of this method include the requirement for addition of water to the subsurface for advancing casing and the time required to drill two holes, the cored section and the washover. One advantage is more rapid drilling penetration rates due to the fluidized condition of the borehole.
- The major disadvantage to this system, only at certain sites, is the requirement for the addition of water to the subsurface.
- Advantages that may offset this disadvantage include greatly increased penetration rates, much less stress on the tools and the overall system, and reduction of heat generated.
- Drilling rates with the rotasonic technology can be as high as 160 feet per day but of course are highly dependent upon the type of lithology being drilled.
- Depth is currently limited to 300 to 400 feet and the size of casings to be advanced is limited to eight inches.
- Rotasonic technology has been demonstrated for environmental applications at the DOE Savannah River Site and Oak Ridge National Laboratory and will soon be implemented at the Fernald Site in Ohio. It has been utilized extensively at a number of other sites including Wright-Patterson Air Force Base.

Competitive Technologies

- Competitive drilling technologies, including the baseline typically used within certain areas of the United States, consist of the following: cable tool, hollow-stem auger, mud rotary, air rotary, dual-wall percussion hammer, dual-tube reverse circulation, and air rotary casing hammer.
- Some of these technologies require the addition of fluids to the subsurface, and many generate significant quantities of hazardous waste when used at environmental restoration sites.
- A more complete discussion of drilling technologies can be found in reference 5. Costs for each of the technologies are very site dependent.

SECTION 5

COST

Introduction

Information in this section was prepared from data provided by the VOCs in Arid Soils Integrated Demonstration at the DOE Hanford Site and the Mixed Waste Landfill Integrated Demonstration at the DOE Sandia National Laboratory to the Los Alamos National Laboratory (LANL), tasked to perform technology cost analyses as an independent team for the DOE Office of Environmental Management Office of Technology Development (EM-50).

- The LANL cost analysis was not meant to involve comprehensive cost estimation for borehole drilling and/or well completion. Thus, the final cost-per-foot numbers would not be expected to match actual contract rates.
- The data provided to Los Alamos for the Hanford demonstrations relied solely on work performed in 1991-1992. This cost information was based on using 15-year-old drilling equipment and did not incorporate any of the advancements developed as a result of the technology development CRADA program in place over the last few years. Cost information from the later demonstrations will be available in the near future. Preliminary information suggests that costs have been significantly reduced, by as much as a factor of three.
- The testing at Sandia involved drilling of smaller diameter holes. Costs at Hanford are higher for this and a number of other reasons. Costs cannot be correlated from site to site.

Cost Comparisons

Two conventional technologies will be used as baselines for comparison to ResonantSonic Drilling. At Hanford, cable-tool drilling is considered to be the baseline for this cost analysis. At Sandia mud rotary drilling was considered the baseline for the cost analysis. A side-by-side comparison of three technologies was performed based on the following assumptions:

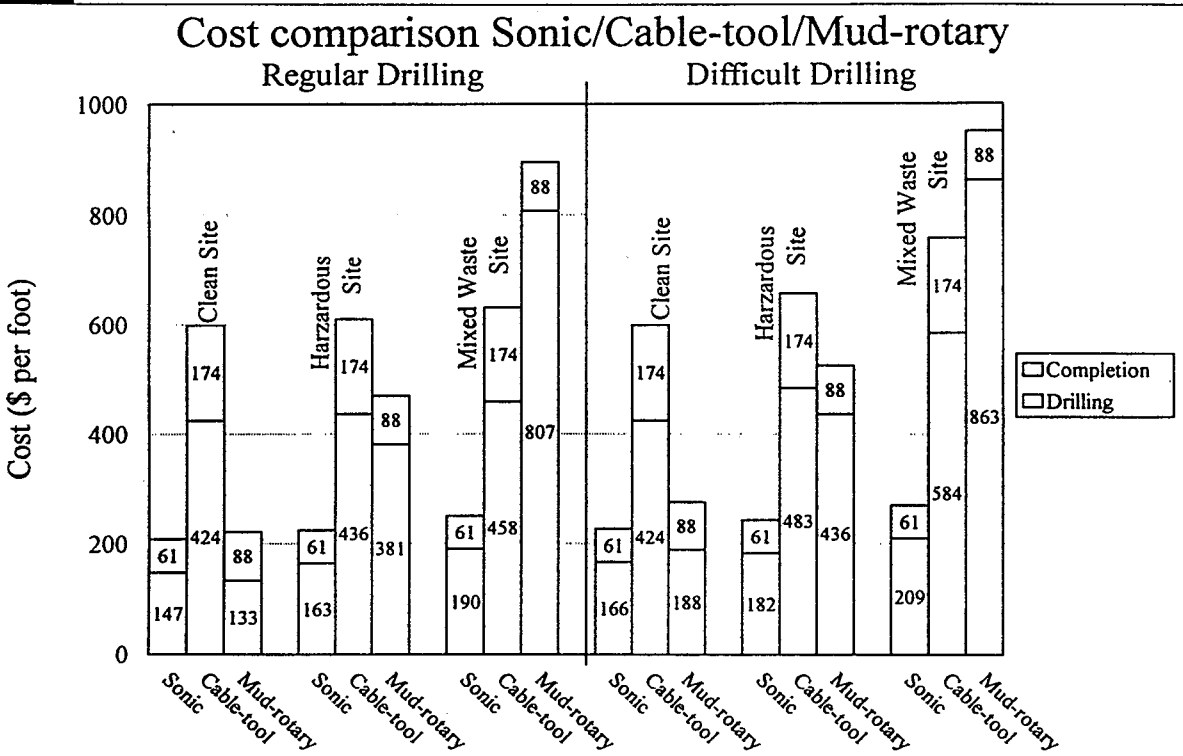
- The scenario assumed a hypothetical 150-foot well to be drilled in three environments: 1) a clean environmental site, containing no hazardous or radioactive material, 2) a hazardous environmental site (EPA listed), and 3) a mixed-waste site, containing both hazardous and radioactive waste.
- Two separate soil conditions were considered: 1) regular drilling, which refers to the somewhat easier drilling of unconsolidated formations, and 2) difficult drilling, which refers to cobble/boulder/consolidated and clay layers where greater resistance to drill advance is encountered.
- Capital costs were included as rig rental to produce an overall drilling rate on a cost-per-foot basis. The table below presents a dollars/foot comparison of the three methods of drilling.

Capital and Operating Costs

Capital costs for the three systems are all within the same order of magnitude. The cost of a ResonantSonic drill rig is only an estimate but the capital cost is a small contributor, approximately 5% of the cost per foot for monitoring wells.

Capital Costs	ResonantSonic Drilling	Cable-Tool Drilling	Mud-Rotary Drilling
Drill Rig Equipment Cost	$ 400,000	$ 200,000	$ 450,000

The operational and maintenance costs for the three systems are comparable on a per-hour basis. The variance begins to be evident at a price-per-foot cost because of the speed at which ResonantSonic and mud-rotary drilling can proceed. ResonantSonic drilling is slower than mud-rotary but does not generate significant quantities of waste to be disposed of when working in a contaminated environment.



Cost Results

- The demonstrations at Sandia show that the technology may begin to compete with mud-rotary drilling at clean sites.
- At contaminated sites, ResonantSonic drilling is clearly more cost effective.
- 1994 drilling at Hanford showed lower costs.
  - 3 holes were drilled to an average depth of 309 feet, 11-inch diameter.
  - 2 of these holes were completed as 4-inch wells and 1 was completed as a 3-inch piezometer.
  - Drilling costs were $194 per foot; costs including a field sampling team were $253 per foot.
- Recent drilling at Hanford to install shallow 3-inch piezometers has been accomplished for as little as $30 per foot.
- Additional cost information using the new drilling equipment is needed to validate the cost effectiveness of the ResonantSonic technology. Prudence should be exercised in using the 1991-1992 cost data.

