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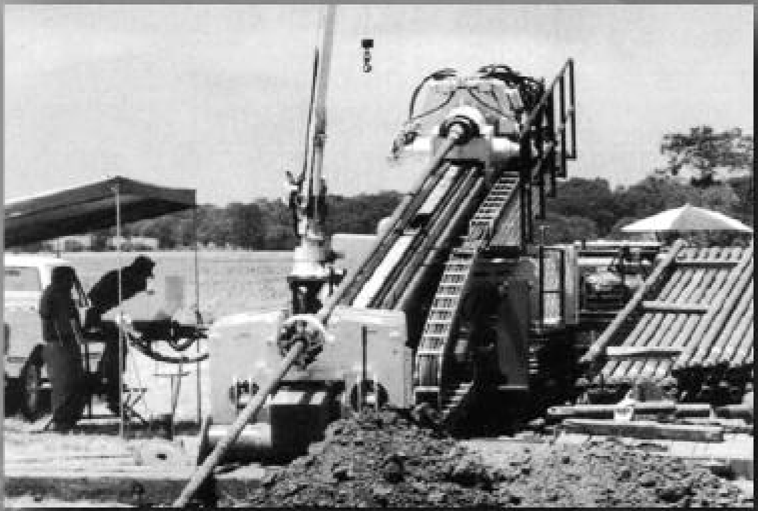
Analysis of Selected Enhancements for Soil Vapor Extraction



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ACRONYMS AND ABBREVIATIONS

μg/L	Micrograms per liter
AAEE	American Academy of Environmental Engineers
AC	Alternating current
Accutech	Accutech Remedial Systems, Inc.
AS/SVE	Air sparging and soil vapor extraction
bgs	Below ground surface
BTEX	Benzene, toluene, ethylbenzene, and xylene
^{o}C	Degrees Celsius
cfm	Cubic feet per minute
cfm/ft	Cubic feet per minute per foot
cm/s	Centimeters per second
CPVC	Chlorinated polyvinyl chloride
DNAPL	Dense nonaqueous-phase liquid
DOE	U.S. Department of Energy
DPE	Dual-phase extraction
Echo	Echo-Scan, Inc.
Electro-Voice	Electro-Voice, Inc.
EPA	U.S. Environmental Protection Agency
ER	Electrical resistance
ERT	Electrical resistance tomography
^{o}F	Degrees Fahrenheit
Frac	Frac Rite Environmental, Ltd
FRX	FRX, Inc.
GAC	Granular activated carbon
gpm	Gallons per minute
GRO	Gasoline range organics
HDPE	High density polyethylene
Hz	Hertz
in/sec	Inches per second

ACRONYMS AND ABBREVIATIONS (Continued)

ISB	In situ bioremediation
JFK	John F. Kennedy Airport
K	Hydraulic conductivity
KAI	KAI Technologies, Inc.
kVA	Kilovolt-ampere
kW	Kilowatts
LNAPL	Light nonaqueous-phase liquid
MHz	Mega-hertz
mg/kg	Milligrams per kilogram
mg/L	Milligrams per liter
mm Hg	Millimeter of mercury
MPE	Multi phase extraction
NAPL	Nonaqueous-phase liquids
PCB	Polychlorinated biphenyls
PCE	Tetrachloroethene
ppb	Parts per billion
psi	Pounds per square inch
PT/SVE	Pump-and-treat system combined with soil vapor extraction
PVC	Polyvinyl chloride
RFH	Radio-frequency heating
scfm	Standard cubic feet per minute
SERP	Hughes Steam Enhanced Recovery Process
SITE	Superfund Innovative Technology Evaluation
SPSH	Six phase soil heating
SRS	Savannah River site
SVE	Soil vapor extraction
SVOC	Semivolatile organic compounds
SVVS®	Subsurface Volatilization and Ventilation System
TCA	Trichloroethane
TCE	Trichloroethene

ACRONYMS AND ABBREVIATIONS (Continued)

Tetra Tech	Tetra Tech EM Inc.
TIO	Technology Innovation Office
TOU	Thermal oxidation unit
TPH	Total petroleum hydrocarbons
UST	Underground storage tank
V	Volts
VEP	Vacuum enhanced pumping
VISITT	Vendor Information System for Innovative Treatment Technologies
VOC	Volatile organic compound
WDNR	Wisconsin Department of Natural Resources
yd^3	Cubic yard

NOTICE

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FOREWORD

Soil vapor extraction (SVE) has been used at many sites to remove volatile organic compounds (VOC) from soil in the vadose zone. The effectiveness of SVE, however, is limited at sites with complex geology or by the distribution of contaminants in the subsurface and saturated soils. In recent years, research and field demonstrations have been conducted using innovative technologies and procedures to enhance the treatment effectiveness and removal rates of VOCs from vadose zone soil and of VOCs dissolved in groundwater and adsorbed to saturation zone soils. This report assists the site manager considering SVE as a treatment remedy by providing an evaluation of the current status of enhancement technologies. The five SVE enhancement technologies evaluated in this report are air sparging, dual-phase extraction, directional drilling, pneumatic and hydraulic fracturing, and thermal enhancement. The report discusses the background and applicability; provides an engineering evaluation; evaluates performance and cost; provides a list of vendors; discusses strengths and limitations; presents recommendations for future use and applicability; and lists references cited for each SVE enhancement technology.

EXECUTIVE SUMMARY

This report provides an engineering analysis of, and status report on, selected enhancements for soil vapor extraction (SVE) treatment technologies. The report is intended to assist project managers considering an SVE treatment system by providing them with an up-to-date status of enhancement technologies; an evaluation of each technology's applicability to various site conditions; a presentation of cost and performance information; a list of vendors specializing in the technologies; a discussion of relative strengths and limitations of the technologies; recommendations to keep in mind when considering the enhancements; and a compilation of references.

The performance of an SVE system depends on properties of both the contaminants and the soil. SVE is generally applicable to compounds with a vapor pressure of greater than 1 millimeter of mercury at 20°C and a Henry's Law constant of greater than 100 atmospheres per mole fraction. SVE is most effective at sites with relatively permeable contaminated soil and with saturated hydraulic conductivities of greater than 1×10^{-3} or 1×10^{-2} centimeter per second (cm/s). SVE by itself does not effectively remove contaminants in saturated soil. However, SVE can be used as an integral part of some treatment schemes that treat both groundwater and the overlying vadose zone.

Enhancement technologies should be considered when contaminant or soil characteristics limit the effectiveness of SVE or when contaminants are present in saturated soil. The five enhancement technologies covered in this report are as follows and are described in the following subsections:

- Air Sparging
- Dual-phase Extraction
- Directional Drilling
- Pneumatic and Hydraulic Fracturing
- Thermal Enhancement

AIR SPARGING

This popular technology expands the remediation capabilities of SVE to the saturated zone. One of the limitations of SVE alone is that it does not effectively address contaminated soils within the capillary fringe and below the groundwater table. Air sparging can enhance the remediation capabilities of SVE in the capillary fringe zone to include remediation of chemicals with lower volatilities and/or chemicals that are tightly sorbed. This technique also enhances biodegradation of aerobically-degradable contaminants and can significantly reduce the remediation time for contaminated sites.

Air sparging is a process during which air is injected into the saturated zone below or within the areas of contamination. Air injection can be performed through vertical or horizontal wells or sparging probes. The choice is largely determined by the site geology, site location, depth to groundwater, contaminant distribution, operational considerations, and a cost comparison analysis. As the injected air rises through the formation, it may volatilize and remove adsorbed volatile organic compounds (VOC) in soils within the saturated zone as well as strip dissolved contaminants from groundwater. Air sparging is most effective at sites with homogeneous, high-permeability soils and unconfined aquifers contaminated with VOCs. Air sparging also oxygenates the groundwater and soils, thereby enhancing the potential for biodegradation at sites with contaminants that degrade aerobically.

The effectiveness of air sparging for remediating contaminated sites is highly dependent on site-specific conditions. Less difficult at sites with homogeneous, high-permeability soils and unconfined aquifers, air sparging has been used at sites with heterogeneous, less-permeable soils and soils containing low-permeability layers with some effectiveness. Before selecting air sparging as an enhancement to SVE, site-specific groundwater, soil, and contaminant conditions as well as cleanup goals and project objectives should be assessed.

DUAL-PHASE EXTRACTION

Like air sparging, dual-phase extraction (DPE) combines soil and groundwater treatment for cleaning up VOC contamination. By removing both contaminated water and soil gases from a common extraction well under vacuum conditions, simultaneous treatment can be achieved, reducing both the time and cost of treatment. DPE provides a means to accelerate removal of nonaqueous-phase liquids (NAPL) and dissolved groundwater contamination, remediate capillary fringe and smear zone soils, and facilitate removal of vadose zone soil contaminants. DPE is most effectively implemented in areas with saturated soils exhibiting moderate to low hydraulic conductivity (silty sands, silts, and clayey silts). Lower permeability soils enable formation of deeper water table cones of depression, exposing more saturated soils and residual contamination to extraction system vapor flow. By lowering the groundwater table at the point of vapor extraction, DPE enables venting of soil vapors through previously saturated and semisaturated (capillary fringe) soils. High vacuums typically associated with DPE systems enhance both soil vapor and groundwater recovery rates.

Three basic types of DPE have been developed including:

> <u>Drop-tube entrainment extraction.</u> Extraction of total fluids (liquid and soil vapors) via vacuum applied to a tube inserted in the extraction well. Groundwater and vapors are removed from the extraction well in a common pipe manifold, separated in a gas/liquid separator, and treated.
>
> <u>Well-screen entrainment extraction.</u> Extraction of groundwater and soil vapors from a common borehole screened in the saturated and vadose zones. Groundwater is aspirated into the vapor stream at the well screen, transported to the treatment system in a common pipe manifold, separated in a gas/liquid separator, and treated.
>
> <u>Downhole-pump extraction.</u> Extraction of groundwater using a downhole pump with concurrent application of vacuum to the extraction well. Groundwater and soil vapors are removed in separate pipe manifolds and treated.

Variations to each type of DPE have been developed to enhance overall system performance. The type of DPE most suitable to any site is dictated by soil hydraulic and pneumatic properties, contaminant characteristics and distribution, and site-specific remediation goals. Relative costs for the different types are also largely determined by these factors.

Use of DPE for remediation of contaminated sites is most advantageous for sites contaminated with volatile compounds and for soils with moderate to low hydraulic conductivity. The presence of existing monitoring wells in strategic locations may provide an opportunity for minimizing system capital costs through conversion of the wells for extraction. Before a DPE system is implemented, efforts should be undertaken to assess groundwater and soil characteristics as well as project objectives for determining which type of DPE is appropriate for the site.

DIRECTIONAL DRILLING

Directional drilling employs the use of specialized drill bits to advance curved boreholes in a controlled arc (radius) for installation of horizontal wells or manifolds for SVE and sparging technologies. Horizontal wells can be used for enhancement of groundwater extraction, air sparging, SVE, and free product removal systems. The number of horizontal wells installed for environmental remediation projects has increased dramatically in recent years; more than 400 new horizontal wells were projected to be installed in 1996 (Wilson 1995a). Horizontal directional drilling, when applied to appropriate geologic environments and contaminants, can result in better performance and lower overall cost than vertical wells.

Horizontal wells can be installed in most geologic materials that are suitable for soil vapor extraction and air sparging, including unconsolidated sands, silts, and clays, as well as bedrock. Borehole lengths of between 200 and 600 feet, with depths of less than 50 feet are most common; however, longer and deeper boreholes have been successfully installed.

There are two types of directionally drilled boreholes: blind and continuous. Blind boreholes terminate in the subsurface; the well is installed from the entrance of the borehole. Continuous boreholes are reoriented upward and return to the ground surface. In continuous boreholes, the well is installed from the exit point and pulled into the borehole by the drill rig. An overview of a horizontal well installation by directional drilling is as follows:

- A pilot hole is advanced. Upon arriving at a target depth, the drilling tool is reoriented to drill a horizontal borehole. Electronic sensors in the drill tool guidance system provide orientation, location, and depth data to the driller.

- The hole is enlarged using a reaming drill bit, by pushing or pulling the bit through the pilot hole. In a continuous borehole, the reaming drill bit tool is inserted into the borehole at the exit point and pulled back to the drill rig.

- The well is installed by pushing or pulling the well casings into the borehole. In continuous boreholes, well installation generally occurs during the reaming phase described previously.

Installation of horizontal wells may be more expensive than installation of vertical wells. A careful analysis should be conducted to determine the costs and benefits of a horizontal well drilling program.

PNEUMATIC AND HYDRAULIC FRACTURING

Pneumatic and hydraulic fracturing are recognized methods adapted from the petroleum industry that induce fractures to improve the performance of extraction or injection wells. The two enhancement technologies involve the injection of either gases (typically air) or fluids (either water or slurries) to increase the permeability of the area around an injection well, thereby allowing increased removal or degradation rates of contaminants and potentially more cost-effective remediation. Pneumatic and hydraulic fracturing enhancement technologies are most applicable to low-permeability geologic materials, such as fine-grained soils, including silts, clays, and bedrock. The typical application of pneumatic and hydraulic fractures is to improve the performance of wells used during SVE remediation. Fracturing also can increase the recovery of free-phase fluids by increasing the discharge of recovery wells. Such applications closely resemble the recovery of oil from petroleum reservoirs. In addition, pneumatic and hydraulic fracturing also are being developed and used to enhance remediation technologies, such as DPE, in situ bioremediation including bioventing, thermal treatment including hot gas injection, in situ vitrification, free product recovery, and groundwater pump-and-treat systems.

Pneumatic fracturing typically involves the injection of highly pressurized air into soil, sediments, or bedrock to extend existing fractures and create a secondary network of conductive subsurface fissures and channels. The pore gas exchange rate, often a limiting factor during vapor extraction, can be increased significantly as a result of pneumatic fracturing, thereby allowing accelerated removal of contaminants. Recent application to saturated zones has provided evidence that the process also can effectively enhance remediation of saturated zones.

In hydraulic fracturing, water or a slurry of water, sand, and a thick gel is used to create distinct, subsurface fractures that may be filled with sand or other granular material. The fractures are created through the use of fluid pressure to dilate a well borehole and open adjacent cracks. Once fluid pressure exceeds a critical value, a fracture begins to propagate. Fractures may remain open naturally, or they may be held open by permeable materials, known as “proppants” (typically sand), injected during fracture propagation. Hydraulic fractures injected beneath the water table have shown to effectively enhance remediation of saturated zones.

To apply pneumatic or hydraulic fracturing effectively, the basic principles of fracturing, as well as the site geology, hydrology, and contaminant distribution must be understood. Thorough site characterization is necessary since fracturing may be an unnecessary step at sites that have high natural permeabilities. When fractures are to be induced for SVE remediation, design variables such as the selection of proppants and well completion specifications must be considered. Because of the great variability of geologic materials, conducting pilot-scale field tests is advisable before full-scale fracturing installations are implemented.

Although most environmental applications of pneumatic and hydraulic fracturing involve fluid injection to induce fractures and improve the performance of wells, a few cases have involved the use of detonating explosives to enhance permeability of crystalline bedrock and improve contaminant recovery. Environmental applications of blast-enhanced fracturing techniques have been adapted from the mining and geothermal industries and are well documented in the literature. To date, blast-enhanced fracturing has been used only with pump-and-treat methods, but it also may be useful in improving the performance of certain in situ technologies used at sites with naturally fractured aquifers in coherent bedrock. This technology is not suitable or useful for fracturing soils or shallow aquifers, or near buildings or other structures that cannot withstand vibrational impacts.

THERMAL ENHANCEMENT

Thermal enhancements for SVE involve transferring heat to the subsurface to increase the vapor pressure of VOCs or semivolatile organic compounds (SVOC) or to increase air permeability in the subsurface formation by drying it out. The removal of contaminants by SVE is controlled by a number of transport and removal mechanisms including gas advection, chemical partitioning to the vapor phase, gas-phase contaminant diffusion, sorption of contaminant on soil surfaces, and chemical or biological transformation. Thermal enhancement technologies raise the soil temperature to increase the reaction kinetics for one or all of these removal and transport mechanisms. In general, thermal enhancement technologies should be considered during soil remediation for one or more of the following applications: removal of sorbed organic compounds with low vapor pressures, reduction of treatment time for difficult matrices, treatment of NAPLs, and enhancement of biological activity in soil.

Thermal enhancement technologies include hot air or steam injection, radio-frequency heating (RFH), electrical resistance (ER) heating, and thermal conduction heating. Past applications of steam injection technologies have focused primarily on moving and vaporizing free petroleum product in the subsurface toward extraction wells for removal. Hot air injection has been used to increase the vapor pressure of VOCs and SVOCs in the vadose zone, thus decreasing remediation time and increasing contaminant removal. Use of ER heating and RFH has primarily focused on increasing mass removal rates of contaminants in low-permeability soil. Thermal conduction heating enhances conventional SVE treatment by heating the soil surface to volatilize contaminants. These thermal enhancement technologies are described in the following paragraphs.

Steam injection: This technology enhances conventional SVE treatment by injecting steam into the contaminated region. Contaminants are pushed ahead of the condensing water vapor toward the extraction wells. Additionally, some of the contaminants are vaporized or solubilized by the injection of steam and are moved toward vacuum extraction wells or a vacuum well at the soil surface. Steam injection technology is typically more applicable to regions with medium- to high-permeability soils, where the condensate front can move through the formation more freely. The subsurface geology must provide a confining layer below the depth of contamination to not allow contamination to migrate vertically downwards. In addition, a low permeability surface layer may be needed to prevent steam breakthrough for shallow soil applications.

Hot Air Injection: This technology is similar to steam injection, but hot air is used in place of steam. Hot air is used to volatilize the contaminants for removal at an extraction well. The resulting off-gas is then treated. The main strength of hot air injection technologies is their comparatively low cost. However, hot air injection is not a very efficient means for delivering heat to the subsurface because of the relatively low heat capacity of air. Because both steam injection and hot air injection involve injecting a fluid under pressure into the subsurface, the same geological concerns apply for hot air injection as with steam injection.

Radio-Frequency Heating: For RFH, energy is delivered to the contaminated region using electrodes or antennae that emit radio-frequency waves. These radio waves increase molecular motion, which heats the soil. Electrodes are either placed on the surface at the contaminated area or inserted into holes drilled into the contaminated area. The vaporized contaminants resulting from the heated soil are then transported to the extraction wells by an applied vacuum. RFH is effective for treating VOCs in low-permeability soil in the vadose zone.

Electrical Resistance Heating: This technology uses the soil as a conduction path for electrical current. The energy dissipated because of resistance is transformed into heat. A typical application of ER heating involves an array of metal pipes inserted into the contaminated region by drilling. An electrical current is then passed through these pipes to heat the contaminated region and drive off soil moisture and target contaminants. The volatilized gas is then collected under vacuum by extraction wells. ER heating is effective for treating VOCs in low-permeability soil in the vadose zone.

Thermal Conduction Heating: In thermal conduction heating, a heat source is placed on the surface of the contamination or inserted into the formation, and heat is supplied to the contaminants by conduction. The supplied heat volatilizes the target contaminants collected under vacuum by extraction wells or surface shroud. There has been limited application of this thermal enhancement technology to remediate hazardous waste sites. Thermal conduction heating can be used to remove VOCs in medium- to low-permeability soil. This technology is easily implemented and is relatively inexpensive; however, heat conduction by this method is very slow and inefficient and requires that a large temperature gradient be maintained for acceptable heating rates to be achieved.

Thermal enhancement technologies can enhance treatment efficiency and removal rates if certain site or contaminant characteristics constrain SVE treatment efficiency. Steam injection/stripping should be considered for sites that contain free petroleum product or high concentrations of total petroleum hydrocarbons (TPH). Additionally, some of the contaminants are vaporized or solubilized by the injection of steam and are moved toward the extraction wells by an applied vacuum. However, application of steam injection/stripping systems is limited to medium- to high-permeability soils. ER heating is more appropriate for heating and drying low-permeability soil in the vadose zone. RFH and ER heating can be used to heat soil if site conditions restrict the use of injection wells.

CHAPTER 1.0

INTRODUCTION

Under Contract No. 68-W5-0055 with the U.S. Environmental Protection Agency's (EPA) Office of Solid Waste and Emergency Response Technology Innovation Office (TIO), Tetra Tech EM Inc. (Tetra Tech), has prepared this engineering analysis of and status report on selected enhancements for soil vapor extraction (SVE) treatment technologies. TIO was established to advocate the development and use of innovative treatment technologies for remediation and corrective action related to hazardous waste. This report provides additional information on SVE technologies as presented in EPA's document, *SVE Enhancement Technology Resource Guide* (EPA/542-B-95-003, October 1995).

1.1 BACKGROUND

SVE has been used at many sites to remove volatile organic compounds (VOC) from soil in the vadose zone; however, the treatment effectiveness of SVE is limited at sites with complex geology or by the distribution of contaminants in the subsurface. In recent years, research and field demonstrations have been conducted using innovative technologies and procedures designed to enhance the treatment effectiveness and removal rates of VOCs from vadose zone soil and of VOCs dissolved in groundwater. Evaluating the current status of enhancements for SVE technologies will assist site managers who may be considering SVE as part of an integrated treatment remedy. The five enhancements that are evaluated in this report are air sparging, dual-phase extraction (DPE), directional drilling, pneumatic and hydraulic fracturing, and thermal enhancement. Table 1-1 presents a summary of the five SVE enhancement technologies presented in this report.

This report evaluates engineering methodologies related to SVE technologies. Recent advancements of in-situ bioremediation techniques have demonstrated that SVE technologies greatly enhance and sustain the aerobic bioremediation processes by providing oxygen (or heat) to naturally occurring soil microbials. This report does not address the evaluation and implementation of SVE systems to promote biodegradation of site contaminants. It is important to recognize the biochemical dynamics of a contaminated site and design a remediation technology that addresses both site characteristics and biochemical characteristics. Engineers and site managers should consider the physical and biochemical processes in the site characterization and design phases of remediation projects. Other technologies may enhance SVE treatment effectiveness (for example, bioventing); however, this report focuses solely on the enhancements listed above.

Listed below are some general SVE reference manuals that have proven to be helpful for the technologies discussed in this report.

American Academy of Environmental Engineers. 1994. Innovative Site Remediation Technology. Volume 1 - Bioremediation; Volume 2 - Chemical Treatment; Volume 3 - Soil Washing/Soil Flushing; Volume 4 - Stabilization/Solidification; Volume 5 - Solvent/Chemical Extraction; Volume 6 - Thermal Desportion; Volume 7 - Thermal Destruction; Volume 8 - Vacuum Vapor Extraction.
William Anderson, ed.

Battelle Memorial Inst. 1994. Air Sparging for Site Remediation. February 23.

Battelle Memorial Inst. 1994. Applied Biotechnology for Site Remediation. March 8.

Nyer, Evan. 1996. In Situ Treatment Technology. Geraghty & Miller. April 3.

Soesilo, J. Andy and Stephanie Wilson. 1997. Site Remediation Planning and Management. Lewis Publishers. January 14.

Suthersan, Suthan S. 1996. Remediation Engineering Design Concepts. Lewis Publishers. October 24.

U.S. Army Corps of Engineers. 1995. Soil Vapor Extraction and Bioventing Engineering Manual - Engineering and Design. EM 1110-1-4001. November.

EPA. 1991. Soil Vapor Extraction Technology Reference Handbook. Office of Research and Development. EPA/540/2-91/003. February.

EPA. 1994. Design, Operation, and Monitoring of In Situ Soil Vapor Extraction Systems. Office of Research and Development. EPA/600/F-94/037. September.

1.2 OBJECTIVES

The following five specific objectives have been developed for this report:

- Describe the background, applicability, and assessment of SVE enhancements
- Perform an engineering evaluation of each technology to evaluate performance, cost, strengths, and weaknesses

- Evaluate the current status of each technology
- Compile a vendor list for each technology
- Make recommendations for future use and applicability of each technology

The general approach used to meet these objectives is discussed in Section 1.3.

1.3 APPROACH

A five-step approach was used to identify, collect, and review information to fulfill the objectives listed in Section 1.2 for each of the five SVE enhancements. The approach consisted of conducting the following five tasks:

- **Conduct literature reviews -** Studies conducted by academic institutions, Federal agencies, state programs, and other entities were reviewed to identify previous applications of enhancement technologies
- **Collect performance information -** Performance information was collected from the literature reviewed for each technology, as well as through database queries, such as the Vendor Information System for Innovative Treatment Technologies (VISITT)
- **Collect cost information -** Because the benefits of implementing enhancement technologies must be weighed against the costs of the technologies, cost information was collected from literature searches and other sources whenever possible to assess the costs of implementing SVE alone versus the costs of implementing SVE with an enhancement technology
- **Contact and interview experts in the field -** SVE enhancement experts familiar with the outcome of field demonstrations were contacted to collect additional insight into implementing enhancement technologies at sites and to determine the state of the art in each technology
- **Contact and interview vendors -** Technology vendors were contacted to collect additional, unpublished performance and cost data to supplement information collected during the literature review

One objective for preparing this document was to identify vendors for each technology. However, the list of vendors identified for each technology should not be considered to be a comprehensive representation of all vendors that exist for each technology. The list of vendors were identified by the following methods:

- Initially, technology vendors were identified by accessing the Vendor Information System for Innovative Treatment Technologies (VISITT) database (EPA 1996). The VISITT database provides vendor information for innovative treatment technologies.

- Vendors were also identified through a networking process. These vendors were interviewed by phone to confirm their services. In many instances, vendor contacts provided the names of additional vendors providing technology services in the same field. In these cases, additional vendors were also contacted, interviewed, and added to the lists.

The term "vendor" is more appropriate for some technologies than others. Some technologies, such as dual-phase extraction and air sparging, are systems commonly designed and installed by a number of environmental companies. For other technologies, such as directional drilling and pneumatic and hydraulic fracturing, vendors are technology-specific and provide services specific to these systems.

1.4 REPORT ORGANIZATION

This report contains seven chapters, including this introduction. Chapter 2 presents a background discussion of SVE and the enhancement technologies. Chapters 3 through 7 present in-depth assessments of the five SVE enhancement technologies: air sparging, DPE, directional drilling, pneumatic and hydraulic fracturing, and thermal enhancement, respectively. The in-depth assessments provide information as follows:

- The applicability of the enhancement
- Cost and performance information
- List of technology vendors
- Strengths and limitations
- List of references
- Figures
- Tables (including cost and vendor information)

Appendix A contains a photographic log displaying examples of the technologies presented in this report. Appendix B contains a bibliography of published works collected during the course of research for topics presented in this report.

TABLE 1-1

SUMMARY OF ENHANCEMENTS FOR SOIL VAPOR EXTRACTION
(Page 1 of 3)

Technology	Air Sparging	Dual-Phase Extraction	Directional Drilling	Pneumatic and Hydraulic Fracturing	Thermal Enhancement
Description	Injection of air occurs below or within contaminated zones through wells or sparging probes. The injected air removes adsorbed VOCs in soil and dissolved contaminants in groundwater as the air rises through the formation. The increase in dissolved oxygen can also increase biodegradation of aerobically degradable contaminants.	Removal of contaminated water and soil gases from a common extraction well takes place under vacuum conditions. Groundwater extraction exposes soil formerly in the capillary fringe and saturated zones to the extraction system vapor flow. The three primary methods used are drop-tube entrainment, well-screen entrainment, and downhole-pump extraction.	Installation of extraction or injection wells in the most beneficial location relative to the area of contamination, and soil anisotropy maximizes the results of an SVE system. This technology increases the useful zone of influence of the well and reduces short circuiting problems in vertical boreholes.	Injection of gases (typically air) or fluids (either water or slurries) into low-permeable soil and sediments increases the performance of extraction or injection wells used in SVE. Development of fractures may occur in saturated sediments as well as in the vadose zone.	The transfer of heat to the subsurface improves or speeds up contaminant transport and removal mechanisms such as gas advection, chemical partitioning to the vapor phase, gas phase contaminant diffusion, sorption of contaminant on soil surfaces, and chemical or biological transformation. Methods include steam or hot air injection, radio-frequency heating, electrical resistance heating, and thermal conduction.
Status	In use at many sites in the United States and Europe since the 1980s.	Currently in use at many sites in the United States.	First applied to environmental remediation in 1988; the number of horizontal wells used for environmental remediation has increased dramatically in recent years.	Adapted from the petroleum industry in 1990; a number of pilot- and full-scale applications of fracturing enhancement SVE conducted in recent years.	Several full-scale applications of steam and hot air injection and electrical resistance technologies conducted in recent years; commercial systems available. Several pilot-scale applications of radio-frequency heating and electrical heating have also been conducted, but commercial systems are relatively limited.

TABLE 1-1

SUMMARY OF ENHANCEMENTS FOR SOIL VAPOR EXTRACTION
(Page 2 of 3)

Technology	Air Sparging	Dual-Phase Extraction	Directional Drilling	Pneumatic and Hydraulic Fracturing	Thermal Enhancement
Applicable Situations	Most effective at removing volatile contaminants from the saturated zone at sites with homogeneous, high-permeability soils and unconfined aquifers; also, used with some success in heterogeneous, less-permeable soil and in soil with low-permeable layers.	Most applicable at sites with multiple phase (soil and groundwater or soil, groundwater, and free product) contamination and low to moderate hydraulic conductivity soils. High vacuum enhances soil vapor and groundwater recovery rates in low-permeable soil formations.	Suitable in many geologic materials ranging from unconsolidated sands and silt. Often used where access for vertical wells is limited, the contaminant zone is long and thin, or the geologic materials are very anisotropic.	Generally used at sites with low-permeable soil and sediment, such as clay, silt, or sedimentary bedrock, where fracturing may increase permeability and improve fluid flow during the remediation process.	Often used in situations involving sorbed organic compounds with low vapor pressure, difficult matrices, or nonaqueous phase liquids. Also used to enhance biological activity in soil.
Limiting Factors	Distribution of air channels may be affected by lithological and operational control of air flow. Diffusion of contaminants into channels is slow; however, cycling or pulsing may reduce diffusion limitations. Performance may be difficult to measure or interpret.	Hydraulic and pneumatic properties of soil determine which type of dual-phase extraction system would be most effective. Groundwater extraction rates required for effective operation in permeable soils may be prohibitive, and extraction depths may be limited.	Installation in clay and bedrock can be difficult because of smearing along the borehole wall and slow drilling rates. Highly fluctuating water tables can cause problems in horizontal well SVE systems.	Geology and site conditions control the size, shape, orientation, and effectiveness of the fractures.	Site geology typically controls which thermal enhancement method is appropriate.

TABLE 1-1

SUMMARY OF ENHANCEMENTS FOR SOIL VAPOR EXTRACTION
(Page 3 of 3)

Technology	Air Sparging	Dual-Phase Extraction	Directional Drilling	Pneumatic and Hydraulic Fracturing	Thermal Enhancement
Site-specific Considerations	Soil heterogeneity greatly affects the distribution of air channels and the effectiveness of air sparging.	Operating costs may be high in permeable soil formations because of high water extraction rates and resulting treatment requirements.	The initial installation of horizontal wells may be more expensive than the installation of vertical wells, but other efficiency improvements may compensate for some of this difference in cost. Careful site characterization studies are necessary to correctly place and design well screens.	Most effective in low-permeable, over-consolidated soil, sediment, or sedimentary bedrock, such as shale and siltstone.	Steam injection is limited to medium- to high-permeable soil. Electrical resistance heating is effective in low-permeable soil in the vadose zone. Thermal conduction can be used in medium- to low-permeable soil, but is sometimes slow and inefficient. Radio-frequency or electrical resistance heating can be used at sites where the use of injection wells is restricted.
Technological Advancements	Air sparging is becoming increasingly more important in providing oxygen to aerobic, in situ bioremediation projects.	Dual-phase extraction is an aggressive technology that is uniquely suited to sites with multiple-phase contamination. Soil and groundwater contamination, as well as free-phase liquids and capillary fringe/smear zone contamination, can be addressed.	The cost of horizonal wells continues to decline. Horizontal wells will be used more routinely in the near future.	Pneumatic and hydraulic fracturing are becoming increasingly more important in improving soil permeabilities for the delivery or extraction of fluids from low-permeable environments. Fracturing likely will be applied more routinely to many in situ remediation technologies in the future.	Steam and hot air injection are being used at full-scale to decrease the time required for remediation. Radio-frequency and electrical resistance heating require process automation to reduce costs and operator requirements.

Notes:		
	NAPL	Nonaqueous-phase liquid
	SVE	Soil vapor extraction
	VOC	Volatile organic compound

CHAPTER 2.0

BACKGROUND: SOIL VAPOR EXTRACTION ENHANCEMENT TECHNOLOGIES

SVE is an in situ remediation technique used to remove VOCs from vadose zone soil. Air flow is induced through contaminated soil by applying a vacuum to vapor extraction vents and creating a pressure gradient in the soil. As the soil vapor migrates through the soil pores toward the extraction vents, VOCs are volatilized and transported out of subsurface soil. Advantage of SVE systems over other remediation technologies for soil contaminated with organics are the relative simplicity of installing and operating the system and the minimal amount of equipment required.

The performance of an SVE system depends on properties of both the contaminants and the soil. The most important contaminant property is its volatility, which can be measured by its vapor pressure and its Henry's Law constant. Vapor pressure is the pressure exerted by a vapor phase constituent and the Henry's Law constant is the ratio of the partial pressure of a chemical’s concentration in solution at equilibrium. SVE is applicable to compounds with a vapor pressure of greater than 1 millimeter of mercury (mm Hg) at 20 °C and a Henry’s Law constant of greater than 100 atmospheres per mole fraction (EPA 1991). SVE is most effective at sites with relatively permeable contaminated soil. SVE systems are installed above the water table and thus do not affect contaminated soil within the saturated zone. Air sparging systems installed below the water table are effective in removing contaminants from the groundwater but do not remove contaminants in the saturated soil per se (although desorption and equilibration with the water phase follow).

Enhancement technologies should be considered when contaminant or soil characteristics limit the effectiveness of SVE, or when contaminants are present in saturated soil. The five enhancement technologies covered in this report are as follows:

- **Air sparging -** Air sparging can be used with SVE to treat VOC contamination, such as gasoline, solvents, and other volatile contaminants, present in the saturated zone. Air sparging involves injecting air into the saturated zone below the contaminated area. The air rises through channels in the saturated zone and carries volatilized contaminants up into unsaturated soils, where the contaminants are subsequently removed using SVE. Air sparging also increases the dissolved oxygen levels in the groundwater, thereby enhancing subsurface biodegradation of contaminants that are aerobically degradable.

- **DPE -** DPE enhances contaminant removal by extracting both contaminated vapors and groundwater from the subsurface. DPE involves the removal of contaminated vapors and groundwater from the same borehole. A vacuum applied to the borehole extracts contaminated vapors from unsaturated soils and simultaneously entrains contaminated groundwater. The groundwater is subsequently separated from the vapors and treated using standard aboveground treatment methods. The groundwater table within the zone of influence of a DPE well is lowered, exposing the capillary fringe and previously saturated soils to the extraction vacuum and enabling more effective remediation of these soils than traditional SVE systems.

- **Directional drilling -** Directional drilling technologies allow SVE to be conducted in areas not easily accessed by vertical drilling techniques. Directional drilling, along the geometry of the contaminated zone, may increase the zone of influence of a single extraction or injection well. Directional drilling also enhances SVE by reducing air short-circuiting within the borehole in vertical well systems.

- **Pneumatic and hydraulic fracturing -** Pneumatic and hydraulic enhancement technologies increase SVE efficiency in low-permeability soils by creating cracks or sand-filled fractures. Pneumatic fracturing involves injecting air into low permeability soils to create fractures, thus increasing the permeability of the soil. Hydraulic fracturing creates sand-filled fractures which also enhance the permeability of the subsurface formation. These enhancements can allow the application of SVE in low-permeability, silty clay formations where in situ cleanup may be impossible without enhancing soil permeability.

- **Thermal enhancement -** Thermal enhancements for SVE may involve a number a different technologies aimed at transferring heat to the subsurface to (1) increase the vapor pressure of VOCs or semivolatile organic compounds (SVOC) to enhance their removal via SVE or (2) dry soil to increase air permeability. Thermal enhancement technologies include hot air or steam injection, electrical resistance (ER) heating, radio-frequency heating (RFH), and thermal conduction heating.

The site geology, contaminant characteristics, and surface features determine which enhancement technology will be the most effective. Thermal processes can raise the vapor pressure of a contaminant, thus making it more amenable to removal by SVE. Pneumatic and hydraulic fracturing, directional drilling, and thermal processes may increase the air permeability of low permeability soil. Pneumatic and hydraulic fracturing increase permeability by injecting a fluid under pressure into the soil, whereas directional drilling uses mechanical processes to increase soil permeability. Thermal processes use heat to dry soil and increase air permeability. Air sparging and DPE should be considered if contamination is present in saturated soil at a site and conventional SVE is limited by the rate of vaporization of VOCs from groundwater in the saturated soil.

As shown above, several enhancements may be appropriate for modifying contaminant or site characteristics to increase SVE effectiveness; therefore, the following considerations describing the applicability of SVE and the selected enhancements are suggested:

1. Excavate and treat contaminated soil ex situ, if the source is small and near the surface.

2. Biovent, if the source is amenable to aerobic bioremediation.

3. Apply SVE if contaminants are volatile and bioventing and excavation are not practical. Directional drilling should be considered during remedial design of the SVE system and not necessarily as an enhancement per se.

4. Apply pneumatic or hydraulic fracturing if the soil permeability is low (hydraulic conductivity of less than 10^{-6} centimeters per second [cm/s]).

5. Apply thermal enhancement if the vapor pressures of the contaminant of concern are low (less than 0.5 mm Hg at ambient conditions), or where high soil moisture content prevents adequate air exchange.

6. Apply DPE if light nonaqueous phase liquid (LNAPL) is present or if the capillary fringe is targeted for cleanup.

7. Air sparge to distribute oxygen in the groundwater and vadose zone and to induce bioremediation and contaminant stripping in groundwater if desired.

Specific recommendations for application of each enhancement are discussed in Chapters 3 through 7.

CHAPTER 3.0

AIR SPARGING

Air sparging is an innovative treatment technology that expands the remediation capabilities of SVE to the saturated zone. One of the limitations of SVE alone is that it does not effectively address contaminated soils within the capillary fringe and below the groundwater table or contaminated groundwater. Air sparging enhances the remediation of deeper soils and groundwater. Air sparging can significantly reduce the remediation time frames for contaminated sites as compared with conventional SVE systems.

Air sparging was first used in Germany in the mid-1980s. The technology spread to other parts of Europe and the United States in the late 1980s. Air sparging has become popular for remediating contaminated sites in recent years and is currently being used at many sites throughout the United States.

The following sections provide an overview of air sparging and its use with SVE, describe conditions under which the technology is applicable, outline the engineering factors considered in designing and operating an air sparging system, summarize the performance and costs of case studies, discuss vendors that provide air sparging services, outline strengths and limitations of the technology, and provide recommendations for using the technology at contaminated sites. Cited figures and tables follow references at the end of the chapter.

3.1 TECHNOLOGY OVERVIEW

Air sparging, also known as “in situ air stripping” and “in situ volatilization,” is a process in which air is injected into the saturated zone below or within the areas of contamination through a system of wells. As the injected air rises through the formation, it may volatilize and remove adsorbed VOC in soils as well as strip dissolved contaminants from groundwater. Air sparging is most effective at sites with homogeneous, high-permeability soils and unconfined aquifers contaminated with VOCs.

SVE is commonly used with air sparging to capture the volatiles that air sparging strips from soil and groundwater. The volatile contaminants are transported in the vapor phase to the vadose zone, where they are drawn to extraction wells and treated using a standard off-gas treatment system. Air sparging can remediate contaminants in the vadose zone that would not be remediated by vapor extraction alone (that is, chemicals with lower volatilities and/or chemicals that are tightly sorbed) (EPA 1995).

Air sparging also oxygenates the groundwater and soils, thereby enhancing the potential for biodegradation at sites with contaminants that degrade aerobically. At one fuel spill site, approximately 70 percent of the contaminants was remediated through biodegradation and 30 percent through volatilization (Billings and others 1994). In general, the primary removal mechanism for highly volatile contaminants is volatilization, and the primary removal mechanism for low volatility contaminants is biodegradation (Brown and others 1994). Vapor extraction appears to be the more dominant removal mechanism during the early phases of treatment, while biostimulation processes dominate during later phases.

An air sparging system includes the following components:

- Air sparging wells or probes to inject air into the saturated zone
- A manifold, valves, and instrumentation to transport and control the air flow
- An air compressor or blower to push air into the saturated zone through the air sparging wells or probes
- A properly designed SVE system to capture the contaminated vapors in the vadose zone

A cross-section of a typical air sparging system design, including vertical sparge and SVE wells and surface treatment units, is shown in Figure 3-1. A similar system using horizontal sparge and SVE wells is shown in Figure 3-2. Air sparging system characteristics are summarized in Table 3-1 and discussed in subsequent sections.

3.2 APPLICABILITY

Air sparging is most effective at sites with homogeneous, high-permeability soils and unconfined aquifers contaminated with halogenated or nonhalogenated and aerobically biodegradable VOCs. The technology can also be effective at less ideal sites, such as those with heterogeneous, low to medium permeability, stratified soils. Table 3-2 summarizes the factors affecting the applicability of air sparging.

Modifications to injection of air in a sparging system include the following:

- Supplemental injection of nutrients to enhance biodegradation
- Substitution of nitrogen for air to reduce the formation of ferric oxide in the pore spaces of aquifers with high iron concentrations
- Supplemental injection of air with other gases such as ozone or oxygen or substitution of oxygen for air to increase the availability of oxygen for biodegradation
- Supplemental injection of methane as a cometabolizer for chlorinated solvents
- Supplemental injection of toluene as a cometabolizer for trichloroethene (TCE)

Air sparging can be used in conjunction with other innovative enhancement technologies such as hot air injection, fracturing, and RFH.