SECTION 6

REGULATORY/POLICY ISSUES

Regulatory Considerations

- The ResonantSonic drilling technology requires all of the normal permits associated with other drilling technologies. No special permits should be required.
- The Hanford demonstration did not require NEPA review because the testing was part of the site characterization activities for the Expedited Response Action (ERA), meeting the requirements for a categorical exclusion. Drilling at many of the DOE federal sites, such as the Savannah River Site, is considered under NEPA to be a categorical exclusion.
- Wells must be constructed according to state standards but should not present any difficulties over other drilling methods.
- Normal drilling activities require that investigative-derived wastes (drilling fluids, cuttings, and equipment decontamination fluids) be handled according to RCRA.
- OSHA requirements must be reviewed because ResonantSonic drilling, like all drilling methods, produces noise levels that are considered dangerous to workers not wearing proper protection. New style heads have significantly reduced noice levels.

Regulatory Advantages

- The ResonantSonic drilling technology has a regulatory advantage over the mud rotary technique, and to a lesser extent cable-tool technique, in that it does not require any addition of fluids to the well. Some states do not allow the addition of material into the ground at contaminated sites. ResonantSonic drilling permits installation of wells under these restrictions.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Health and Safety issues for the installation and operation of ResonantSonic drilling are essentially equivalent to those for conventional drilling technologies. Worker exposure to hazardous and radioactive materials will be less because drilling fluids are not used and cuttings are not generated.
- Level D personnel protection was used during the operation of the ResonantSonic drilling system.

Community Safety

- ResonantSonic drilling does not produce routine release of contaminants.
- No unusual or significant safety concerns are associated with transport of equipment samples, waste, or other materials associated with ResonantSonic drilling.

Environmental Impacts

- ResonantSonic drilling systems require relatively little space similar to other drilling systems.
- Visual impacts are minor, but operation of the drill rig create moderate noise in the immediate vicinity.

Socioeconomic impacts and Community Perception

- ResonantSonic drilling has a minimal economic or labor force impact.
- The general public has limited familiarity with ResonantSonic drilling.

SECTION 7

LESSONS LEARNED

Implementation Considerations

- When considering the selection of ResonantSonic at a particular site, the ResonantSonic drilling technology must be compared with other drilling technologies and evaluated on the basis of specific site needs and conditions.
  - At Hanford it has been compared with the baseline cable tool technology, and at Sandia it has been compared with a baseline mud rotary system (see cost section).
- Waste minimization is a significant feature of sonic drilling.
  - At Hanford sites characterized as not difficult, ResonantSonic drilling generated about the same amount of waste as the cable tool system, whereas under difficult drilling conditions sonic generated approximately one-fourth the amount of waste.
  - Comparison of ResonantSonic drilling to mud rotary shows significant minimization of waste using the sonic method.
- Heating of core materials to be sampled for volatile chemical contaminants remains an issue for drilling technologies where no fluid is used to cool the formation, especially under difficult drilling conditions.
  - Both ResonantSonic and cable tool have been shown to generate core temperatures from 70 to 140 degrees Fahrenheit under difficult drilling conditions at Hanford.
  - Hollow-stem augering has been demonstrated to increase core temperatures to 107 degrees Fahrenheit, but temperatures average 76 degrees.
  - New techniques to minimize temperature elevations in core materials have been developed, demonstrated, and should be implemented when collecting core samples for chemical analyses of volatile components (see Section 4, Hanford CRADA).

Technology Limitations/Needs for Future Development

- Richterich (1994) noted that "further study of factors such as lithology, penetration rates, amount of vibration, rotation, etc. should be studied to improve the quality of the core runs."
- Few drilling companies can provide ResonantSonic drilling services. Thus, the costs of mobilization may preclude the cost effective use of the technology, especially when only a few boreholes are required to complete a job.
- Further demonstration and implementation of the Sandia National Laboratory dynamics monitoring system should be completed so that imminent drill pipe failures can be predicted in real-time and coordinated with a system shutdown. In addition, improved understanding of the dynamics of ResonantSonic drilling will ultimately lead to further improvements in tool-joint design.
- Needs include design and manufacture of different-sized drilling rigs so that the right system can be used for the job, optimizing costs incurred.
- Work is under way to combine the ResonantSonic technology with push technology such as the cone penetrometer to assist with penetration of thin, hard layers. Development of this new system will create a new niche that will enhance the drilling toolbox.

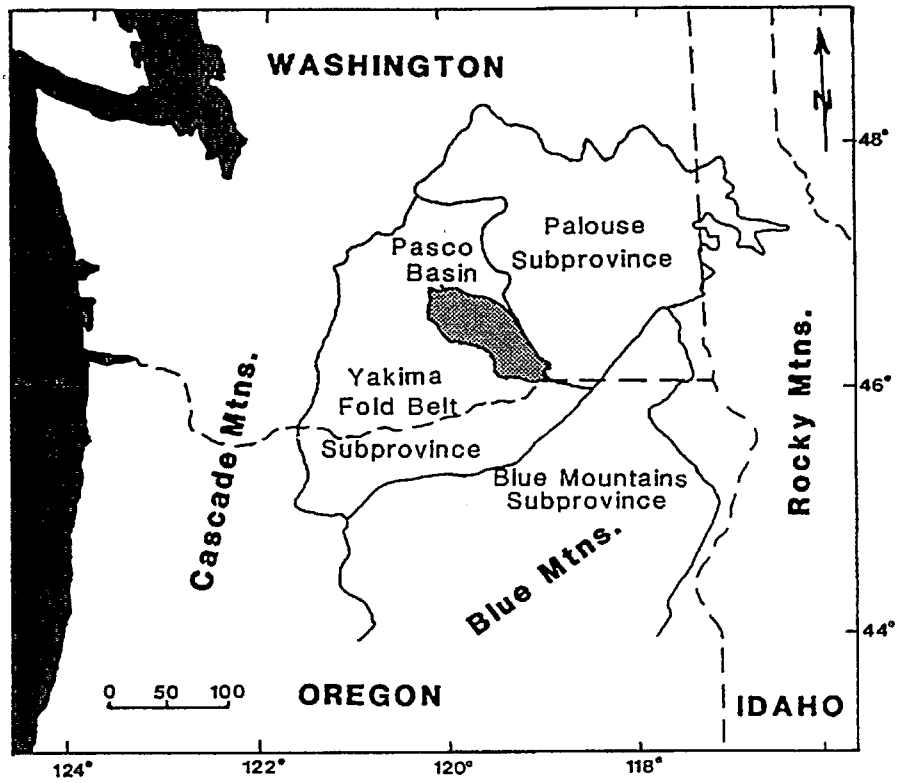
Technology Selection Considerations

- Development, manufacture, and implementation of drilling systems with capabilities of multiple technologies will likely provide the lowest cost/highest quality methodology under difficult drilling conditions.
  - Using the WDC new drilling rig, wells at Hanford were installed using the ResonantSonic Casing Drive Method in the unsaturated zone and the ResonantSonic dry core method conbined with cable-tool hole-cleanout technology below the water table.
  - Many sites will benefit from the application of push technology for small-diameter and shallower holes. However, a relatively large percentage of sites will require innovative drilling technology such as sonic.
- Specific job requirements and site conditions will dictate the application of the best drilling technology or combination of technologies at a particular site. Innovative technologies, such as ResonantSonic drilling, should be considered within the toolbox of available technologies.

DEMONSTRATION SITE CHARACTERISTICS

- Field demonstrations of the sonic drilling technology described in this report were conducted at both the DOE Hanford Site and Sandia National Laboratory.