3.3 ENGINEERING DESCRIPTION

Proper design and operation of an air sparging system requires knowledge of the site conditions, as well as an understanding of the way air sparging enhances the remediation of contaminated sites. Even though air sparging is being used at many sites throughout the country, air flow in the subsurface, especially within the saturated zone, is not well understood. Information from research and remediation of contaminated sites is continually refining the concepts of air flow in the subsurface, and therefore, the ways in which air sparging systems are designed and operated.

This section addresses important air flow concepts as well as design and operational components of an air sparging system. Section 3.3.1 discusses subsurface air flow and operational methods that can reduce the limitations posed by low air flow. Section 3.3.2 describes the engineering components of an air sparging system, including the types, design, and operation of the equipment. Section 3.3.3 describes methods typically used to monitor the performance of an air sparging and soil vapor extraction (AS/SVE) system.

3.3.1 Air Flow Within the Subsurface

The flow of injected air in both the horizontal and vertical directions in a contaminated aquifer is of primary importance during air sparging. Anything that controls the air flow, whether it is operational or lithological, can influence the effectiveness of the system (Brown and others 1994).

Air injected into aquifer materials has been shown to typically migrate in channels, and little airflow moves in the form of bubbles as proposed in earlier studies (Hinchee 1994; Wisconsin Department of Natural Resources [WDNR] 1995). If bubbles do form and move, the bubbles would likely induce advective water flow, resulting in substantial contact between the air and aquifer materials. Research indicates that an average grain size of 2.0 millimeters or larger is necessary for bubble flow to occur; this is found at a small percentage of sites. If bubbles do not form at a site, air will flow in channels and primarily have contact with the contaminated soil and groundwater within the channels.

There is a growing amount of research that indicates that the ability of an in situ air sparging system to clean an aquifer is a function of the air channel density in a formation (WDNR 1995). Increasing the air flow rate can greatly increase air channel density, but not necessarily the zone of influence of the well. Generally, a more desirable air channel distribution is achieved in uniform, coarse-grained soils. Sparging in fine-grained or highly stratified soils can require pressures that approach or exceed soil fracturing pressures. The creation of fractures in the soil matrix can result in a loss of system efficiency or in some cases can actually improve channel distribution; however, when fracturing occurs, the effects are likely irreversible (Marley 1995).

The distribution of channels and thus the effectiveness of air sparging can be greatly affected by slight heterogeneities in the soil matrix. Since air flow in the subsurface will follow the path of least resistance, the majority of air channels form in the most permeable zones (Marley 1995). Thus, transfer of volatile contaminants into air channels and oxygen into the aquifer can only be accomplished in the bulk of the formation by diffusion processes. When diffusion works alone, the process is slow. The contaminants must migrate several inches to several feet (that is, the typical distance between air channels) by diffusion to reach an air channel (WDNR 1995). The air channel diameter is typically quite small (approximately the size of the pore space between the soil particles); therefore, the surface area of the air and water interface of each air channel is extremely small, resulting in limited mass exchange rates. In addition, the groundwater at a distance from the air channel can be quite high in VOC content, while the water in the air channel will have reduced VOC content. This often creates a concentration gradient within the groundwater regime.

Cycling or pulsing of the air flow during operation of an air sparging system promotes mixing of the water in the treatment zone, effectively increasing the contact between the air and contaminated aquifer materials and reducing the effects of diffusion limitations and contaminant concentration gradients that form during continuous operation (WDNR 1995; Marley 1995). This allows for increased volatilization as well as enhanced biodegradation. Although there is some speculation that pulsing the system creates new air channels in the formation, studies indicate that air channels appear to be stable and do not seem to move over time or because of varying air flow rates (Johnson 1994). Varying the pressure within the air channels, however, could result in changed channel diameters, thus inducing some water flow and improving the effectiveness of air sparging (Hinchee 1994). Cycling has the potential to cause buildup of fines, potentially clogging the well (WDNR 1995). This effect can be reduced by installing a check valve on each well to reduce back flow. Biofouling of the well screen or sparging probe is also a concern under the increased oxygen concentrations associated with this technology (Johnson 1994).

By manipulating air flow to the sparging wells at a site, cycling can reduce air emissions from the SVE system, thereby potentially reducing the costs of off-gas treatment (WDNR 1995). Reducing air flow through cycling or lower injection rates can increase the effect of biodegradation relative to volatilization. Biodegradation can reduce the costs of remediation by reducing the amount of contaminants that the SVE system must remove and treat, especially during later phases of treatment. The need for off-gas treatment typically increases operational costs by a factor of 1.5 to 2 (EPA 1995). Reducing air flow to optimize biodegradation and minimize off-gas treatment, however, could result in longer remediation times, thereby potentially increasing costs. Cycling the air flow at a site can also reduce capital and energy costs.

The site geology can greatly affect the flow of air in a formation. A low permeability layer above the saturated zone can limit vertical air flow to the SVE system placed in the unsaturated zone, resulting in substantial lateral migration of contaminated vapors from the sparge well. The potential for uncontrolled migration of sparge vapors increases with increasing sparge depth because of the potential for channeling along subsurface features. One technique used to increase the vertical permeability of a stratified formation is through the use of sand chimneys (EPA 1995; Tetra Tech 1996a). Sand chimneys are sand-packed borings installed through low permeability layers. They provide passive air flow between the subsurface layers, increasing both SVE and biodegradation rates.

3.3.2 Equipment Requirements and Operational Parameters

The basic equipment needed to conduct air sparging at a contaminated site includes air sparging wells or probes, a manifold, valves, instrumentation, an air compressor, a vacuum blower, an air/water separator, and air emissions treatment equipment (Figure 3-1).

Pilot tests are often conducted at a site to determine air sparging system design parameters such as air entry pressures, vacuum requirements, air flow rates, and effective zones of influence for the sparging and extraction components. Alternatively, it can be more cost effective at some sites to use existing information about the site conditions to conservatively design an air sparging system with increased well density, rather than conduct pilot tests, especially at sites where a shallow installation depth minimizes the cost of installing additional wells (Tetra Tech 1996a, b).

Both pilot testing and full-scale air sparging operations at a site are initiated by operating the extraction system without air sparging to establish a baseline for vapor extraction capability and emissions, as well as to avoid buildup of vapors in the formation. After a few hours to a few days, the air sparging system is turned on. Operation of the air sparging system requires ongoing monitoring and system adjustment to maximize performance.

3.3.2.1 Air Sparging Wells and Probes

Air is injected through vertical wells, nested wells, horizontal wells, combined horizontal/vertical wells, or direct push sparging probes. The type of well chosen depends on the site conditions and cost effectiveness of each method.

The placement of sparging wells or probes at a site will depend primarily on the areal delineation of the remediation area and the soil-specific zone of influence. The zone of influence is often estimated during pilot testing by measuring parameters such as dissolved oxygen or contaminant concentrations in monitoring wells; oxygen, carbon dioxide, and contaminant concentrations in SVE off-gas or soil vapor probes; and/or changes in the water table elevation caused by a water table rise in response to air injection. Tracer gas mapping of air channel distribution and SVE system capture effectiveness is also used to estimate the zone of influence. The depth at which air will be injected and the screen length are determined by the site geology, depth to groundwater, contaminant type and distribution, and well type. Another option is to construct and install the equipment in phases, and use the first phase installation to conduct a pilot test. The results of the pilot test can then be used to complete the design and installation of the system.

The use of neutron probes to assess air flow in the subsurface during pilot testing and operation is increasing, although wide spread use of this technology may be limited by cost and the regulatory requirements of using the probes that contain a low-level radioactive source (Baker et al 1996). Electrical resistivity tomography can also be used to assess the air flow by measuring the resistivity of the subsurface between two or more boreholes (Lundegard et al 1996). This technique is also becoming more popular yet still is not used routinely at air sparging sites.

The following paragraphs describe vertical and horizontal wells, typical zones of influence, effective sparging depth, and screen configuration for each type of well. Direct push sparging probes are also discussed.

Vertical Wells

Vertical air sparging wells are the most commonly used type of wells (Figure 3-1). These wells are installed using conventional drilling techniques such as hollow-stem auger methods. The well diameter is typically 2 inches or greater to allow the use of conventional well development equipment. Air is injected into the wells either through a manifold system or sparging probes installed in the wells. Vertical wells have been installed in aquifers up to about 150 feet deep; however, a depth limitation for vertical wells was not reported. Multiple-depth completions, which allow air injection at different depths, can be used at sites with groundwater levels that fluctuate significantly.

Placement of vertical wells is largely determined by the estimated or calculated injection zone of influence at the site. Zones of influence of 5 to 30 feet (measured radially) have been observed in coarse soils and 60 feet or greater in stratified soils (Marley 1995). At sites with zones of influence of 60 feet or greater, preferential lateral air flow was probably occurring. Sparging well spacings of greater than 30 feet may not be successful (Tetra Tech 1996c).

The majority of sparge air flows out of the well screen near the top of the screen where the pressure head is at a minimum and follows a path determined largely by the site geology. The top of the well screen should be located no less than 5 feet below the vertically delineated remediation zone (Marley 1995). If the sparge point is placed shallower than this, the zone of influence is very limited, and an excessive number of sparge points is required to remediate a unit volume of contaminated soil. Alternatively, the top of the screen should be set 5 feet below the seasonal low static water table (WDNR 1993). Sparging well screen lengths of 1 to 5 feet are recommended (WDNR 1993; Marley 1995).

At sites where lateral displacement of contaminated groundwater is a concern, an array of defensive sparging wells or an intercepting sparging trench downgradient of the remediation area can be used to prevent spreading of the contamination as an alternative to the pump-and-treat technology.

Horizontal Wells

Horizontal wells are installed using innovative horizontal trenching or drilling techniques (Figure 3-2). Horizontal wells can be used to remediate contamination under buildings and into other hard-to-reach areas. These wells are particularly effective at sites that present shallow aquifers and long, thin contaminant plumes, such as those caused by leaking pipelines.

Horizontal wells are generally installed perpendicular to the groundwater flow direction so that the groundwater flows through the wells. High flow rates must be used to inject air through long lengths of horizontal screen; still, it is possible that more air will exit the well at the air injection end of the screen and less air will reach the far end of the screen (Tetra Tech 1996c). A more even distribution of air flow can be achieved by using design techniques to allow control of the air flow trajectory.

The use of horizontal sparging within an aquifer increases the surface area exposed to the injected air, thus providing a greater zone of influence than vertical wells (Tetra Tech 1996c). Heterogeneities in the soil matrix, however, can cause the air to flow out of the screen in discrete zones along the length of the screen, reducing the effective zone of influence of the well.

Both horizontal air sparging and extraction wells can be used to remediate a contaminated site. Alternatively, because the zone of influence of extraction wells is generally greater than that of air sparging wells, it can be more cost effective to use vertical extraction wells in combination with horizontal injection wells (Tetra Tech 1996c). The depth of the wells required at a site is a primary factor in comparing the cost effectiveness of installing vertical or horizontal wells. Horizontal trenching techniques can be used to install wells to depths up to 30 feet below grade (Tetra Tech 1996d). Drilling techniques similar to those used to install utility lines can be used to install horizontal sparging wells to depths of about 40 feet below grade. These horizontal drilling techniques can be cost competitive with vertical well installation. More costly horizontal drilling techniques must be used for wells greater than 40 feet in depth. These techniques are discussed in Chapter 5.0. Installation of vertical wells generally tends to be more cost effective than horizontal wells for depths between 40 and 100 feet, and installation of horizontal wells tends to be more cost effective between 100 and 150 feet (Tetra Tech 1996c).

Direct Push Sparging Probes

Direct push techniques can be used to install sparging probes into the subsurface without installing a groundwater well. Typically, a 2-inch casing equipped with a fall-off bottom is driven into the ground with a hammer assembly. After a sparging probe and air tube are installed in the casing, the casing is withdrawn, and the boring is backfilled. The sparging probe air tube is then connected to an aboveground air supply.

The depth to which direct push techniques can be used is limited by geological restrictions on penetrating the subsurface. Greater depths can be attained in porous soils. Use of sonic waves can encourage easier penetration. Probes can typically be installed to about 40 feet below grade using direct push techniques and have reportedly been used up to 100 feet below grade (Tetra Tech 1996c).

Probes installed directly into the subsurface can reportedly be as effective at remediating a site as probes installed in groundwater wells (Tetra Tech 1996c). Soil and water samples can be collected during either well or direct push probe installation. Groundwater wells may be subsequently be used for water and vapor monitoring.

3.3.2.2 Manifolds, Valves, and Instrumentation

The manifold is typically buried underground and constructed of 2-inch or larger diameter steel, polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC), or high density polyethylene pipe (HDPE). If pressures higher than 15 pounds per square inch (psi) are anticipated, use of manifold materials at anticipated operational temperatures and pressures should be evaluated to prevent damage to the manifold from excessive pressure and temperatures. PVC and CPVC may not withstand elevated temperatures or pressures. PVC pipe is not recommended by many pipe suppliers for compressed air service. In addition, if the manifold is buried within the frost zone or placed above ground, it may need to be protected with insulation and/or heat tape.

Several devices can be installed to optimize operation of the sparging system. The following devices may be included in the system design:

- A filter on the air intake of the compressor to prevent particulates from damaging the air compressor or entering the air stream.
- A check valve between each well and the manifold to prevent temporary high pressure in the screened interval from forcing air and water back into the manifold system after the system is shut off
- A throttle valve at each well to allow the well to be isolated from the system or to adjust the air flow rate to the well
- A solenoid valve on each well to allow the well to be cycled several times per day (requires installation of a control panel with a timing device)
- A port at each well to temporarily attach a flow meter for measurement of air flow at each well

- A port to allow temporary attachment of a pressure gauge and thermometer at each well or well cap or at the manifold near each well to monitor the air injection pressure and air temperature at each well

- A manual pressure relief valve immediately after the air compressor outlet to exhaust excess air from the manifold

- A permanent pressure gauge, thermometer, and flow meter between the manifold system and the manual pressure relief valve to measure total system flow, temperature, and pressure

- An automatic pressure relief valve to prevent excessive pressure from damaging the manifold or fracturing the aquifer in the event of a system blockage

In addition, installation of devices that would automatically shut down the air sparging system in the event of air extraction equipment failure is recommended (WDNR 1995). Operation of the air sparging system in the absence of the extraction system could spread the contamination in the formation or cause the migration of vapors into buildings or utility conduits, creating an explosion hazard. A sensor placed on a gas probe near critical structures to monitor for negative soil gas pressure or on the SVE stack to monitor for positive pressure can continuously monitor the soil venting system.

Operation of the AS/SVE system requires ongoing monitoring and system adjustment to maximize performance. Computer systems can be used to completely or partially automate the monitoring and/or system adjustments.

3.3.2.3 Air Compressor or Blower

The air compressor or blower chosen for a site should be large enough to inject sufficient pressure and flow to at least one well and possibly to multiple wells simultaneously (WDNR 1993). The air compressor or blower should produce sufficient pressure to depress the water level in all wells below the top of the screen during both seasonal high and low water table conditions. Air compressors and blowers should be rated for continuous duty. Common air compressor types include oil-free reciprocating and rotary screw compressors, rotary lobe blowers, centrifugal blowers, and regenerative blowers. Compressors and blowers should not use lubricants or fluids that could enter the air stream and reach the groundwater.

Air injection pressures are determined by the static water head above the sparge point, the required air entry pressure of the saturated soils, and the air injection flow rate (Marley 1995). Higher pressures will produce higher air injection flow rates and will likely produce additional air channels. Too high an injection pressure can displace contaminated vapors and water and spread the contamination to previously unaffected areas. Minimum air-entry pressures of 1 to 2 psi in excess of the hydrostatic head at the top of the injection well screen are recommended (Marley 1995). Fine-grained soils generally require higher air-entry pressures (factor of 2 or more than the minimum).

Over pressuring may create fractures in the sparging well annular seal or within the soil. Forty to 50 percent porosity in the soil matrix should be assumed, and a 5 psi safety factor should be included to calculate the air pressure for a site (WDNR 1995). Alternatively, the maximum pressure should be 60 to 80 percent of the calculated pressure exerted by the weight of the soil column above the top of the screen (WDNR 1995).

The rate at which air will be injected must be determined after considering the site geology, contaminant type and distribution, and remediation goals. Higher air flow rates increase the volatilization component of remediation, and lower rates increase the biodegradation component of remediation. Air flow of at least 5 standard cubic feet per minute (scfm) per well should be injected. If the permeability is too low to allow 5 scfm, in situ air sparging may not be the appropriate remedial method for the site (WDNR 1995). The relationship between air injection and air extraction varies from a recommended air injection to air extraction ratio of 1 to 4 (WDNR 1995) to an air flow maintained at 80 percent of the vacuum rate (EPA 1995).

There is growing evidence that the ability of an in situ air sparging system to clean an aquifer is a function of the air channel density in the soil (WDNR 1995). Increasing the air injection rate can greatly increase the air channel density within the zone of influence of a sparging well; however, the zone of influence of the well is not significantly affected by the increase in injection rate or channel density (WDNR 1995; Marley 1995).

3.3.3 Monitoring of System Performance

System adjustments are made based on monitoring of changing subsurface conditions. Monitoring includes measurement of parameters related to volatilization, air flow, and bioactivity (such as carbon dioxide and oxygen). The parameters typically used to monitor the performance of an air sparging system include the following:

- Dissolved oxygen and contaminant concentrations in groundwater
- Oxygen, carbon dioxide, and contaminant concentrations in extracted air
- Microbial populations and activity (including in situ respiration tests)
- Air flow and extraction rates
- Air flow regions using neutron probe measurements or electrical resistivity tomography
- Sparging and vacuum pressure measurements
- Changes in the water table elevation caused by a water table rise in response to air injection
- Tracer gas mapping of air channel distribution and SVE system capture effectiveness
- Zone of influence for both vacuum and sparging wells
- Continuity of blower and compressor operation

There is growing evidence that pilot tests and full-scale operations often provide overly optimistic results if those results are based only on groundwater samples from monitoring wells (WDNR 1995; Hinchee 1994). This is especially true if dissolved oxygen in monitoring wells is the basis for estimating effectiveness. The vast majority of air channels are found in the most permeable zones, and monitoring well filter packs are typically more permeable than the native soils; therefore, air channels formed during the in situ air sparging process will preferentially intersect and flow through monitoring well filter packs. As a result, the water in monitoring well filter packs and the wells themselves usually receive much more air flow than the rest of the aquifer, resulting in more aggressive treatment. Determining monitoring system performance using chemistry changes in monitoring wells yields overly optimistic results. These changes are generally not representative of the aquifer as a whole.

Practitioners often measure the effectiveness of air sparging by monitoring the oxygen, carbon dioxide, and/or contaminant levels in air extracted from the vadose zone before operating the air sparging system and comparing these data to measurements taken after air sparging is initiated. Typically, the data indicate an increase in the remediation rate with air sparging, followed by a drop in the rate as the subsurface reaches equilibrium. At one site, the remediation rate showed a 10-fold increase and reached an equilibrium equivalent to a three-fold increase over SVE alone (Terra Vac, Inc. 1995). The extent to which this effect is caused by the removal of contaminants from the aquifer or by improved removal from the vadose zone is not known (Hinchee 1994). At some sites, contaminant concentrations in air extracted from the SVE system may decrease or remain the same with the addition of air sparging (Tetra Tech 1997). This effect may be due to dilution of the extracted air by the addition of sparged air into the subsurface.

Monitoring air pressure in the vadose zone does provide some indication of the influence of air sparging on the vadose zone but does not appear to correlate with the effect on the underlying aquifer (Hinchee 1994). Similarly, the water table rise observed during air sparging seems to correlate with the area in which air is injected; however, the way this can be expected to correlate with the area of effective treatment is not clear.

The best indicator of system performance or the effectiveness of an air sparging system is the long-term improvement in soil and groundwater quality after the system has been shut down for a period of time (Clark and others 1995). A site is often monitored following completion of air sparging operations because of the possibility of rebounding groundwater contaminant concentrations (Tetra Tech 1996e). Regulatory agencies are often reluctant to officially close a site based on water, soil gas, or SVE off-gas data. Collection and analysis of soil samples at the site are sometimes required to confirm that the contaminants in the subsurface have been removed.

3.4 PERFORMANCE AND COST ANALYSIS

Air sparging has been selected to remediate many contaminated sites across the country, including fuel service stations, industrial sites, and government facilities. Many projects are still in the design or operational phase. Many sites have met or are approaching the closure requirements of the regulatory agencies. Some level of performance and cost data is available for many sites; however, comprehensive data are often difficult to obtain. Table 3-3 lists 29 sites remediated by air sparging. It provides data on soil types, contaminant types, reported contaminant concentrations in groundwater (initial and final), and the time needed to achieve those final contaminant concentrations.

This section presents three case studies from the literature and discussions with technology experts and vendors. The evaluation of the performance and cost at each site is based on the data available.

3.4.1 Performance

The performance of the air sparging technology at three sites is described in the following subsections.