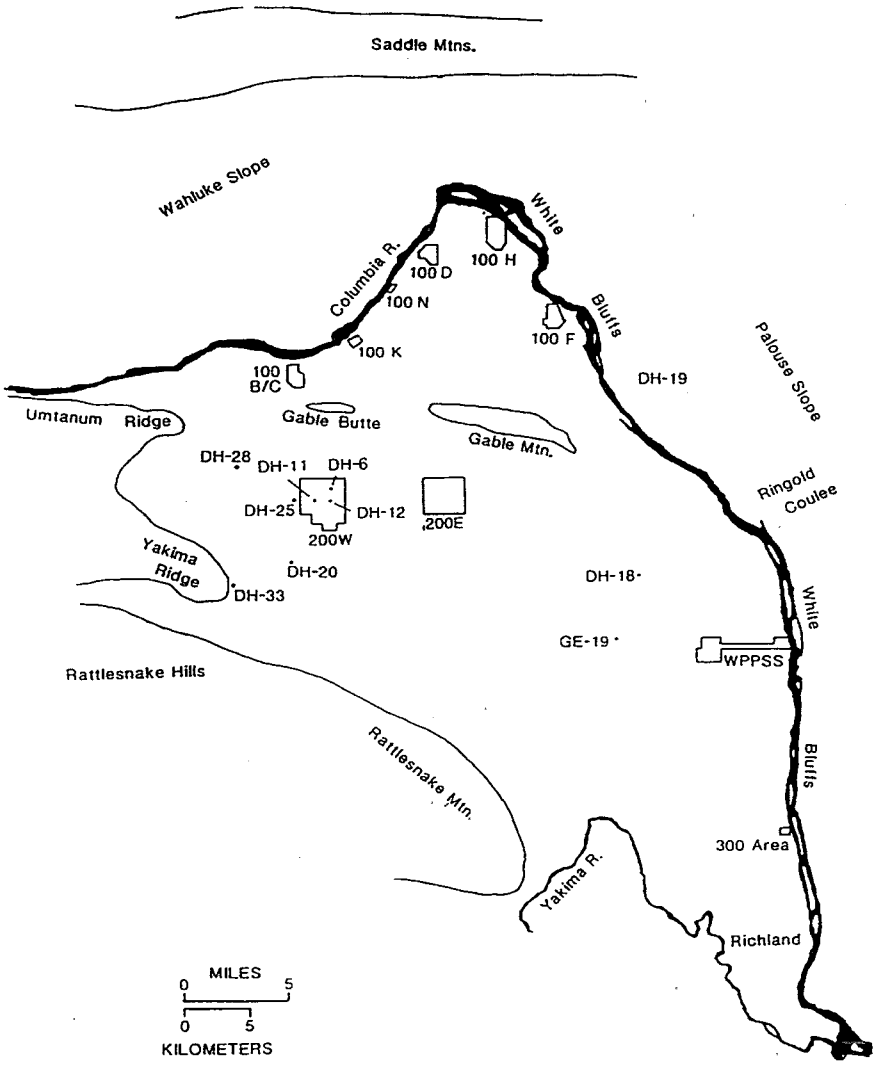
Geographic/Geologic Setting of Washington



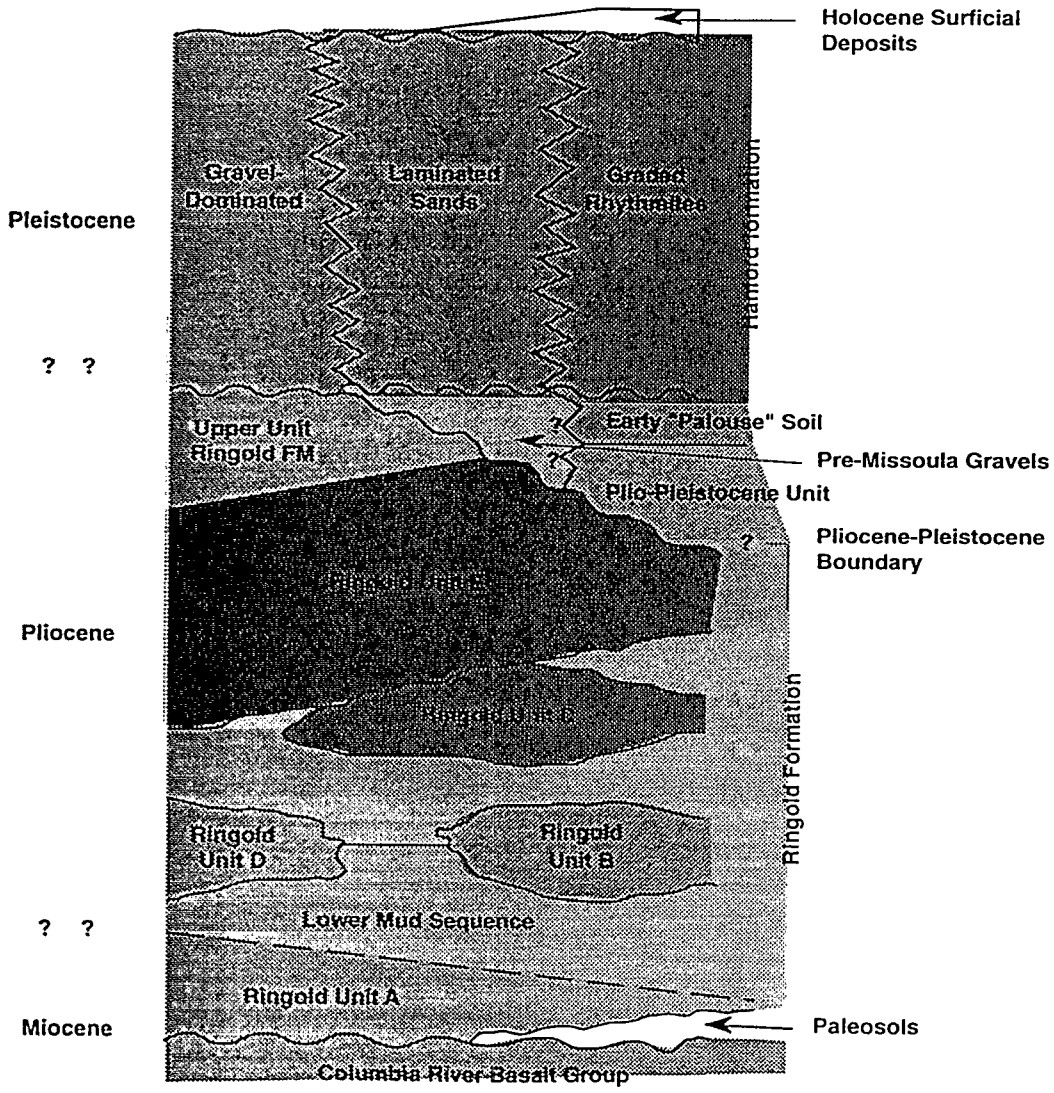
Most of the drilling for the ResonantSonic demonstrations occurred within the Hanford Formation, which contains two facies:

(1) a coarse-grained sand and granule-to-boulder gravel from which matrix is commonly lacking, and
(2) fine- to-coarse-grained sand and silt that commonly display normally graded rhythmites a few centimeters to several decimeters thick. In general, the coarse facies is composed of approximately 50 percent sand and gravel, 45 percent cobble, and five percent boulder, and ranges in thickness from 20 feet to greater than 200 feet. The underlying fine facies consists of 5 to 60 feet of silts and fine sands, which in turn are underlain by Plio-Pleistocene Palouse soils, which consist of eolian silts and clay overlying a caliche layer of cemented silt, sand, and gravel.