3.4.1.1 U.S. Department of Energy Savannah River Integrated Demonstration Site

Air sparging was used to remediate chlorinated VOCs at the U.S. Department of Energy (DOE) Savannah River “M Area” Integrated Demonstration Site in Aiken, South Carolina, using the DOE-patented In Situ Bioremediation (ISB) system (DOE 1996). The demonstration site is located within a much larger plume that is actively being treated using pump-and-treat technologies. Process wastewater containing chlorinated solvents was released from a process sewer into an unlined settling basin and nearby stream between 1954 and 1985. High concentrations of solvents were detected in soil and groundwater near the original discharge locations. TCE and tetrachloroethene (PCE) comprised 99 percent of the total contaminant mass.

Before the application of the ISB system at the demonstration site, the TCE and PCE concentrations in groundwater ranged from 10 to 1,031 micrograms per liter (μg/L) and 3 to 124 μg/L, respectively. TCE sediment concentrations ranged from 0.67 to 6.29 milligrams per kilogram (mg/kg) and 0.44 to 1.05 mg/kg, respectively. The soils at the site are relatively permeable sands with thin lenses of clayey sediments. The groundwater table is at 120 feet below grade.

A horizontal injection well with a screened length of 310 feet was placed below the water table at a depth of 175 feet. A horizontal extraction well with a screened length of 205 feet was placed in the vadose zone semiparallel to the injection well at a depth of 80 feet (see Figure 3-2 for general reference). A vacuum was initially applied at 240 scfm, and air injection was then applied at 200 scfm. Several different modes of gaseous nutrient injection were applied during the demonstration, including continuous injection of methane, pulsed injection of methane, and pulsed injection of methane plus continuous injection of nitrous oxide and triethyl phosphate to supply nitrogen and phosphate for enhanced biodegradation. Monitoring and system control were nearly completely automated.

The demonstration was operated for about 13 months from February 1992 to April 1993. During this time, 16,934 pounds of VOCs was removed or degraded. The vacuum component removed 12,096 pounds of VOCs, and the bioremediation component degraded and mineralized an additional 4,848 pounds of VOCs. Mass balance calculations indicate that 41 percent more VOCs were destroyed using methane and nutrient injection than with air sparging alone. Biostimulation was greatest with pulsed methane injection, as evidenced by increases in microbial populations with a decrease in TCE levels (Hazen and others 1994).

Overall TCE and PCE concentrations in groundwater decreased by as much as 95 percent, reaching concentrations below detectable limits (that is, less than 2 μg/L in some wells) and well below drinking water standards of 5 μg/L (Hazen and others 1994). Soil gas TCE and PCE declined by more than 99 percent. Total sediment concentrations of TCE and PCE declined from 0.100 mg/kg to nondetectable concentrations at most areas. Overall, the site was considered about 80 to 90 percent clean following the 13-month demonstration project (Tetra Tech 1996c).

3.4.1.2 Toluene Remediation at a Former Industrial Facility

A former industrial facility in Massachusetts used and stored toluene as part of a shoe adhesive manufacturing process (Envirogen, Inc. 1996). Toluene was accidentally released from site operations, and dissolved and free phase toluene were detected in vadose and saturated soils and groundwater. The soils at the site are homogeneous medium to coarse sands. The water table fluctuates seasonally from 3 to 7 feet below grade.

Following completion of pilot tests, a remedial design was developed for a 3/4-acre remedial target area. The design included 70 air sparging points and 70 SVE wells. In addition to sparging and SVE wells within the target area, the system included a defensive line of sparging and SVE wells near the site perimeter to prevent downgradient contaminant migration. The system used a total air injection rate of 100 cubic feet per minute (cfm) and a total extraction rate of 300 cfm.

The system operated between May 1993 and early 1996. Approximately 20,881 pounds of toluene-range hydrocarbons was removed in the first 23 months of operation from the bulk of the site. The system continued operating to remove contaminants from hot spots. Closure of the site was obtained in early 1996 based on the analytical results of soil, soil gas, and groundwater samples collected from the site.

3.4.1.3 Electro-Voice, Inc., Demonstration Site

Air sparging was used to perform a Superfund Innovative Technology Evaluation (SITE) demonstration at the Electro-Voice, Inc. (Electro-Voice), facility in Buchanan, Michigan (EPA 1995), using the Subsurface Volatilization and Ventilation System (SVVS®). The Electro-Voice facility actively manufactures audio equipment. The demonstration site was an open area near the facility where paint shop wastes had been discharged to the subsurface via a dry well between 1964 and 1973. During previous remedial investigation studies at the site, organic and inorganic contaminants were detected in soil and groundwater associated with the former dry well area.

Eleven vertical SVE wells and nine vertical air injection wells were installed in the treatment area. The vacuum extraction wells were installed with a 5-foot section of screen set to intersect a sludge layer found at 12 to 18 feet below grade in a clay-rich horizon. The air injection wells were installed with a 1-foot screened interval positioned approximately 10 feet beneath the 46-foot deep water table. Sand chimneys were installed to facilitate vertical air circulation in the highly stratified soils at the site. The air flow rate was maintained at about 80 percent of the vacuum flow rate. Monitoring and system control were mostly automated, with minimal operator control required.

Pretreatment data were collected from 20 boreholes randomly positioned in the treatment area, which included approximately 2,300 cubic yards (yd^3) of contaminated soil. The data indicated that a portion of the site contained target VOC concentrations near or below the detection limits; therefore, only the portion of the site at which significant contaminant concentrations were detected, referred to as the "hot zone," was selected for assessment of the performance of the SVVS® system. The hot zone included approximately 800 yd^3 of contaminated soil and encompassed four extraction wells and three sparging wells. The previously installed system was operated over the entire treatment area.

The demonstration operated from August 1992 through July 1993. The reduction in the sum of target VOC components in vadose zone soils averaged 80.6 percent over the 1-year period. This greatly exceeded the developer's claim of a 30 percent reduction. The sludge layer in which the highest pretreatment concentrations were detected was the only horizon that did not undergo almost complete remediation. The pretreatment and posttreatment concentrations of the target VOC components in vadose zone soil horizons are summarized in Table 3-4. The data for individual target VOC components are summarized in Table 3-5.

VOC contamination in saturated zone soils was reduced by 99.3 percent. Contamination was not detected in groundwater during system operation; therefore, the remedial capabilities of the SVVS® system for groundwater at the site were not assessed during the demonstration.

Operation of the SVVS® over the entire treatment area did not affect the performance of the system in the hot zone. However, installation of the system in noncontaminated soils was not an effective use of resources and emphasizes the importance of accurately defining the location and extent of contamination before implementing a remedial system.

3.4.2 Cost Analysis

The air sparging technology is applicable to sites contaminated with gasoline, diesel fuels, and other hydrocarbons, including halogenated compounds to enhance SVE. The technology can be applied to contaminated soils, sludges, free-phase hydrocarbon product, and groundwater. A number of factors could affect the estimated cost of treatment. Among them were the type and concentration of contaminants, the extent of contamination, groundwater depth, soil moisture, air permeability of the soil, site geology, geographic site location, physical site conditions, site accessibility, required support facilities and availability of utilities, and treatment goals. It is important to thoroughly and properly characterize the site before implementing this technology to insure that treatment is focused on contaminated areas. Cost analysis for two case studies are provided to understand the variability in costs in applying this technology.

3.4.2.1 Cost for Department of Energy-Patented In Situ Bioremediation System

The cost analysis for ISB is based on data provided by the Savannah River Site (SRS) VOCs in soils and groundwater at nonarid sites integrated demonstration and was performed by the Los Alamos National Laboratory. The conventional technology of pump-and-treat system combined with soil vapor extraction (PT/SVE) was used as the baseline technology against which ISB was compared. To compare the two remediation systems, a number of assumptions were made:

- PT/SVE would remove the same amount of VOCs as the vacuum component of ISB when operated for the same time period
- Four vertical SVE and four pump-and-treat wells would have the same zone of influence as two horizontal wells used for ISB
- Volatilized contaminants from both technologies 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

Capital and operating costs for ISB and PT/SVE are summarized in Table 3-6.

Capital costs for the baseline technology are comparable with the innovative technology of ISB. The cost to install horizontal wells for ISB exceeds installation costs of vertical wells. However, horizontal drilling costs are decreasing as the technology becomes more widely used and accepted. If horizontal wells can clean a site faster, operating costs will decrease significantly. Fixed equipment costs for ISB include gas mixing and injection equipment for providing the nutrients required for stimulation of the bioremediation portion of the innovative technology. The cost to biodegrade as little as 900 pounds of TCE/PCE would offset the additional bioenhancement costs (that is, methane and trace nutrient supplements and methane monitoring equipment) compared to air sparging alone (Hazen and others 1994).

The annual operating costs are comparable between the baseline and the innovative remediation technology. However, the treatment time is estimated to be 10 years to remediate the demonstration site using the baseline PT/SVE and only 3 years using ISB. Actual treatment times are estimates, and field experience indicates that the PT/SVE estimate is on the optimistic side, since the objective is the Safe Drinking Water

Act maximum of 5 μg/L for TCE/PCE. Consumable and labor costs are approximately 85 percent of the total cost per pound of the VOCs remediated for both technologies. Figure 3-4 shows the relative importance of each category on overall costs for both ISB and PT/SVE.

3.4.2.2 Cost for Subsurface Volatilization Ventilation System

The cost analysis for the SVVS® is based on assumptions and costs provided by Brown & Root Environmental, the operator of the system at the site, and on results and experiences from the SITE demonstration operated over a 1-year period at the Electro-Voice facility. The cost associated with treatment by the SVVS® process, as presented in this economic analysis, is defined by 12 cost categories that reflect typical cleanup activities performed at Superfund sites. These 12 cost categories are as follows:

- Site preparation
- Permitting and regulatory requirements
- Capital equipment (amortized over 10 years)
- Startup
- Consumables and supplies
- Labor
- Utilities
- Effluent treatment and disposal costs
- Residuals and waste shipping, handling, and storage services
- Analytical services
- Maintenance and modifications
- Demobilization

Table 3-7 shows the itemized costs for each of the 12 cost categories on a year-by-year basis for a hypothetical 3-year full-scale remediation of the Electro-Voice facility. The total cost to remediate 21,300 yd^3 of soil was estimated to be $220,737 or $10.36/$yd^3$. This figure does not include any treatment of the off-gases. If effluent treatment costs are included, it would increase costs to $385,237 or $18.09/$yd^3$.

Figure 3-3 shows the relative importance of each category on overall costs. It shows that the largest cost component without effluent treatment was site preparation (28 percent), followed by analytical services (27 percent), and residuals and waste shipping, handling, and storage (13 percent). Labor accounted for a relatively small percentage (9 percent), excluding travel, per diem, and car rental expenses. These four categories alone accounted for 77 percent of the costs. Utilities and capital equipment accounted for 6 and

8 percent respectively, and the remaining cost categories each accounted for 4 percent or less. Effluent treatment costs would have accounted for 43 percent of the total cleanup cost if it had been conducted at the Electro-Voice site. Cost figures provided here are “order-of-magnitude” estimates and are generally accurate to plus 50 percent to minus 30 percent.

3.5 VENDORS

Many companies are involved in various aspects of air sparging technology, including equipment manufacture and installation as well as the design and operation of air sparging systems. Some companies have patented air sparging techniques or process name trademarks. Vendors of air sparging technology that were identified are included in Table 3-8.

3.6 STRENGTHS AND LIMITATIONS

The following list outlines some of the strengths of using air sparging with SVE at sites contaminated with VOCs:

- Air sparging expands remediation capabilities of SVE to the saturated zone.
- In air sparging, both volatilization and biodegradation processes contribute to remediation of VOCs.
- By using air sparging, biodegradation can be potentially further enhanced by supplementing air with other gases and/or nutrients.
- Air sparging eliminates the need to remove and treat large quantities of groundwater using expensive pump-and-treat methods.
- Air sparging has been shown to be more cost effective than conventional PT/SVE.
- Air sparging effectively creates a crude air stripper in the subsurface, with the soil acting as the “packing.”
- In air sparging, the sparged air elevates the dissolved-oxygen content in the subsurface, thus enhancing natural biodegradation.
- Cycling or pulsing the air flow during air sparging can increase mixing in the saturated zone, thus increasing volatilization and biodegradation of contaminants.

The following list outlines some of the limitations of using air sparging at sites contaminated with VOCs:

- Air flow dynamics in the subsurface, and therefore the mechanisms of air sparging remediation, are not well understood.
- Limited performance data are available.
- Operational and lithological controls influence the air flow in the subsurface, thereby controlling the remediation potential of air sparging.
- A low permeability layer above the saturated zone in stratified soils can limit vertical air flow, resulting in substantial lateral migration of contaminated vapors from the sparge well.
- Excess subsurface pressure can aggravate the spread of contaminated vapors, free phase product, or dissolved contaminants and may create fractures in the sparging well annular seal or within the formation.
- The usefulness of standard monitoring practices for assessing the performance of air sparging is not clearly understood.
- As a rule of thumb, performance of air sparging decreases in less permeable soils.
- Preferential air channeling and poor air distribution are expected to increase significantly in less permeable soils and increase with soil heterogeneity.
- Clogging of the aquifer, sparging probes, or well screens due to enhanced bacterial growth or precipitation of metals under increased oxygen levels can reduce the permeability at a site.
- There is a potential for rebound of contaminant concentrations after air sparging is discontinued.

3.7 RECOMMENDATIONS

The effectiveness of air sparging for remediating contaminated sites is highly dependent on site-specific conditions. Before selecting air sparging as an enhancement to SVE, the site-specific groundwater, soil, and contaminant conditions, as well as cleanup goals and project objectives, should be assessed. Consideration of air sparging as the remedial choice should include a comparison of the cost effectiveness of air sparging to other technologies.

Air sparging is most effective at sites with homogeneous, high-permeability soils and unconfined aquifers that are contaminated with halogenated or nonhalogenated, aerobically biodegradable VOCs. Air sparging is less effective, but also has been used at sites with heterogeneous, less-permeable soils and soils containing low-permeability layers.

The methods of injecting air into the saturated zone should be compared. Air injection can be performed through vertical or horizontal wells or sparging probes. The choice is largely determined by the site geology, site location, depth to groundwater, contaminant distribution, operational considerations, and a cost comparison analysis. Vertical wells have been used to depths of 150 feet below grade. Horizontal wells can be used to greater depths and are effective at remediating contamination under buildings and in elongated plumes. Sparging probes can typically be used to depths of 40 feet below grade using direct push techniques and have been used to 100 feet below grade.

Operation of an air sparging system at a contaminated site should focus on-going monitoring and system adjustment to respond to the changing subsurface conditions. The available data are too limited to determine whether a continuous or pulsed operating strategy is best. If mass transfer limitations prove to govern air sparging system behavior, continuous operation will probably be the preferred option. Should the pulsing of the air injection flow rate enhance mixing in the subsurface, a properly timed pulsed operation could deliver enhanced performance.

3.8 REFERENCES

This section includes references cited in Chapter 3.0. A comprehensive bibliography is provided in Appendix B.

Baker, Ralph S., R. Pemmireddy, and D. McKay. 1996. Evaluation of Air-Entry Pressure During In Situ Air Sparging: A Potentially Rapid Method of Feasibility Assessment. Proceeding of the First International Symposium on In-Situ Air Sparging. Las Vegas, Nevada. October 24-25, 1996.

Billings, and Associates, Inc. 1996a. Project Description for Firehouse Site. Available on World Wide Web. July 28.

Billings and Associates, Inc. 1996b. Project Description for BF1 Site. Available on World Wide Web. July 28.

Billings and Associates, Inc. 1996c. Project Description for Bloomfield Site. Available on World Wide Web. July 29.

Billings, J.F., A.I. Cooley, and G.K. Billings. 1994. Microbial and Carbon Dioxide Aspects of Operating Air-Sparging Sites. Air Sparging for Site Remediation, ed. Robert E. Hinchee. Lewis Publishers. Ann Arbor, Michigan. Pages 112-119.

Brown, R.A., R.J. Hicks, and P.M. Hicks. 1994. Use of Air Sparging for In Situ Remediation. Air Sparging for Site Remediation, ed. Robert E. Hinchee. Lewis Publishers. Ann Arbor, Michigan. Pages 38-55.

Clark, T.R, R.E. Chaudet, and R.L. Johnson. 1995. Assessing UST Corrective Action Technologies: Lessons Learned about *In Situ* Air Sparging at the Dennison Avenue Site, Cleveland, Ohio. U.S. Environmental Protection Agency Project Summary. EPA/600/SR-95/040. March. Risk Reduction Engineering Laboratory. Cincinnati, Ohio.

Envirogen, Inc. 1996. Project Summary: Former Industrial Facility Remediation, Massachusetts for Confidential Chemical Company. October 1992 to June 1996.

Hazen, T.C., K.H. Lombard, B.B. Looney, M.V. Enzien, J.M. Dougherty, C.B. Fliermans, J. Wear, and C.A. Eddy-Dilek. 1994. Summary of In-Situ Bioremediation Demonstration (Methane Biostimulation) via Horizontal Wells at the Savannah River Site Integrated Demonstration Project. In-Situ Remediation: Scientific Basis for Current and Future Technologies, Thirty-Third Hanford Symposium on Health and the Environment. Battelle Press. November 7 through 11, 1994.

Hinchee, Robert E. 1994. Air Sparging State of the Art. Air Sparging for Site Remediation, ed. Robert E. Hinchee. Lewis Publishers. Ann Arbor, Michigan. Pages 1-13.

Johnson, R.L. 1994. Enhancing Biodegradation with In Situ Air Sparging: A Conceptual Model. Air Sparging for Site Remediation, ed. Robert E. Hinchee. Lewis Publishers. Ann Arbor, Michigan. Pages 14-22.

Loden, Mary E. 1992. A Technology Assessment of Soil Vapor Extraction and Air Sparging. Prepared for the U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory. Cincinnati, Ohio. April.

Lundegard, Paul D., D. La Brecque. 1996. Integrated Geophysical and Hydrologic Monitoring of Air Sparging Flow Behavior. Proceedings of the First International Symposium on In-Situ Air Sparging. Las Vegas, Nevada. October 24-25, 1996.

Marley, Michael C. 1995**.** Unpublished. The State of the Art in Air Sparging Technology.

Tetra Tech EM Inc. (Tetra Tech). 1996a. Personal Communication between Dawn Cosgrove of Tetra Tech and Rick Billings of Billings and Associates, Inc. August 22.

Tetra Tech. 1996b. Personal Communication between Dawn Cosgrove of Tetra Tech and Dr. Gale Billings of Billings and Associates, Inc. July 18.

Tetra Tech. 1996c. Personal Communication between Dawn Cosgrove of Tetra Tech and Brian Looney of Westinghouse Savannah River Company. August 23.

Tetra Tech. 1996d. Personal Communication between Dawn Cosgrove of Tetra Tech and Donald Justice of Horizontal Technologies, Inc. July 19.

Tetra Tech. 1996e. Personal Communication between Dawn Cosgrove of Tetra Tech and Dom DiGuilo of the U.S. Environmental Protection Agency, National Risk Management Research Laboratory, Subsurface Protection and Remediation Division. August 23.

Tetra Tech. 1996f. Personal Communication between Dawn Cosgrove of Tetra Tech and Alla Werner of Envirogen, Inc. August 29.

Tetra Tech. 1997. Personal Communication between Dawn Cosgrove of Tetra Tech and Dave Becker of the U.S. Army Corps of Engineers. May 7.

Terra Vac Corporation. 1995a. Project Description for Underground Storage Tanks-Irvine, California. July 23.

Terra Vac Corporation. 1995b. Project Description for Fabricated Metal Products-New Paris, Indiana. May 5.

Terra Vac, Inc. 1995c. Project Summary: Gasoline Service Station - Fremont, California. May 5.

U.S. Army Corps of Engineers. 1995. Soil Vapor Extraction and Bioventing Engineering and Design. EM1110-1-4001. November 30.