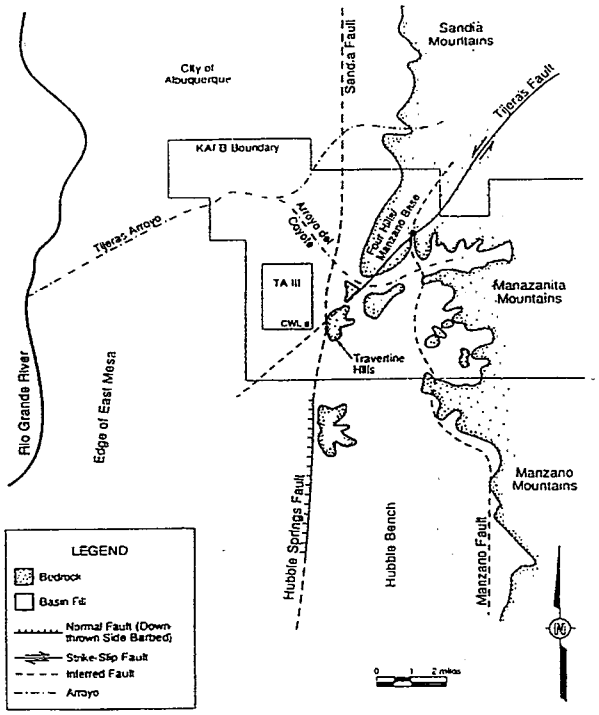
Geographic Setting of Hanford Site



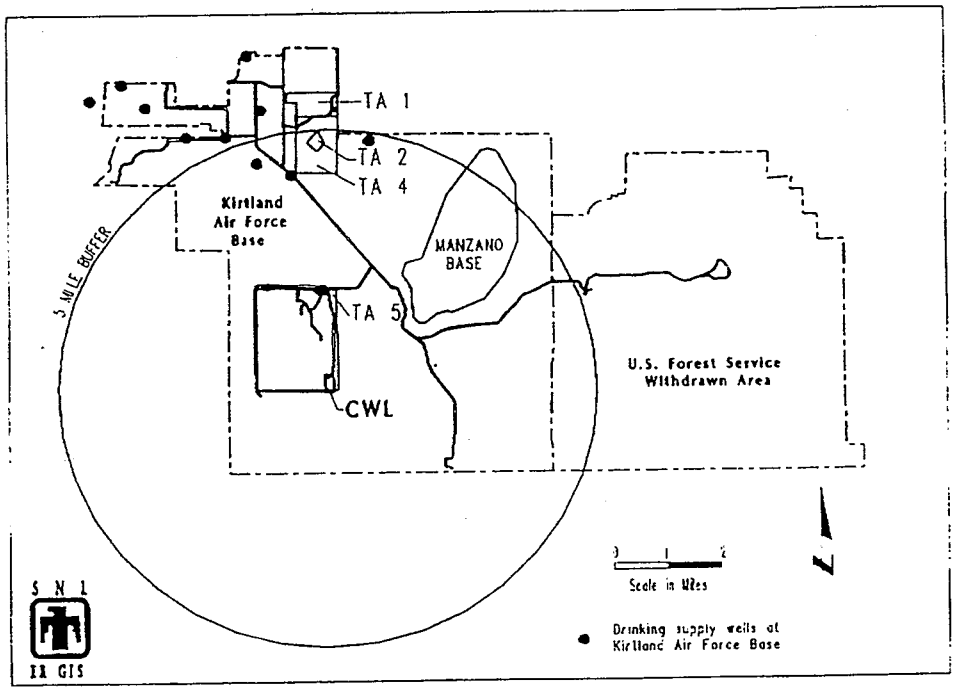
Generalized Stratigraphy of the Suprabasalt Sediments at the Hanford Site