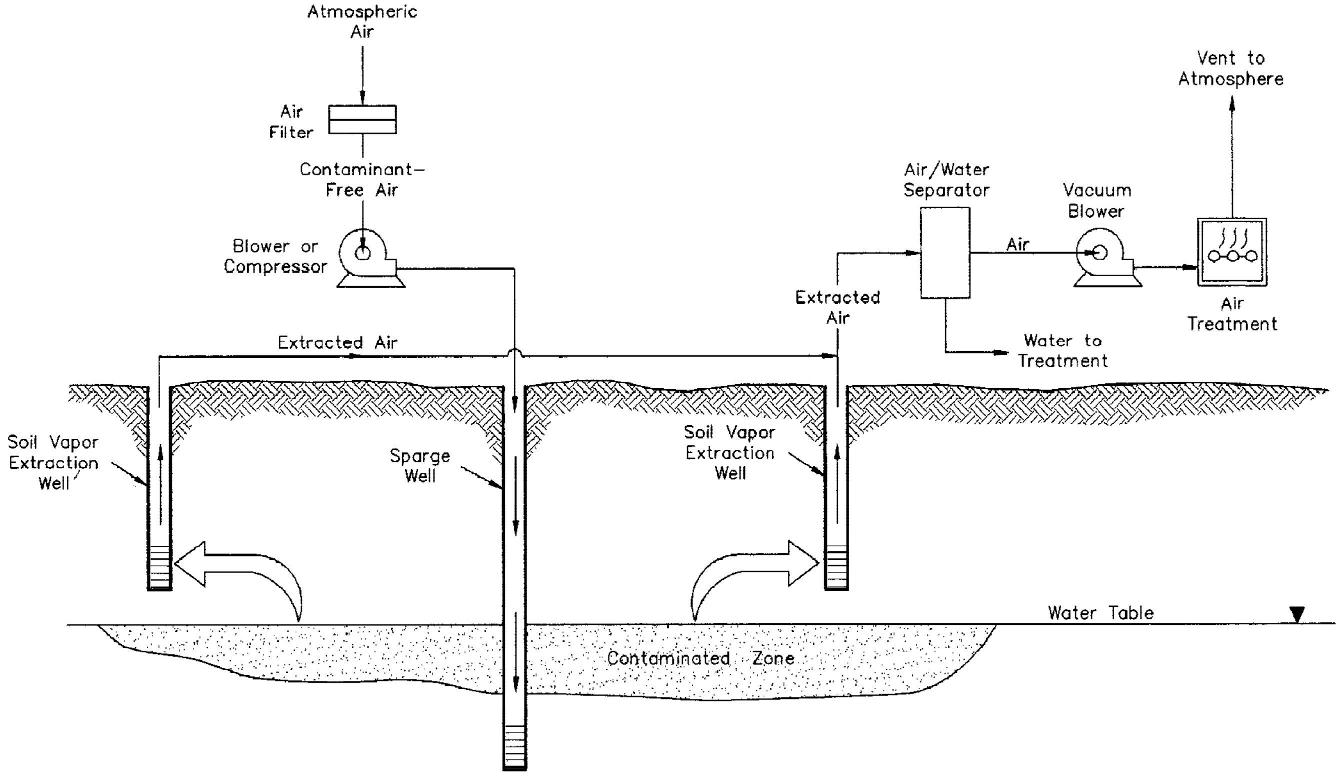
U.S. Department of Energy. 1996. Innovative Technology Summary, In Situ Bioremediation Using Horizontal Wells, U.S. Department of Energy Savannah River M Area Process Sewer Integrated Demonstration Site, Aiken, South Carolina. Available on the World Wide Web. June 27.

U.S. Environmental Protection Agency. 1995. Subsurface Volatilization Ventilation System (SVVS)®, Innovative Technology Evaluation Report. Office of Research and Development. Washington, D.C. EPA/540/R-94/529. August.

Wisconsin Department of Natural Resources (WDNR). 1993. Guidance for Design, Installation, and Operation of In Situ Air Sparging Systems. September.

WDNR. 1995. Errata Sheet for the Guidance for Design, Installation, and Operation of In Situ Air Sparging Systems, dated September 1993. August 11.

FIGURE 3-1
TYPICAL AIR SPARGING ENHANCEMENT TO SOIL VAPOR EXTRACTION SYSTEM

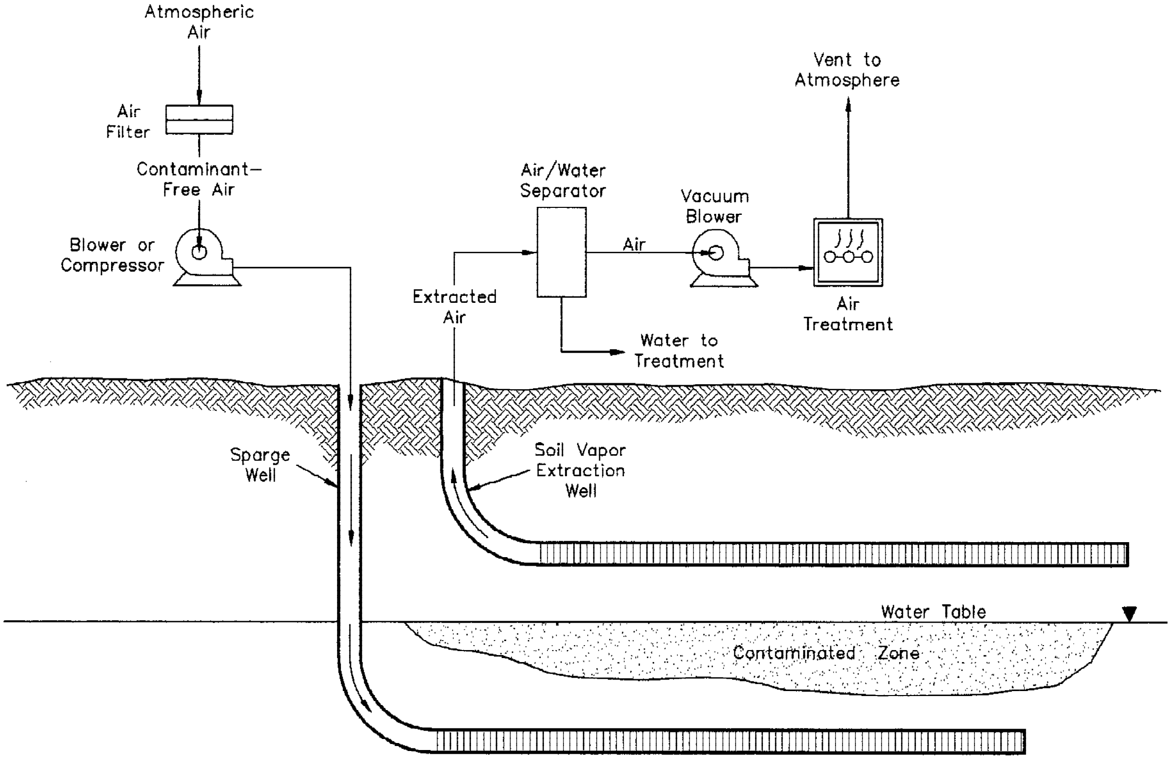


SOURCE: MODIFIED FROM U.S. ARMY CORPS OF ENGINEERS 1995

TYPICAL AIR SPARGING ENHANCEMENT
TO SOIL VAPOR EXTRACTION SYSTEM

FIGURE
3-1

FIGURE 3-2
HORIZONTAL AIR SPARGING AND SOIL VAPOR EXTRACTION WELL SYSTEM

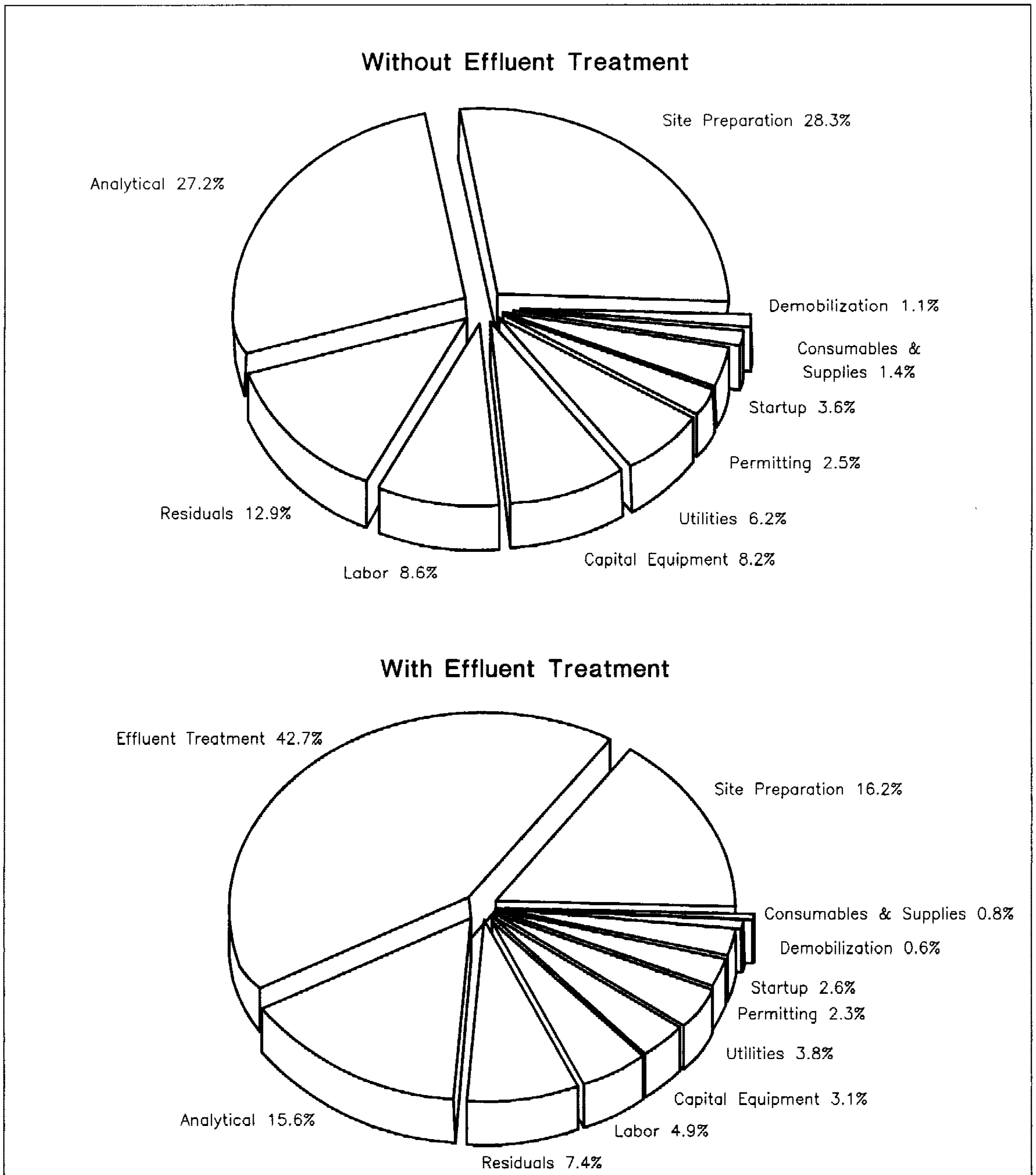


SOURCE: MODIFIED FROM U.S. ARMY CORPS OF ENGINEERS 1995

HORIZONTAL AIR SPARGING AND SOIL VAPOR EXTRACTION WELL SYSTEM

FIGURE
3-2

FIGURE 3-3
3-YEAR REMEDIATION COST BREAKDOWN


Without Effluent Treatment

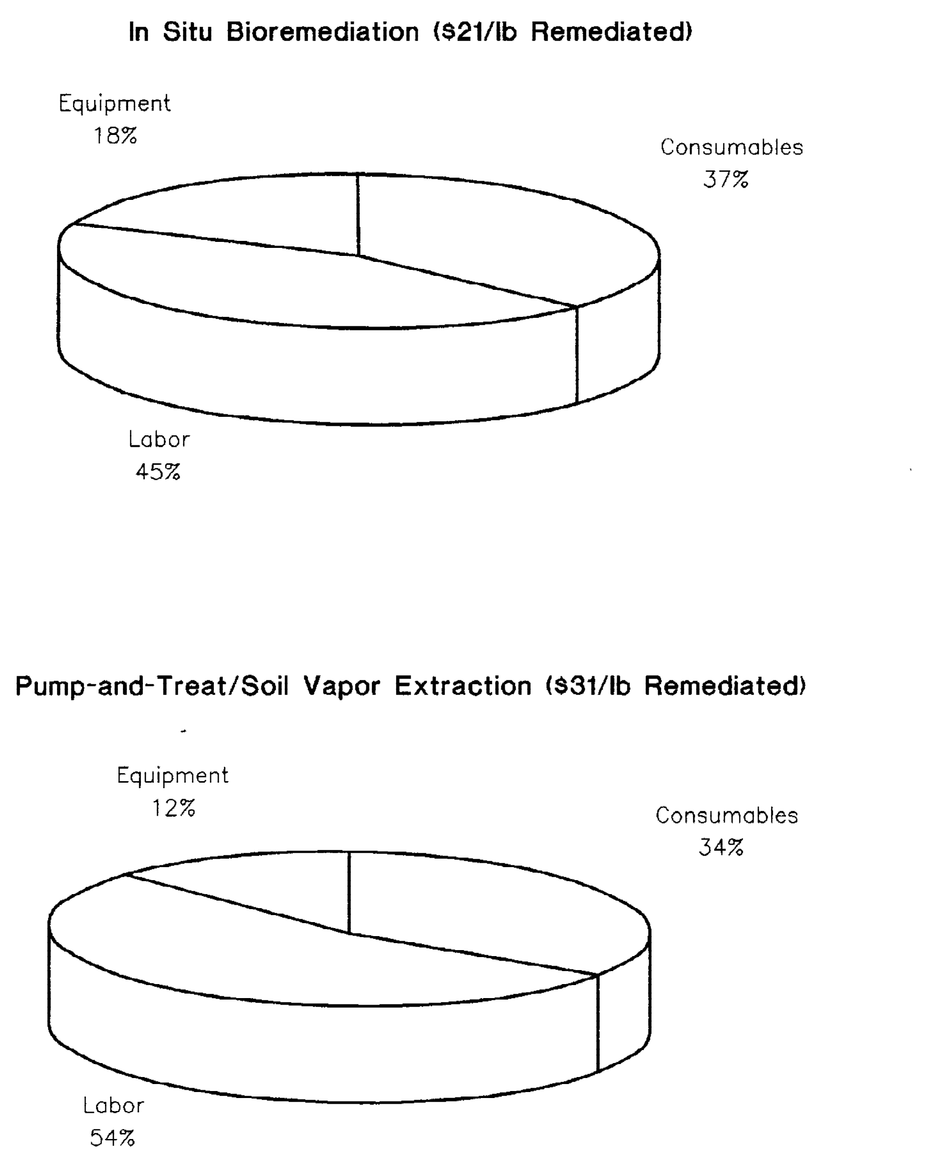
With Effluent Treatment

SOURCE: MODIFIED FROM EPA 1995

3-YEAR REMEDIATION COST BREAKDOWN

FIGURE
3-3

FIGURE 3-4
REMEDIATION COST BREAKDOWN FOR IN SITU BIOREMEDIATION AND PUMP-AND-TREAT/SOIL VAPOR EXTRACTION



In Situ Bioremediation ($21/lb Remediated)

Pump-and-Treat/Soil Vapor Extraction ($31/lb Remediated)

SOURCE: MODIFIED FROM DOE 1996

REMEDIATION COST BREAKDOWN FOR IN SITU BOREMEDIATION AND PUMP-AND-TREAT/SOIL VAPOR EXTRACTION

FIGURE
3-4

TABLE 3-1

AIR SPARGING SYSTEM CHARACTERISTICS

Topic	Description
Geological Applicability	• Ideal site: homogeneous, high-permeability soils and unconfined aquifers • Average site: moderately heterogeneous soils with minimal low-permeability layers
Contaminant Applicability	• Volatile organic compounds that are aerobically biodegradable • None or thin layer of free-phase product
System Components	• Vertical or horizontal extraction and injection wells or sparging probes • Manifold, valves, and instrumentation • Air compressor or blower • Properly designed SVE system
Monitoring Parameters	• Dissolved oxygen and contaminant concentrations in groundwater • Oxygen, carbon dioxide, and contaminant concentrations in SVE off-gas or soil vapor • Microbial populations and activity • Air flow and extraction rates • Air pressure measurements • Water levels • Tracer gas mapping of air flow in subsurface
Cleanup Capabilities	• Capable of achieving maximum contaminant levels for volatile constituents in groundwater • Estimated cleanup time is 1 to 4 years[a]
Costs	• $15 to $120 per cubic yard[b]

Notes:

a Range of estimated cleanup times is based on case studies. Actual cleanup time depends on many factors, including site-specific contaminant, geologic conditions, and cleanup goals.

b The range of cost per cubic yard is based on case studies and vendor claims and estimates. The total actual cost to remediate a site is highly dependent on site-specific contaminant and geologic conditions as well as cleanup goals. The cost range includes capital, operation, and maintenance costs. Note that these costs are based on estimates of in situ volumes.

SVE soil vapor extraction

TABLE 3-2

FACTORS AFFECTING APPLICABILITY OF AIR SPARGING

Factor	Parameter	Desired Range or Conditions
Contaminant	Volatility	High (K_H >1 x 10^{-5} atm-m^3/mole)
	Solubility	Low (<20,000 mg/L)
	Biodegradability	High (BOD_5 >0.01 mg/L)
	Presence of free product	None or thin layer
Geology	Soil type	Coarse-grained soils
	Heterogeneity	No impervious layers above sparge interval Permeability increases towards grade if layering present
	Permeability in the saturated zone[a]	>1 x 10^{-5} cm^2 if horizontal:vertical is <2:1 >1 x 10^{-4} cm^2 if horizontal:vertical is >3:1
	Hydraulic conductivity	>1 x 10^{-3} cm/s[b]
	Depth to groundwater[c]	>5 feet
	Aquifer type	Unconfined
	Saturated thickness	5 to 30 feet

Sources: Modified from Brown and others 1994, Loden 1992, Wisconsin Department of Natural Resources 1995

Notes:

a	From Loden 1992.
b	From Brown and others 1994.
c	From Wisconsin Department of Natural Resources 1995
d	One practitioner has used air sparging on sites with permeabilities as low as 1 x 10^{-12} cm^2 (Tetra Tech EM Inc. 1996f).
e	One practitioner claims to have cleaned site with hydraulic conductivities as low as 1 x 10^{-6} cm/s (EPA 1995).
f	Although air sparging is most suited to shallow aquifers, it has been effective in aquifers 150 feet below grade (Loden 1992).

cm	centimeters
cm/s	centimeters per second
BOD	biological oxygen demand
K_H	Henry’s Law coefficient
atm-m^3	atmosphere-cubic meter
mg/L	milligrams per liter

TABLE 3-3

SUMMARY OF PUBLISHED INFORMATION ON AIR SPARGING SITES
(Page 1 of 3)

Site	Citation	Soil Type	Contaminants	Cleanup Time[a] (months)	Initial Groundwater Concentration (mg/L)	Final Groundwater Concentration (mg/L)
Isleta	Ardito & Billings 1990	Alluvial sands, silts, clays	Leaded gasoline	2	MW-1, -3, -5 BTEX: 4, 18, 25	MW-1, -3, -5 BTEX: 0.25, 8, 6
Conservancy	Billings 1990	Silty sand Interfacing clay layer	Gasoline	5	Benzene: 3 to 6	59% average benzene reduction after 5 months
Buddy Beene	Billings 1991	Clay	Gasoline	2	—	8.5% reduction/month
Bernalillo	Billings 1990	—	Gasoline	17	—	BTEX and MTBE: <5.5
Los Chavez	Billings 1990	Clay	Gasoline	9	—	40% benzene, xylenes reduction, 60% toluene reduction, 30% ethylbenzene reduction
Arenal	Billings 1990	—	Gasoline	10	Benzene: >30	Benzene: <5
BF1	Billings and Associates, Inc. 1996b	NR	Fuel	12	Benzene: 22,000 to 32,000	Benzene: 29 to 50
Bloomfield	Billings and Associates, Inc. 1996c	NR	Fuel	48	NR	BTEX below cleanup standards
Firehouse	Billings and Associates, Inc. 1996a	NR	Fuel	30	Benzene: 400 to 600	Benzene: 0.5 to 4
Dry Cleaning Facility	Brown 1991	Coarse sand Natural clay barrier	PCE, TCE, DCE, TPH	4	Total VOCs: 41	Total VOCs: 0.897
Savannah River	U.S. Department of Energy 1996	Sands, thin clay lenses	TCE, PCE	13	TCE: 10 to 1,031 PCE: 3 to 124	TCE: <5 PCE: <5

TABLE 3-3

SUMMARY OF PUBLISHED INFORMATION ON AIR SPARGING SITES
(Page 2 of 3)

Site	Citation	Soil Type	Contaminants	Cleanup Time[a] (months)	Initial Groundwater Concentration (mg/L)	Final Groundwater Concentration (mg/L)
Former Industrial Facility	Envirogen, Inc. 1996	Sands	Toluene	23	NR	NR
Electro-Voice	EPA 1995	NR	VOC	12	NM[b]	NM[b]
Berlin	Harress 1989	Sand, silty lenses Aquitard-clay	c-1,2-DCE, TCE, PCE	24	c-1,2-DCE: >2	c-1,2-DCE: >0.440
Bielefeld, Nordrhein -Westfalen	Harress 1989	Fill, sand, silt Aquitard-siltstone	PCE, TCE, TCA	11	PCE: 27; TCE: 4.3; TCA: 0.7	Total VOCs: 1.207
Munich, Bavaria	Harress 1989	Fill, gravel, sand Aquitard-clayey silt	PCE, TCE, TCA	4	PCE: 2.2; TCE: 0.4; TCA: 0.15	PCE: 0.539; TCE: 0.012; TCA: 0.002
Nordrhein, Westfalen	Harress 1989	Clayey silt, sand Aquitard-siltstone	Halogenated hydrocarbons	4 6	Location A THH: 1.5 to 4.5 Location B THH: 10 to 12	Location A THH: 0.010 Location B THH: 0.200
Bergisches Land	Harress 1989	Fractured limestone	Halogenated hydrocarbons	15	THH: 80	THH: 0.4
Pluderhausen, Baden - Wurtternburg	Harress 1989	Fill, silt, gravel Aquitard-clay	TCE	2	1.20	0.23
Mannhelm - Kaesfertal	Herrling 1991	Sand	PCE, chlorinated hydrocarbons	—	—	—
Gasoline service station	Kresge 1991	Sand and silt	Gasoline	24	Total BTEX: 6 to 24	Total BTEX: 0.380 to 7.6
Savannah River	Looney 1991	Sand, silt, and clay	TCE, PCE	3	TCE: 0.5 to 1.81 PCE: 0.085 to 0.184	TCE: 0.010 to 1.031 PCE: 0.003 to 0.124
Gasoline service station	Marley 1990	Fine-coarse sand, gravel	Gasoline	3	Total BTEX: 21	Total BTEX: <1
Solvent spill	Middleton 1990	Quaternary sand and gravel	TCE, PCE	3	Total VOCs: 33	Total VOCs: 0.27

TABLE 3-3

SUMMARY OF PUBLISHED INFORMATION ON AIR SPARGING SITES
(Page 3 of 3)

Site	Citation	Soil Type	Contaminants	Cleanup Time[a] (months)	Initial Groundwater Concentration (mg/L)	Final Groundwater Concentration (mg/L)
Solvent leak at degreasing facility	Middleton 1990	Fill, sandy and clayey silts	TCE	2	0.200-12	<0.010-0.023
Chemical manufacturer	Middleton 1990	Sandy gravel Aquitard-clay	Halogenated hydrocarbons	9	THH: 1.9 to 5.417	THH: 0.185 to 0.320
Truck distribution facility	MWR 1990	Sands	Gasoline & diesel fuel	Ongoing	Total BTEX: 30	—
Irvine	Terra Vac, Inc. 1995a	Clays, sandy silts, clayey sands and silts, gravel	Gasoline	9	NR	below cleanup standards
New Paris	Terra Vac, Inc. 1995b	Sand with some gravel, clay layers	PCE, TCE	18	PCE: 250	PCE: 9

Notes:

a Cleanup times represent the time interval between initial and final groundwater concentration reported in the table. Actual remediation time may be longer.
b Demonstration assessed remediation capabilities for vadose zone soils only.