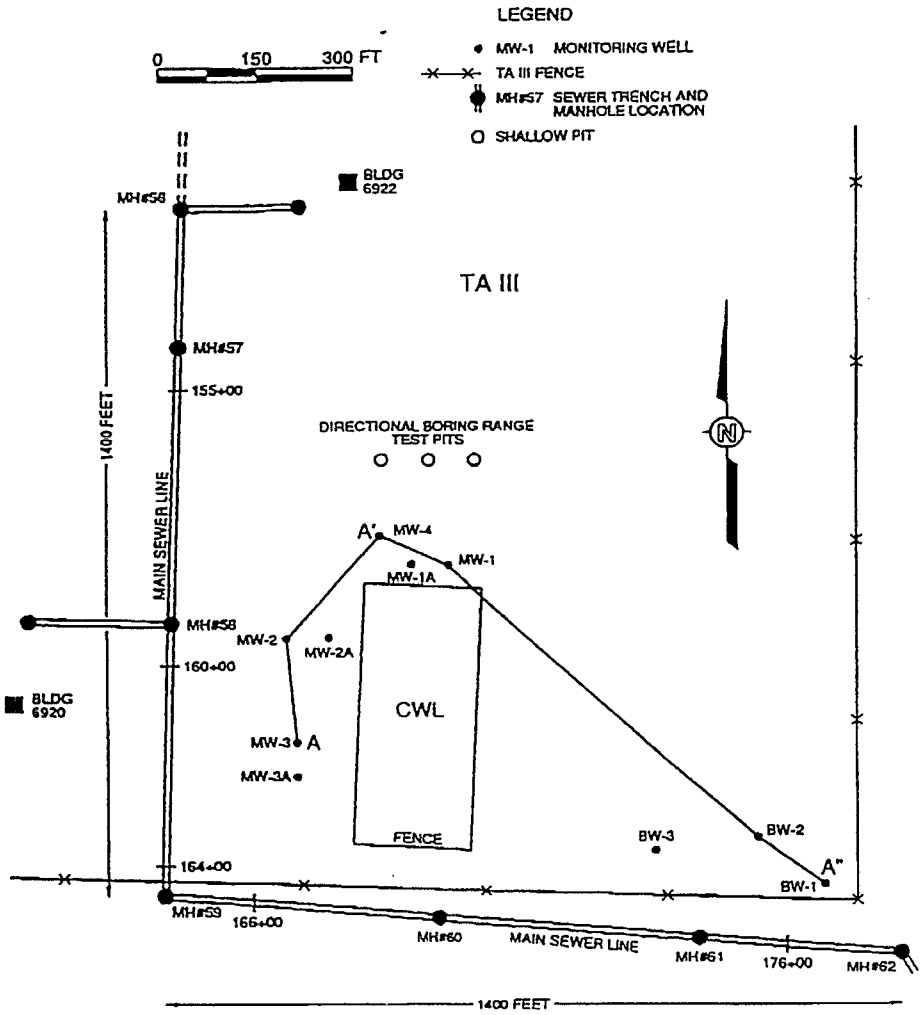
- Below the Palouse soils is about 20 feet of fluvial sands and muds underlain by relatively well compacted fluvial gravels, all of the Ringold Formation.
- Most of the demonstration work was conducted in the 200 Areas of Hanford where the depth to the water table is approximately 200 feet.
- The DOE Hanford Site is located in south central Washington State. •The Sandia National Laboratory, at Kirtland Air Force Base in Albuquerque, New Mexico, is located near the east-central edge of the Albuquerque Basin, one of a series of north-south trending basins that make up the Rio Grande rift zone. The basin edges are bounded by uplifted fault blocks. The Albuquerque Basin is presently filled with up to 12,000 feet of Miocene and Pliocene sediments that were eroded from the surrounding highlands. This sequence of sediments, called the Santa Fe Group, consists of basin-fill alluvial fan materials, with channel deposits, debris flows, floodplain deposits, and eolian deposits. The Santa Fe Group sediments are overlain in places by Pliocene Ortiz gravels and Rio Grande River fluvial deposits, interbedded with Tertiary and Quaternary basalts and pyroclastics.
•The sediments are extremely heterogeneous, complexly interlayered units consisting of sands, gravels, and cobbly units. Discontinuous low-permeability layers are present as clay-rich or caliche-cemented zones.
•The water table underlying the site is approximately 500 feet below the surface.
•Wells have been drilled at the site using mud rotary, augers, and air rotary casing hammer techniques.



Location Map of CWL



Water-Supply Wells at KAFB



Generalized Geology and CWL Map Showing Location of Geologic Cross Sections

APPENDIX B

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Assistance was provided by the

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