BTEX	Benzene, toluene, ethylbenzene, and xylenes
DCE	Dichloroethene
EPA	U.S. Environmental Protection Agency
MTBE	Methyl tert-butyl ether
MW	Monitoring well
NM	Not measured
NR	Not reported
PCE	Tetrachloroethene
TCA	Trichloroethane
TCE	Trichloroethene
THH	Total halogenated hydrocarbons
TPH	Total petroleum hydrocarbons
VOC	Volatile organic compounds

TABLE 3-4

PERFORMANCE OF SUBSURFACE VOLATILIZATION VENTILATION SYSTEM FOR REDUCTION IN TARGET CONSTITUENTS IN SOIL HORIZONS IN THE VADOSE ZONE AT THE ELECTRO-VOICE, INC., DEMONSTRATION SITE

Treatment Horizon[b]	**Critical VOC Concentration (mg/kg)**[a]		**Percent Reduction**
	Pretreatment Sampling	**Posttreatment Sampling**	
Upper horizon	321.77	0.74	99.77
Sludge layer	1,661.03	307.69	81.48
Lower horizon A1	96.42	0.98	98.99
Lower horizon A2	37.68	0.42	98.99
Lower horizon B	13.57	0.30	97.79

Source: Modified from U.S. Environmental Protection Agency 1995

Notes:

a	Sum of benzene, toluene, ethylbenzene, xylenes, 1,1-dichloroethene, trichloroethene, and tetrachloroethene
b	The hot zone was delineated into horizons based on lithology and contaminant levels.

VOC	Volatile organic compound
mg/kg	milligrams per kilogram

TABLE 3-5

PERFORMANCE OF SUBSURFACE VOLATILIZATION VENTILATION SYSTEM FOR REDUCTION IN INDIVIDUAL TARGET CONSTITUENTS IN THE VADOSE ZONE AT ELECTRO-VOICE, INC., DEMONSTRATION SITE

Target Constituents	Sum of the Weighted Mean Concentration (mg/kg)		Percent Reduction
	Pretreatment Sampling	Posttreatment Sampling	
Benzene	0.01	0.00	NC
Toluene	92.84	14.42	84.47
Ethylbenzene	37.41	6.06	83.81
Xylenes	205.50	45.28	77.97
1,1-Dichloroethene	0.01	0.00	NC
Trichloroethene	0.36	0.00	NC
Tetrachloroethene	5.37	0.44	91.81

Source: Modified from U.S. Environmental Protection Agency 1995

Notes:

mg/kg	Milligrams per kilogram
NC	Not calculated; a meaningful percent reduction cannot be provided because of low pretreatment concentrations.

TABLE 3-6

SUMMARY OF COST DATA FOR *IN SITU* BIOREMEDIATION AS WELL AS PUMP-AND-TREAT WITH SOIL VAPOR EXTRACTION

Costs	**ISB ($)**	**PT/SVE($)**
Capital		
Site Cost	5,400	7,500
Equipment Cost	9,200	32,000
Design and Engineering	10,000	10,000
Mobile Equipment	18,000	18,000
Well Installation	183,000	50,690
Other Fixed Equipment	183,732	168,665
Mobilization Cost	43,075	64,613
Total Capital Equipment and Mobilization Costs	452,407	341,468
Cost per Pound of Contaminant	21	31
Operation and Maintenance		
Monitoring/Maintenance	71,175	71,175
Consumable Cost	122,215	123,595
Demobilization Costs	43,075	64,613
Total Operational and Maintenance Costs	$236,465	$259,383

Notes:

ISB	In situ bioremediation (includes vacuum extraction; see Section 3.4.1)
PT/SVE	Pump-and-treat system combined with soil vapor extraction

TABLE 3-7

ESTIMATED COST FOR TREATMENT USING THE SUBSURFACE VOLATILIZATION VENTILATION SYSTEM PROCESS OVER A 3-YEAR APPLICATION

Cost Category	First Year	Second Year	Third Year
1. Site Preparation			
Well Drilling & Preparation	$32,500	—	—
Building Enclosure (10' by 15')	$10,000	—	—
Utility Connections	$5,000	—	—
System Installation	$15,000	—	—
Total Costs	$62,500	—	—
2. Permitting & Regulatory Requirements	$10,000	—	—
3. Capital Equipment (amortized over 10 years)			
Vacuum Pump	$450	$450	$450
Blower	$450	$450	$450
Plumbing	$3,333	$3,333	$3,334
Building Heater	$333	$333	$334
Total Costs	$4,566	$4,566	$4,568
4. Startup	$7,957	—	—
5. Consumables			
Health and Safety Gear	$1,000	$1,000	$1,000
6. Labor	$6,300	$6,300	$6,300
7. Utilities			
Electricity (Blower and Pump)	$3,900	$3,900	$3,900
Electricity (Heater)	$660	$660	$660
Total Costs	$4,560	$4,560	$4,560
8. Effluent Treatment and Disposal Costs	N/A	N/A	N/A
9. Residuals and Waste Shipping and Handling			
Contaminated Drill Cuttings	$12,500	—	$6,000
Contaminated Personal Protective Equipment	$6,000	$1,000	$3,000
Total Costs	$18,500	$1,000	$9,000
10. Analytical Services	$20,000	$20,000	$20,000
11. Maintenance and Modifications	N/A	N/A	N/A
12. Demobilization	—	—	$2,500
TOTAL ANNUAL COSTS	$135,383	$37,426	$47,928
TOTAL REMEDIATION COSTS	$220,737		

Source: Modified from Department of Energy 1996

Notes: N/A Not available

— Not applicable

TABLE 3-8

VENDORS OF AIR SPARGING TECHNOLOGIES[a]

Name of Vendor[a]	Address and Phone Number	Point of Contact
Billings and Associates, Inc.	3816 Academy Parkway N-NE Albuquerque, New Mexico 87109 (505) 345-1116	Rick Billings
Terra Vac, Inc.	1555 Williams Drive, Suite 102 Marietta, Georgia 30066-6282 (770) 421-8008	Charles Pineo
Envirogen, Inc.	480 Neponset Street Canton, Massachusetts 02021 (617) 821-5560	Alla Werner
IT Corporation	2925 Briar Park Houston, Texas 77042 (713) 784-2800	John Mastroianni
Quaternary Investigations, Inc.	300 West Olive Street, Suite A Colton, California 92324 (800) 423-0740	Tony Morgon
Horizontal Technologies, Inc.	2309 Hancock Bridge Parkway (33990) P.O. Box 150820 Cape Coral, Florida 33915-0820	Donald Justice
Groundwater Control, Inc.	754 Harrison Avenue Jacksonville, Florida 32220 (800) 843-6133	Jeff Haluch
KVA Analytical Systems	281 Main Street, Box 574 Falmouth, Massachusetts 02541 (508) 540-0561	Steve Leffert
H2 Oil	P.O. Box 9028 Bend, Oregon 97708-9028 (541) 382-7070	Troy York

Note: a This list is not inclusive of all vendors capable of providing air sparging technologies. This list reflects vendors contacted during the preparation of this report.

CHAPTER 4.0

DUAL-PHASE EXTRACTION

DPE technologies involve removal of contaminated groundwater and soil vapors from a common extraction well under vacuum conditions. DPE provides a means to accelerate removal of nonaqueous phase liquid (NAPL) and dissolved groundwater contamination, remediate capillary fringe and smear zone soils, and facilitate removal of vadose zone soil contaminants. When applied to sites with soil, groundwater, and free-phase product contamination, DPE is often referred to as multi-phase extraction (MPE) or total fluids extraction.

The following sections provide a brief overview of the technology, discuss the applicability of DPE to various contaminant types and site characteristics, describe engineering aspects of DPE, examine performance and costs of typical DPE systems, provide a list of vendors that have designed and installed full-scale systems, outline strengths and limitations of DPE technology, and provide recommendations for using DPE. Cited figures and tables appear at the end of the chapter.

4.1 TECHNOLOGY OVERVIEW

DPE involves concurrent extraction of groundwater and soil vapors from a common borehole. DPE enables venting of soil vapors through previously saturated and semisaturated (capillary fringe) soils by lowering the groundwater table at the point of vapor extraction. High vacuums typically associated with DPE systems enhance both soil vapor and groundwater recovery rates. Water extraction rate increases of up to tenfold over conventional downhole pump systems have been reported.

Three basic types of DPE have been developed. Differentiation among the types is based on methods used for extraction of each medium. Following is a brief description of each type:

- <u>Drop-tube entrainment extraction</u>. Extraction of total fluids (liquid and soil vapors) via vacuum applied to a tube inserted in the extraction well. Groundwater and soil vapors are removed from the extraction well in a common pipe manifold, separated in a gas/liquid separator, and treated.
- <u>Well-screen entrainment extraction</u>. Extraction of groundwater and soil vapors from a common borehole screened in the saturated and vadose zones. Groundwater is aspirated into the vapor

stream at the well screen, transported to the treatment system in a common pipe manifold, separated in a gas/liquid separator, and treated.

- <u>Downhole-pump extraction.</u> Extraction of groundwater using a downhole pump with concurrent application of vacuum to the extraction well. Groundwater and soil vapors are removed in separate pipe manifolds and treated.

Variations to each type of DPE have been developed to enhance overall system performance. Ultimately, the type of DPE most suitable to any site is dictated by soil hydraulic and pneumatic properties, contaminant characteristics and distribution, and site-specific remediation goals. Relative costs for the different types are also largely determined by these factors.

4.2 APPLICABILITY

DPE is applicable to sites with the following characteristics:

- VOC contamination
- Soil, groundwater, and free-product contaminant phases
- Low to moderate hydraulic conductivity soils

The following subsections address contaminant properties and phases as well as soil characteristics for which DPE is most effective.

4.2.1 Contaminant Properties

DPE is most effective for remediation of volatile contaminants, such as those typically targeted by SVE systems. Contaminant types commonly treated using DPE include chlorinated and nonchlorinated solvents and degreasers and petroleum hydrocarbons.

Vapor pressure is a commonly used indicator of volatility. Compounds with vapor pressures exceeding 1 mm Hg are generally considered suitable for application of DPE. Another important indicator of volatility is Henry's Law constant, which indicates the extent to which a compound will volatilize when dissolved in water. Because much of the contamination in a soil matrix is dissolved in pore water, the

Henry's Law constant is an indicator of how readily dissolved vadose zone contaminants will volatilize by a vapor extraction system.

Less volatile petroleum hydrocarbons may also be treated by DPE. Introduction of oxygen into the subsurface during the vapor extraction process stimulates aerobic biodegradation of nonchlorinated (and some chlorinated) hydrocarbon compounds and can promote in situ remediation of soil contaminants that would not typically be volatilized and removed by the extraction system. Biological processes have been shown to play a significant role in remediation of petroleum hydrocarbons at sites employing DPE (Roth and others 1995).

4.2.2 Contaminant Phases

DPE systems can be implemented to target all phases of contamination associated with a typical NAPL spill site. These systems remove residual vadose zone soil contamination residing in soil gas, dissolved in soil pore-space moisture, and adsorbed to soil particles. DPE also effectively removes dissolved and free-phase (both light and dense NAPL [LNAPL and DNAPL]) contamination in groundwater.

Remediation capabilities of DPE in the vadose zone are similar to those of SVE. Because it uses in-well groundwater extraction, however, higher vacuums can typically be applied at DPE sites without concerns related to groundwater upwelling. As a result, DPE may also accelerate volatilization and removal of vadose zone contaminants over traditional SVE.

DPE can be implemented for remediation of the capillary fringe and smear zone. VOC concentrations are typically highest in capillary fringe soils because of the tendency of LNAPL to accumulate at the water table. Changes in water level move any accumulation of free product on the surface of the water table and create a smear zone of residual contamination. SVE systems are typically ineffective at volatilizing contaminants in the capillary fringe and smear zone because of their high water content and low effective air-filled porosity of these soils. In addition, water table upwelling at the point of extraction in an SVE system can submerge residual contamination and prevent removal by the vapor extraction system.

Dewatering from the extraction well itself not only counters upwelling effects but results in a cone of groundwater depression. A cone of depression allows soil vapor flow induced by the extraction well vacuum to desiccate previously saturated and partially saturated soils in the capillary fringe and smear zone. As a result of exposure to soil vapor flow, capillary fringe and smear zone contamination can be volatilized and removed by the extraction system. DPE can also expedite removal of saturated soil contaminants in the dewatered zone. VOCs with limited water solubility and high affinity for soil carbon can be more effectively removed by exposure to soil venting and volatilization than by desorption and recovery in a groundwater extraction system.

DPE can accelerate treatment of dissolved groundwater contamination and free-phase product. Groundwater and free product recovery rates are enhanced by the additive effects of hydraulic and pneumatic gradients generated by concurrent extraction of groundwater and soil vapors from the extraction well. Thus, more rapid removal and treatment of contaminants is possible. Vacuum also tends to counteract capillary forces holding LNAPL in soil pore spaces, enabling recovery of free-phase product that would not otherwise be extractable (Baker and Bierschenk 1995).

4.2.3 Soil Characteristics

DPE is most effectively implemented in areas with saturated soils exhibiting moderate to low hydraulic conductivity (silty sands, silts, and clayey silts). Lower permeability soils enable formation of deeper water table cones of depression, exposing more saturated soils and residual contamination to extraction system vapor flow.

DPE systems installed in soils with higher hydraulic conductivities generally require higher equipment and operating costs for effective implementation due to higher water extraction rates and the resulting treatment and disposal requirements. The more broad, shallow cones of depression formed in permeable soils may not adequately expose capillary fringe soils to soil venting. Thus, soils remaining below the water table may act as a continued source of groundwater contamination until the slower process of desorption and removal by groundwater extraction is complete.

As with conventional groundwater extraction systems, depth of saturated soils to a confining medium affects the ability of a DPE system to capture and remediate a groundwater plume.

4.3 ENGINEERING DESCRIPTION

Implementation of DPE involves construction of extraction wells (or modification of existing monitoring wells) and installation of extraction and treatment equipment. Figure 4-1 presents a schematic of a typical DPE system. Generally, the technology required for design and construction of a DPE system is well established and is largely based on experience gained from implementation of separate SVE and groundwater extraction systems. Specific design factors related to the method of DPE employed ultimately determine the physical as well as operating characteristics of the system and influence its ability to achieve site-specific remediation goals. The following subsections discuss general DPE system design and describe characteristics of the three types of DPE systems.

4.3.1 Dual-Phase Extraction System Design

DPE system design considerations include extraction well construction, anticipated vapor and water flow rates, vapor/liquid separation requirements, and vapor and liquid treatment requirements. Site characteristics, including soil pneumatic and hydraulic conductivities, contaminant vertical and horizontal distributions, potential groundwater treatment and discharge requirements, and the presence of existing monitoring or extraction facilities, largely determine which type of DPE will meet remedial design objectives most effectively.

4.3.1.1 Pilot Testing

Well placement and extraction system capacity and design are usually based on the results of pilot testing. Pilot test activities focus on both water and vapor extraction characteristics. Frequently, aquifer hydraulic properties are determined by aquifer step testing followed by pump testing. A conventional vapor extraction test may also be conducted to determine soil vapor flow characteristics and vadose zone of influence. DPE pilot testing is then conducted to determine both step and steady-state characteristics of the extraction system. Parameters that may be monitored during testing include the following:

- Induced vacuum versus distance
- Water drawdown versus distance

- Wellhead vacuum
- Vapor extraction rates
- Groundwater extraction rates
- Vapor hydrocarbon content
- Extracted groundwater quality

Following the pilot test, additional monitoring may be conducted to assess the rate at which system characteristics return to equilibrium.

Analysis of vapor extraction data obtained during pilot testing is similar to that for SVE pilot testing. Parameters related to groundwater extraction, such as extraction flow rate and water table drawdown, are also analyzed. Groundwater modeling data may be used to determine required well spacing. To address varying soil characteristics across a site, full-scale systems may be designed, built, and operated in a phased approach to capitalize on operating data obtained from wells installed during earlier phases (Tetra Tech 1996a).

Smaller full-scale systems may be designed using available physical and theoretical data to avoid incurring costs associated with pilot testing. Typically, when a pilot test is not conducted, both well spacing and extraction equipment are conservatively sized to ensure that the system will perform at expectations or better.

4.3.1.2 Extraction Well Design

Generally, DPE wells are designed with screened intervals above and below the groundwater table at the location of greatest contamination. Selected screen depths must consider the hydrogeology and extent of dewatering required. The lower portion of the extraction well screen and filter pack are generally sized using guidelines for groundwater extraction (WDNR 1993) to prevent entrainment of fines into the extraction system. Well diameter is based on site-specific design factors similar to those for SVE and on requirements of the type of DPE employed; the diameter must be large enough to accommodate any downhole apparatus associated with extraction system requirements. Existing monitoring wells with sufficient diameter and adequate design characteristics (appropriately-sized screen slots) can be converted for use as extraction wells. Downhole pump systems generally require larger diameter wells than either well-screen or drop-tube entrainment systems.

Full-scale DPE systems have been installed to approximately 100 feet below ground surface (bgs). Specific limits on well installation depth have not been reported.

Extraction well spacing is determined by results of pilot testing and by remedial objectives. For sites with dissolved-phase contamination, well spacing is largely based on the groundwater capture radius, or the distance from a well where drawdown is sufficient to overcome the regional water table gradient (Hackenberg and others 1993). Extraction well spacing must provide for adequate dewatering of the contaminated area. Well spacing in areas with free product is generally based on the product capture zone of influence (Tetra Tech 1996b) or the distance from the well where the slope of the free water surface approaches zero. (LNAPL will theoretically not flow toward the well beyond this distance [Hackenberg and others 1993].) For highly contaminated vadose zone source areas, well spacing may be based on an SVE design zone of influence. The SVE design zone of influence is generally more conservative than the actual zone of influence obtained during pilot testing and is selected to achieve accelerated remediation of vadose zone soils.

High vacuums associated with DPE systems may promote short circuiting of air flow at the wellhead from ground surface, particularly in shallow formations. This problem can be circumvented by use of a surface seal. Surface seals are typically constructed by placing an impermeable liner over the extraction area.

4.3.1.3 Extraction Equipment Design

Typical components of the extraction system include an extraction blower, vapor/liquid separator, vapor phase treatment, and liquid phase treatment. Design of extraction system equipment is generally based on desired extraction vacuum, anticipated vapor and groundwater extraction rates, and anticipated vapor and groundwater concentrations and compositions.

The vapor extraction rate from each extraction well is dictated by local soil pneumatic characteristics, well design and screen length, and applied system vacuum. Overall vapor extraction system capacity is frequently determined by multiplying the vapor extraction rate for a single well (as determined through pilot testing or software modeling) by the total number of wells to be installed.

The groundwater extraction rate is affected by water drawdown within the well itself and soil hydraulic characteristics as well as the applied system vacuum. Lowering the water table at the well creates a hydraulic gradient, which induces groundwater (and free product, if any) flow into the well. Vacuum applied at the point of water extraction introduces an additional pneumatic gradient, which can enhance the overall rate of groundwater and free product recovery.

The system groundwater treatment capacity is generally determined by multiplying the groundwater extraction rate for a single well by the total number of wells to be installed. Data from additional aquifer testing or existing operating extraction wells within the treatment system area may also be incorporated into assessment of system groundwater treatment capacity requirements.

The free water surface in the vicinity of a DPE well is a combination of the cone of depression resulting from groundwater extraction and the upwelling caused by vacuum extraction. The shape of the free water surface is critical at sites requiring remediation of capillary fringe soils. Vapor and groundwater extraction rates must be balanced to ensure that the free water surface elevation at any distance from the well does not rise above static water levels as a result of excessive vapor extraction system influence (Hackenberg and others 1993).

Vacuum requirements largely dictate the type of vacuum blower or pump incorporated into the extraction system. Applied DPE vacuums can range up to 28 inches of mercury (approximately 32 feet of water). Types of vacuum pumps commonly used at DPE sites include liquid ring pumps, rotary lobe compressors, and regenerative blowers. Vacuum pumps are selected based on desired operating characteristics (inlet flow rate and achievable vacuum) and desired efficiency. Lower vacuums tend to be associated with downhole pump type systems, which are more common at sites with higher yielding aquifers. High vacuums are more common at sites using well-screen entrainment and drop tube entrainment.

Vapor/liquid separation is generally accomplished upstream of the vacuum blower or pump but can be accomplished downstream of a liquid ring vacuum pump, which can use extracted water as seal fluid if generated in sufficient quantities. Use of extracted water for seal fluid generally requires close monitoring to prevent overheating and failure of the vacuum pump. Placement of the air/water separator upstream of the vacuum pump prevents carryover of silts or sediments into the pump. For sites with floating product, an oil/water separator may also be required.

Vapor and liquid treatment processes are designed to conform with air emission and water discharge requirements. Common vapor treatment technologies used at DPE sites include carbon adsorption and thermal or catalytic oxidation. Water is often treated using air stripping and/or liquid granular activated carbon (GAC) adsorption, as required.

Extraction system materials of construction are determined based on contaminant types and concentrations and on economic factors. Commonly used materials of construction include stainless steel, PVC, and HDPE.

4.3.1.4 System Monitoring

Parameters monitored during full-scale DPE system operation typically include vapor, groundwater, and product recovery rates; system and wellhead vacuums; extracted vapor and groundwater contaminant concentrations; and other parameters required of the vapor and water treatment systems. At sites with aerobically biodegradable hydrocarbons, extracted vapors may also be monitored for parameters related to in situ bioactivity, such as methane, carbon dioxide and oxygen. In situ respiration tests may also be conducted to assess the extent of bioremediation occurring.

4.3.2 Dual-Phase Extraction System Characteristics

This subsection discusses design and operating features of each type of DPE and the unique benefits and drawbacks of each type of system.

4.3.2.1 Drop-Tube Entrainment Extraction

Drop-tube entrainment DPE systems are constructed by inserting a suction tube into the sealed wellhead of an extraction well. As vacuum is applied to the suction tube, soil vapor entering from the unsaturated soils entrains groundwater at the tube tip. Soil vapor and entrained groundwater are transported in a common extraction manifold piping system to an air/water separator, from which vapors are routed to a treatment system. Groundwater drawn off the separator is treated (if necessary) before discharge. A schematic of a drop-tube entrainment extraction well is presented in Figure 4-2.

During startup of an extraction system incorporating drop tubes, it may be necessary to prime the extraction well with air to induce vapor flow through the drop tube if well depth exceeds the applied vacuum (expressed in feet of water). Priming involves the introduction with air into the bottom of the drop tube when it is below the water level in the well to create an air-lifting effect. Self-priming drop-tube designs have been developed to enable automatic priming of the system upon startup. One patented drop-tube design incorporates single or multiple perforations, which enable vapor flow to reduce fluid column density in the well, thus allowing air lift of water from depths greater than the applied vacuum (expressed in feet of water) (Tetra Tech 1996b). Another method involves insertion of an air-bleed tube exposed to atmospheric or compressed air inside the drop tube (Hackenberg and others 1993). Manual priming can be conducted by slowly lowering the drop tube into the extraction well, entraining water at the water level interface until the well is dewatered to design-tube extraction depth.

As the extraction area is dewatered during operation of a drop-tube type system, increases in saturated zone thickness and soil vapor flow are accompanied by a decrease in manifold vacuum at the vapor/liquid separator. As a result, unbalanced conditions may occur in which vacuum at some extraction wells drops below that required to entrain water. Water column buildup in these wells may cut off vapor flow and result in short circuiting. Rebalancing of system vacuums may be necessary to restore vapor flow to all extraction wells.

Liquid and vapor removal in drop-tube type systems is limited by pressure loss through the drop tube. Wellhead vacuum may be reduced by as much as 30 to 50 percent through the suction tube (Brown and others 1994). The ability of a drop-tube system to air lift groundwater from a given depth is a function of applied wellhead vacuum in the annulus between the drop tube and well screen, the air and groundwater flow rates, and the inner diameter of the drop tube (Stenning and Martin 1968).

Drop-tube type systems are generally inefficient for high flow rate groundwater removal and are more effective in soils with low hydraulic conductivity and low groundwater yield. Generally, extraction well yields of 5 gallons per minute (gpm) or less are considered suitable for entrainment extraction. Within a range of approximately 5 to 20 gpm, use of entrainment extraction may be appropriate based on site-specific factors and design goals. At higher water extraction rates, vacuum pump energy requirements increase, and downhole-pump systems may be more appropriate.

During the extraction process, contaminant mass transfer occurs from the liquid to the vapor phase because high system vacuum, high vapor/liquid ratio, and turbulence in the suction tube and extraction piping manifold. This "stripping" action results in reduced extracted groundwater contaminant concentrations and enables more efficient vapor-phase treatment of the contaminants. Groundwater treatment requirements may be reduced or potentially eliminated. Reported stripping efficiencies of approximately 90 percent are common.

Use of a drop-tube type system minimizes DPE equipment as well as instrumentation and controls requirements. A common blower extracts water and vapors; thus, no downhole pump is necessary for groundwater removal. Only one piping manifold is required to transport the extracted media to the treatment system. Existing monitoring wells can be converted to drop-tube type wells.

Removal of free product using a drop-tube entrainment extraction system may be complicated by poor water quality or high hardness content. Emulsification of free product and water can occur in the air/water separator discharge pump or in the vacuum pump if they are situated upstream of the vapor/liquid separator (Tetra Tech 1996b). Hard water can also cause scaling in extraction system piping and equipment.

Several patents apply to various aspects of drop-tube type entrainment extraction, some of which may have overlapping features. Patent holders include Xerox Corporation, International Technologies Corporation, and James Malot of Terra Vac Incorporated.

4.3.2.2 Well-Screen Entrainment

In well-screen entrainment DPE systems, vacuum is applied to a well screened in the vadose and saturated zones. Vapor flow aspirates groundwater at the well screen for entrainment of groundwater. Generally, small diameter wells (2 inch or less) are most effective for this type of DPE (Brown and others 1994), although 4-inch well screens can be used (Tetra Tech 1996c).

For systems in which well depth exceeds applied vacuum (expressed in feet of water), priming may be necessary to induce vapor flow on startup. Priming is achieved by inserting a tube into the extraction well below the water surface to introduce air flow into the well. Reduced fluid column density resulting from introduction of air enables two-phase flow from the well. Groundwater and soil vapors are extracted in the annular space between the primer tube and well casing. After the well is primed, vapor flow from the formation provides the air lift necessary to entrain water in the extracted stream. Low permeability soils may require continued use of a primer to maintain two-phase flow. System hydraulics may facilitate the use of ambient air for priming or may dictate the use of an air compressor to initiate air flow.

Injection of air into the well enhances formation of liquid droplets, which become entrained in the extracted soil vapor. Priming may also be used to enhance mass transfer of DNAPLs by injecting air near the confining layer (EPA 1994). Well-screen entrainment systems benefit from the stripping action of high-extraction vacuum and turbulence in the extraction well and manifold piping. Similar to drop-tube type extraction, water contaminant reductions of approximately 90 percent have been reported.

This type of DPE is the simplest to implement; however, it may have limited effectiveness for water removal from deep wells. Extraction-well entrainment is most effective at sites with shallow groundwater (less than 10 feet bgs) (Brown and others 1994), but it has been used to depths of approximately 27 feet (Tetra Tech 1996c).

Advantages of extraction-well entrainment include simplicity of design and construction. Because a common blower removes both soil vapor and groundwater, downhole pumps and associated controls and instrumentation are not necessary. Systems that do not incorporate continuous priming require only one piping manifold (for extraction). Systems incorporating priming, however, do require installation of an additional piping manifold as well as use of a compressor for air injection.

Clogging of the well screen can decrease extraction effectiveness (Brown and others 1994). Entrainment of silts and solids may occur in wells that are screened too coarsely or do not have properly sized or graded gravel pack. Systems incorporating existing monitoring wells often require regular maintenance to remove accumulated fines from collection points, primarily the air/water separator.

Patents apply to various aspects of well screen entrainment extraction. Patent holders include Xerox Corporation and Dames & Moore Incorporated.

4.3.2.3 Downhole-Pump Extraction

DPE systems incorporating downhole pumps are constructed by lowering a submersible pump into each extraction well and applying vacuum to the sealed wells. Dual-pipe manifolds are constructed for vapor and water removal. A schematic of a downhole-pump extraction well is presented in Figure 4-3.

Operation of the downhole pump is usually based on extraction well water level. Single speed pumps are used to maintain water levels between high and low targets. Variable-speed drive pumps can be set to match groundwater yield and maintain constant water level in the well or can be set to match treatment system capacity. Capital costs for variable-speed drive pumps and associated controls/instrumentation are higher than for single-speed pumps.

Use of downhole pumps is more efficient than entrainment extraction for removal of groundwater (Brown and others 1994). Generally, downhole-pump systems are installed in soils with higher hydraulic conductivities or wells yielding greater than 15 to 20 gpm. For moderate well yields of approximately 5 to 15 gpm, other factors, including design and remedial action objectives and water discharge limitations, may determine whether a downhole-pump system or one of the types of entrainment extraction is used. Downhole-pump extraction may be more effective than entrainment extraction for systems requiring deep well installation.

Downhole-pump systems do not benefit from the stripping action associated with entrainment extraction systems. Groundwater treatment requirements are therefore similar to those expected from conventional pump and treat systems.

4.4 PERFORMANCE AND COST ANALYSIS

The following subsections discuss the performance and cost of five example DPE systems.

4.4.1 Performance

DPE has been implemented at a variety of sites contaminated with gasoline-range petroleum hydrocarbons and VOCs. The following case studies describe the design and performance of five full-scale DPE systems. Three of the case studies involve drop-tube entrainment type systems, one involves well-screen entrainment, and one involves downhole-pump extraction.

4.4.1.1 Underground Storage Tank Release from a Gasoline Station in Houston, Texas

Vacuum enhanced pumping (VEP), a form of drop-tube entrainment extraction, was implemented for remediation of a groundwater contaminant plume at a gasoline station (Mastroianni and others 1994). The VEP system design incorporated a self-priming drop tube in each extraction well and included nine extraction wells, a vacuum blower, a vapor/liquid separator, and an oil separation and water treatment system. Vapor treatment was accomplished using a thermal oxidation system equipped with auto dilution. The vacuum blower was operated at approximately 300 scfm at 12 inches of mercury.

Site soils were overlain by asphalt as well as concrete and consisted of clay to a depth of approximately 16 feet, becoming silty below 13 feet and interbedded silts and sands between 16 and 25 feet. Silty clay extended between 25 and at least 27 feet below grade. Contamination of concern consisted of a groundwater benzene, toluene, ethylbenzene, and xylene (BTEX) plume and an associated free-product plume. The aerial extent of the groundwater plume was approximately 50,000 square feet. BTEX concentrations in a majority of the plume exceeded 30 milligrams per liter (mg/L). The maximum free product thickness was approximately 3 feet.

The system used both new and existing monitoring wells for extraction. The wells were installed to depths of approximately 30 feet with spacings generally between 30 and 50 feet. Initially, recovery and treatment operations for soil vapor, LNAPL, and groundwater were conducted from one extraction well to avoid overloading treatment capacity of the thermal oxidizer used for vapor treatment. As the hydrocarbon content of the process stream from the initial extraction well decreased, additional extraction wells were brought on line. All wells were brought on line within the first 500 hours of system operation.

After 7,000 hours (approximately 290 days) of operation, two small BTEX plumes with concentrations below 2 and 5 mg/L remained. Free product had been completely removed. Cumulative contaminant mass removed from the site was approximately 36,000 pounds (approximately 5,400 gallons). Approximately 1.62 million gallons of groundwater were removed and treated. Following system shutdown, monitoring was conducted at the site until its closure in 1996.

Remediation goals of the system were 50 mg/L TPH, 1 mg/L total BTEX, and 0.5 mg/L benzene.

4.4.1.2 Underground Storage Tank Release from a Former Car Rental Lot in Los Angeles, California

A drop-tube entrainment system was installed to remediate hydrocarbon contamination resulting from leaking underground storage tanks (UST) at a former car rental lot (Trowbridge and Ott 1991). The extraction well network initially consisted of 29 extraction wells incorporating drop tubes, but was later expanded twice to a total of 46 wells to address migration of the contaminant plume. The treatment system consisted of a vapor/liquid separator, vacuum blowers, and catalytic oxidation for vapor treatment. The vacuum blowers were capable of a combined flow of 1,000 scfm at an inlet vacuum of 15 inches of mercury. Water from the separator was treated using liquid-phase GAC. Photographs 4-1, 4-2, and 4-3 (provided courtesy of Terra Vac Incorporated) show an extraction wellhead and the extraction treatment system for this site.

Site soils consisted of brown silty clay to approximately 50 feet bgs. A perched groundwater table was present at depths of approximately 25 to 30 feet bgs. Gasoline-range hydrocarbon contamination at the site ranged in depth from 10 to 35 feet below the surface and covered an area of approximately 280 feet by 450 feet. The highest contaminant concentration detected was 1,400 mg/kg, with an average concentration of 100 mg/kg. Monitoring wells at the site contained up to 3 feet of floating product.

Extraction wells were typically screened from approximately 20 to 35 feet bgs, although some screens extended up to 10 feet bgs, and others extended down to 50 feet bgs. Well spacing was approximately 40 feet, with closer spacings used in areas with higher contaminant concentrations. An average of 20 scfm was obtained from each well at a wellhead vacuum of 10 inches of mercury. After 10 weeks of operation, measured groundwater levels were an average of 5 feet lower than before operations began.

During the 28 weeks of system operation, more than 17,000 pounds of contaminant was removed (2,600 gallons of gasoline equivalent), and 89,000 gallons of groundwater had been extracted and treated. Seventy-five percent of soil samples collected contained nondetectable levels of benzene, and detections in the remaining samples were approximately 0.17 mg/kg. Confirmatory groundwater samples collected from three wells contained nondetectable levels of BTEX and total volatile hydrocarbons. Site closure was obtained in 1991.

4.4.1.3 Release From An Electronics Manufacturing Facility In Texas

A drop-tube entrainment system was installed to remediate VOC contamination at the site of a closed surface impoundment at an electronics facility (GSI 1997). The extraction well network consists of 14 wells incorporating drop tubes. The wells were installed to 25 feet below ground surface and are spaced approximately 20 feet apart. The extraction system includes an air-cooled rotary lobe blower, a liquid/vapor separator, a centrifugal silt removal unit, a groundwater transfer pump, a scale inhibitor addition system, and piping and accessories necessary to form a connection to existing treatment plant facilities. The system vacuum blower was operated at approximately 20 scfm at 20 inches of mercury.

Soils at the site consist of four principle strata. The uppermost unit is a sandy, silty clay with an approximate thickness of 10 to 15 feet (Unit I). Underlying the uppermost unit is a 5 to 8 foot thick layer of silty, clayey, fine sand (Unit II), followed by a 10 to 12 foot layer of sandy, silty, stiff, laminated clay (Unit III). Beneath the upper three layers is a fossiliferous, silty shale. Groundwater in the vicinity of the site occurs within the silty layer (Unit II). At most well locations, the static water level is at a depth of approximately 10 feet below grade. The hydraulic conductivity of the saturated silty sand unit averages approximately 6.1×10^{-5} cm/sec. At the start of system operation, the affected groundwater plume ranged in depth from 15 to 22 feet and extended over an approximate area of 205,000 square feet. The plume contained a maximum concentration of 225 mg/L of chlorinated solvents. Contaminants of concern included phenol (5.83 mg/L), 1,2-dichloroethane (118 mg/L), methylene chloride (88 mg/L), trichloroethylene (8.44 mg/L), and BTEX (0.074 mg/L benzene, 0.305 mg/L toluene, 0.018 mg/L ethylbenzene, and 2.95 mg/L xylene, respectively).

Operation of the system is ongoing; performance information is not available at this time. Remediation goals include <0.001 mg/L (phenol), 0.003 mg/L (1,2-dichloroethane), <0.005 mg/L (methylene chloride, toluene, ethyl benzene, and xylene), and 0.005 mg/L (trichloroethylene and benzene).

4.4.1.4 Underground Storage Tank Release from a Gasoline Station in Indiana

Two-phase vacuum extraction, a form of well-screen entrainment extraction, was implemented to remediate contamination resulting from UST leakage at a gasoline station (Lindhult and others 1995). A soil VOC plume was detected during an environmental audit at a nearby shopping mall. Subsequent investigations revealed that two groundwater plumes were associated with the soil contamination and that one of the plumes had migrated off site from the gasoline station.

The extraction system included a vapor/liquid separator, a vacuum blower, and vapor and water treatment. Five extraction wells were initially installed at depths of approximately 25 feet, and two wells were installed subsequently to address additional areas of contamination. The extraction wells were screened in the vadose and saturated zones. Vacuum of approximately 23 inches of mercury was applied directly to the wells for removal of vapor and groundwater.

Site soils consisted of fairly uniform clays. Results of a soil gas survey indicated that a significant portion of site soils contained VOCs at concentrations exceeding 1,000 mg/kg, and two areas contained concentrations exceeding 10,000 mg/kg. Two groundwater BTEX plumes were associated with the soil contamination: one with maximum BTEX concentrations exceeding 1,000 μg/L and one with maximum BTEX concentrations exceeding 16,000 μg/L. A thin layer of free product was found in one monitoring well.

After several weeks of operation, the thin layer of free product in the monitoring well disappeared. During the initial 142 days of operation, BTEX removal efficiencies in the recovery wells ranged from 93 to greater than 99 percent. After 407 days of operation, total BTEX concentrations in all recovery wells decreased by greater than 97 percent, except for one, which was at 88 percent. Periodic increases in concentrations in the monitoring well were attributed to potential capture of pockets of groundwater that had migrated past the recovery wells. At the time of reporting, the system had reduced BTEX concentrations to below the alternate cleanup criteria of 250 μg/L benzene and 1,000 μg/L total BTEX for on site wells, and 150 and 500 μg/L for benzene and total BTEX, respectively, for off-site wells. Approximately 2,500 pounds of contaminant (334 gallons as gasoline) and 1,051,700 gallons of groundwater were removed and treated.

Water discharged from the system vapor/liquid separator contained total BTEX concentrations ranging from 7 to 1,300 μg/L. Discharge criteria to a publicly owned treatment works was 3,000 μg/L.

4.4.1.5 Release from a Gasoline Underground Storage Tank for a Vehicle Fueling Station at a Hospital in Madison, Wisconsin

A downhole-pump extraction system was implemented for remediation of gasoline contamination resulting from leaking USTs at a hospital (Miller and Gan 1995). The system consisted of one 6-inch diameter vertical extraction well screened from 5 to 30 feet bgs with a 3-foot sump at the bottom to trap sediment. Vapors were extracted from the well using a blower operated at 30 cfm at a vacuum of 40 inches of water column. Contaminated groundwater was recovered using a submersible centrifugal pump with a design flow rate of 10 gallons per minute (gpm) and treated by an air stripper before discharge to an on-site storm sewer.

Site soils consisted of sandy fill from ground surface to 10 to 19 feet bgs. The fill was underlain by a 3- to 4-foot layer of organic silt and peat. Depth to groundwater was approximately 13 to 20 feet.

The system began operation in June 1994. Approximately 8,500,000 gallons of groundwater and 120 pounds of contaminant were removed during the first 1.5 years of operation. Groundwater benzene concentrations dropped from 276 μg/L to 8 μg/L after 6 months of operation and to 2 μg/L after 1.5 years of operation.

The system was shut down in January 1996. Benzene concentrations at the extraction well were found to fluctuate around the cleanup standard of 5 μg/L and had risen to 8 μg/L approximately 6 months after shutdown. The concentration increase was attributed to the presence of residual contamination in the capillary fringe. In spite of a 10 gpm pumping rate from the well, drawdown 5 feet from the recovery well was less than 1 foot. Future plans for the site include increasing the groundwater extraction rate to 20 gpm to enhance dewatering of the capillary fringe.

4.4.2 Cost Analysis

Costs for implementing a DPE system are highly variable and depend on site-specific factors including site soil characteristics, nature and extent of the contaminant plume, and vapor and liquid treatment and discharge requirements.

Table 4-1 presents cost data available for these four case studies. Figure 4-4 relates the cost per pound of contaminant removed and cost per gallon of groundwater removed/treated for Case Study 1.

4.5 VENDORS

DPE systems are often similar to SVE systems in construction and operation, and do not generally employ uniquely developed and manufactured equipment items (beyond patented items such as self-priming drop tubes). Further, consultants without patents related to DPE can design, install, and operate DPE systems contingent upon payment of applicable licensing fees or royalties. Therefore, in addition to patent holders, DPE vendors include companies with experience in design, installation, and operation of DPE systems. Table 4-2 presents a list of such vendors, including identified patent holders who were contacted during preparation of this report.

4.6 STRENGTHS AND LIMITATIONS

The following list outlines the primary strengths of DPE for remediation of sites contaminated with VOCs:

- Increases water extraction rates in low permeability settings
- Increases the vapor extraction zone of influence
- Addresses smear zone and saturated soil contamination
- Enhances removal of free-phase and residual NAPL
- Potentially reduces ex situ groundwater treatment by in-well stripping in entrainment extraction wells
- Potentially eliminates the need for downhole pumps and associated controls and instrumentation through the use of entrainment extraction

The following list outlines the primary limitations of DPE for remediation of sites contaminated with VOCs:

- Less cost-effective for permeable soil types
- Operating costs may be high depending upon blower horsepower requirements and groundwater treatment requirements
- Short-circuiting of airflow from the surface may limit effectiveness

4.7 RECOMMENDATIONS

DPE capitalizes on synergistic effects produced by simultaneous lowering of the groundwater table and increasing extraction well vacuum. Use of DPE for remediation of contaminated sites is most advantageous for sites contaminated with volatile compounds and with moderate to low hydraulic conductivity soils. The presence of existing monitoring wells in strategic locations may provide an opportunity for minimizing system capital costs through conversion of the wells for extraction. DPE can be a cost effective method of rapidly remediating both soil and groundwater contaminated with VOCs. This technology provides for the remediation of the vadose zone, capillary fringe, smear zone, and existing water table by extracting both water and air through the same borehole.

Before a DPE system is implemented, efforts should be undertaken to assess groundwater and soil characteristics and project objectives to determine which type of DPE is appropriate for the site. Any patents that may apply to the technology should be thoroughly researched, and, if necessary, the appropriate licensing and fees should be assessed and included in the project cost estimate.

4.8 REFERENCES

This section includes a list of references cited in Chapter 4. A comprehensive bibliography is provided in Appendix B.

Baker, Ralph S., and J. Bierschenk. 1995. Vacuum-Enhanced Recovery of Water and NAPL: Concept and Field Test. Journal of Soil Contamination. 4(1):57-76.

Brown, Richard A., R.J. Falotico, and D.M. Peterson. 1994. Dual Phase Vacuum Extraction Systems for Groundwater Treatment: Design and Utilization. Superfund XV Conference and Exhibition Proceedings.

Groundwater Service, Inc. (GSI). 1997. Summary of Representative Project Experience. May.

Hackenberg, T.N., J.J. Mastroianni, C.E. Blanchard, J.G. Morse. 1993. Analysis Methods and Design of Vacuum Enhanced Pumping Systems to Optimize Accelerated Site Cleanup.

Kruseman, G.P., and N.A. de Ridder. 1991. Analysis and Evaluation of Pumping Test Data. ILRI, Wageningen, The Netherlands. 1991. Second Edition.

Lindhult, Eric C., J.M. Tarsavage, and K.A. Foukaris. 1995. Remediation in Clay using Two-Phase Vacuum Extraction. National Conference on Innovative Technologies for site Remediation and Hazardous Waste Management Proceedings.

Mastroianni, J., C. Blanchard, T. Hackenberg, and J. Morse. 1994. Equipment Design Considerations and Case Histories for Accelerated Clean-up Using Vacuum Enhanced Pumping.

Miller, Anthony W., and D. R. Gan. 1995. Soil and Groundwater Remediation Using Dual-Phase Extraction Technology. Superfund 16 Conference and Exhibition Proceedings.

Tetra Tech EM Inc. (Tetra Tech). 1996a. Personal Communication Between Ronna Ungs of Tetra Tech and James Malot of Terra Vac Corporation. August 14.

Tetra Tech. 1996b. Personal Communication Between Ronna Ungs of Tetra Tech and John Mastroianni of IT Corporation. August 27.

Tetra Tech. 1996c. Personal Communication Between Ronna Ungs of Tetra Tech and Dan Guest of Smith Environmental Technologies Corporation. August 30.

Roth, Robert, P. Bianco, M. Rizzo, N. Pressly, and B. Frumer. 1995. Phase I Remediation of Jet Fuel Contaminated Soil and Groundwater at JFK International Airport Using Dual-Phase Extraction and Bioventing. Superfund 16 Conference and Exhibition Proceedings.

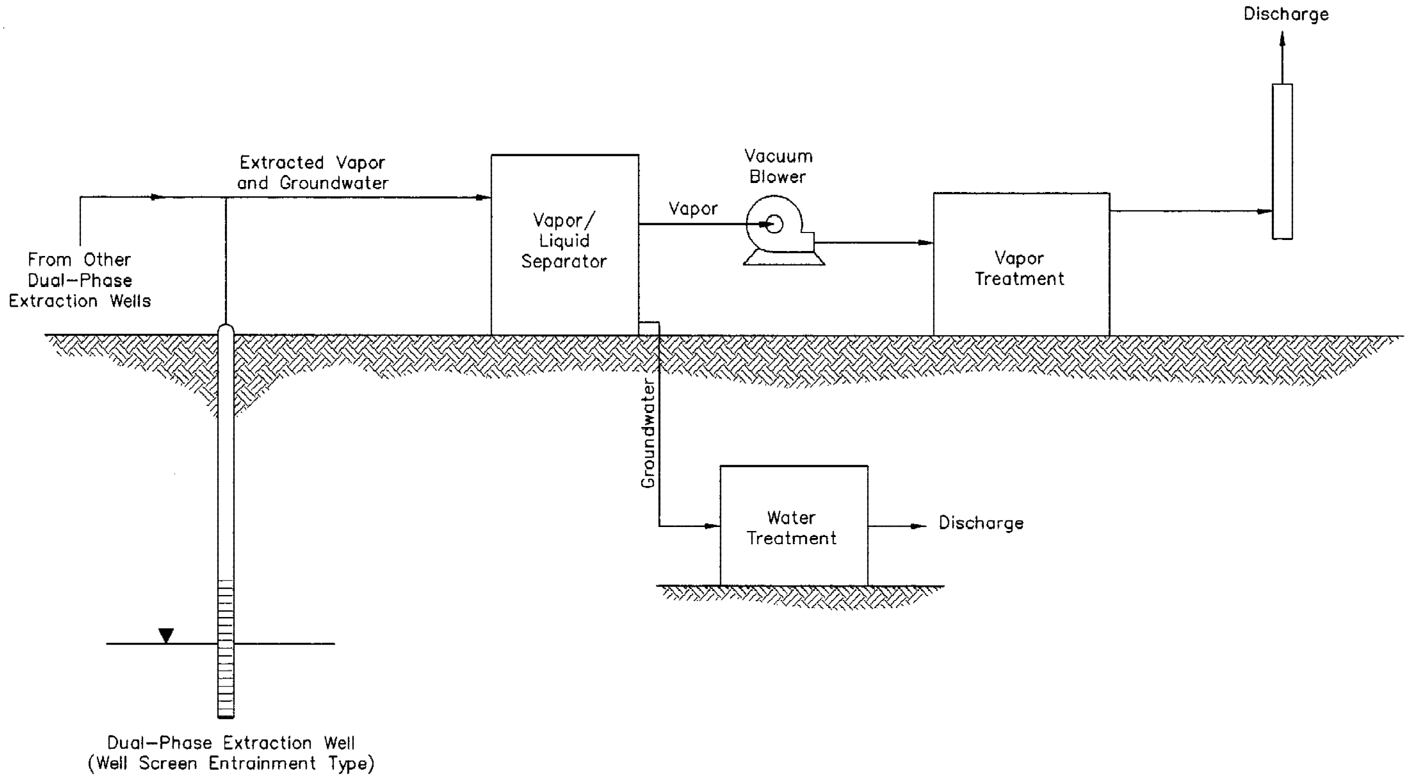
Stenning, A.H., and C.B. Martin. 1968. An Analytical and Experimental Study of Air-Lift Pump Performance. Transactions of the ASME Journal of Engineering for Power. April. Pages 106-110.

Trowbridge, Bretton E., and D.E. Ott. 1991. The Use of In-Situ Dual Extraction for Remediation of Soil and Groundwater. National Groundwater Association and National Water Well Association.

U.S. Environmental Protection Agency (EPA). 1994. Vendor Information System for Innovative Treatment Technologies (VISITT), Version 4.0. Database Prepared by Office of Solid Waste and Emergency Response, Technology Innovation Office. Cincinnati, Ohio.

Wisconsin Department of Natural Resources. 1993. Guidance for Design, Installation, and Operation of Soil Venting Systems. PUBL-SW185-93. July.

FIGURE 4-1
SCHEMATIC OF A DUAL-PHASE EXTRACTION SYSTEM

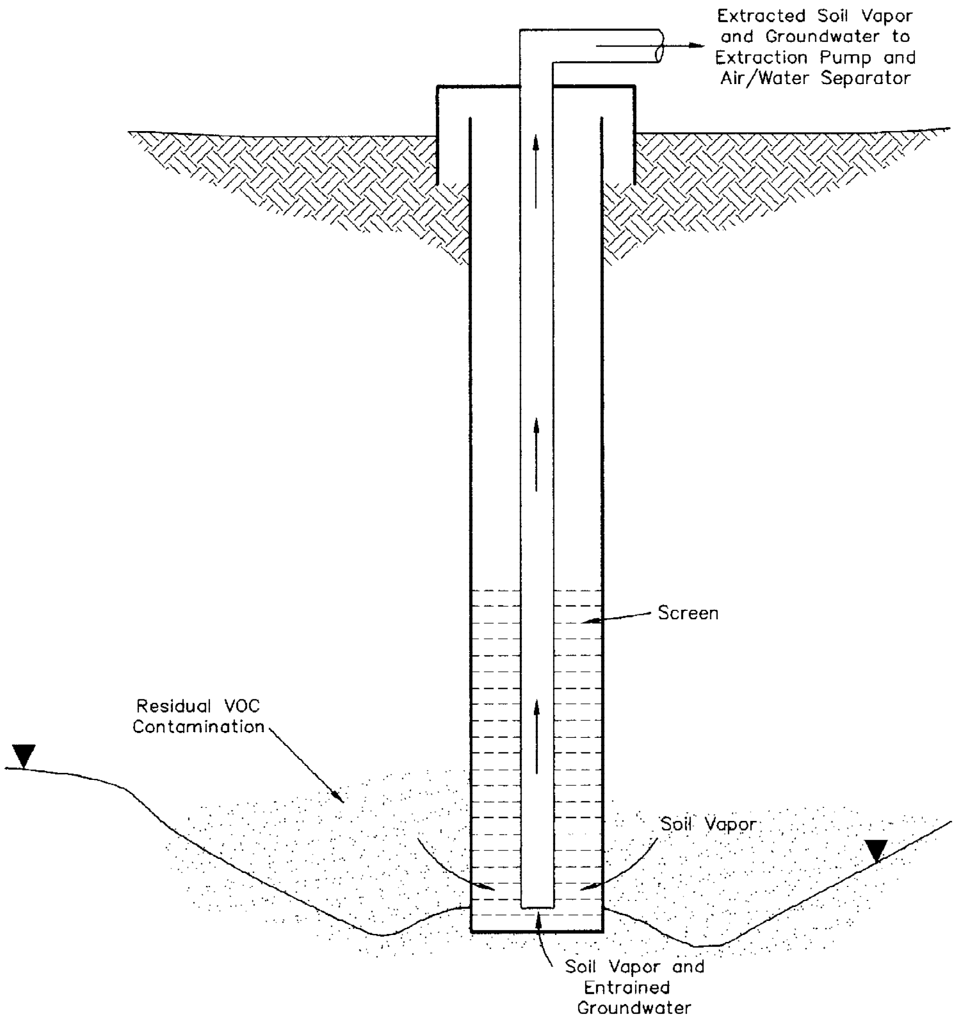


SOURCE: MODIFIED FROM McCOY AND ASSOCIATES, INC 1992

SCHEMATIC OF A DUAL-PHASE EXTRACTION SYSTEM

FIGURE 4-1

FIGURE 4-2
DROP-TUBE ENTRAINMENT EXTRACTION WELL

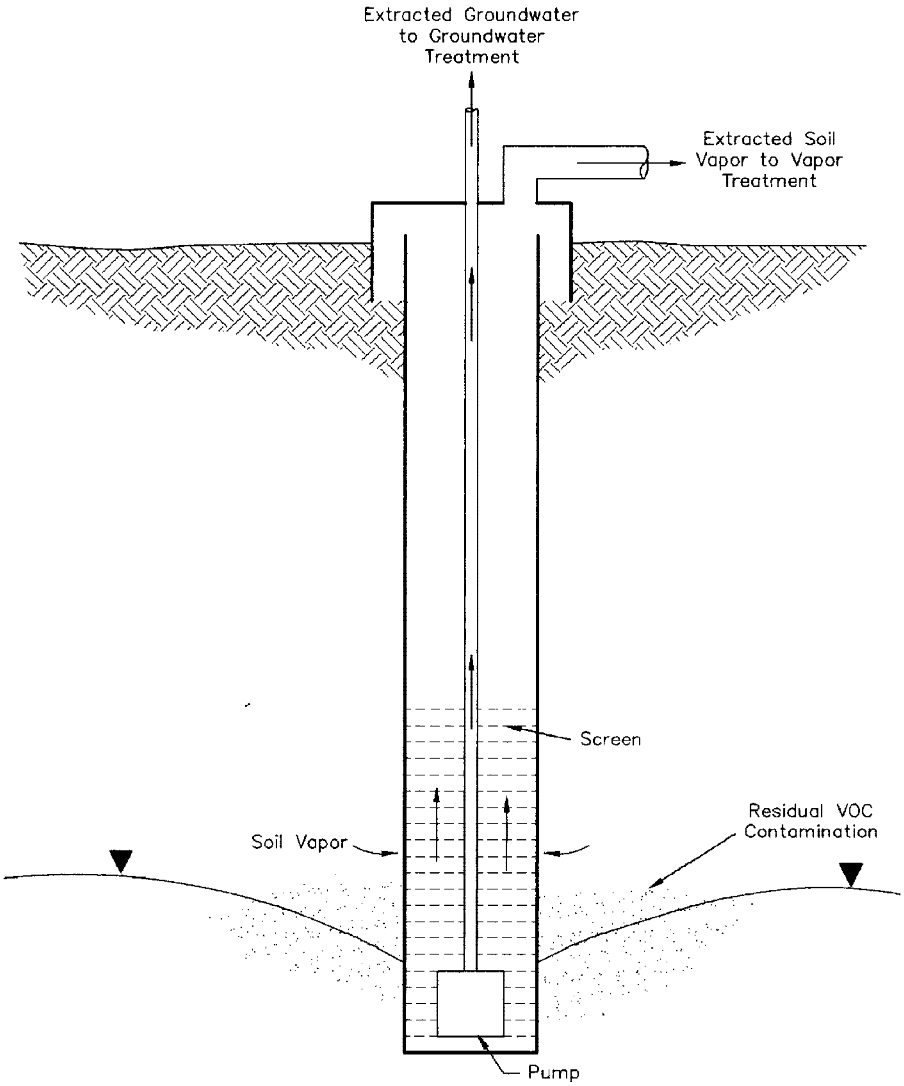


SOURCE: MODIFIED FROM KOERNER AND LONG 1994

DROP-TUBE ENTRAINMENT EXTRACTION WELL

FIGURE
4-2

FIGURE 4-3
DOWNHOLE-PUMP EXTRACTION WELL

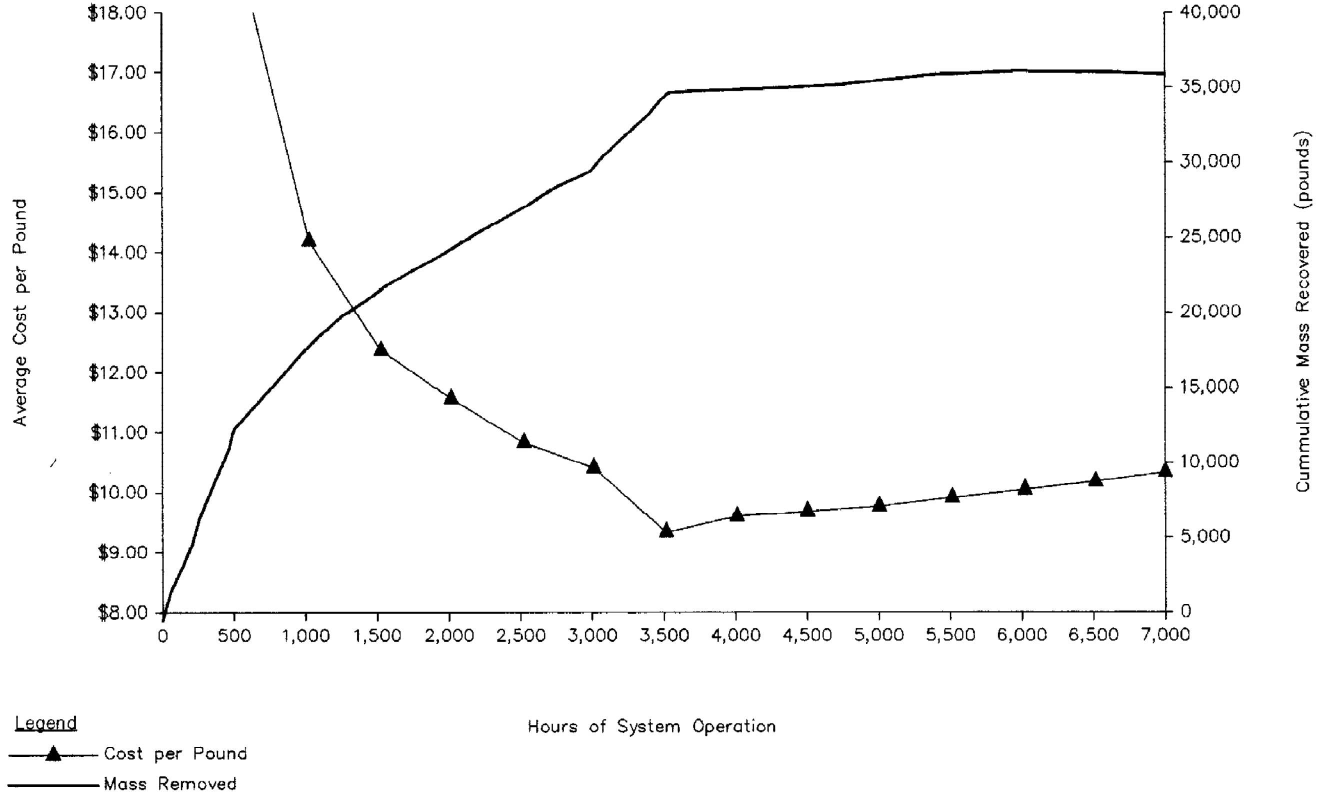


SOURCE: MODIFIED FROM KOERNER AND LONG 1994

DOWNHOLE-PUMP EXTRACTION WELL

FIGURE
4-3

FIGURE 4-4
EXTRACTION SYSTEM PERFORMANCE



EXTRACTION SYSTEM PERFORMANCE

FIGURE
4-4

TABLE 4-1

COST DATA FOR DUAL-PHASE EXTRACTION TECHNOLOGIES

Case Study	Vendor/Consultant	Total Cost ($)	Capital Cost ($)	Cost per pound of contaminant removed ($)	Cost per gallon of groundwater ($)
1	IT Corporation	380,000	—	10	0.23
2	Terra Vac	600,000	—	40	7.00
3	Groundwater Services, Inc.	—	—	—	—
4	Dames & Moore	331,600	60,000	130	0.31
5	Eder Associates, Inc.	—	58,000	—	—

Note:

— Information is not available

TABLE 4-2

VENDORS OF DUAL-PHASE EXTRACTION TECHNOLOGIES

Name of Vendor	Address and Phone Number	Point of Contact
Dames & Moore	2325 Maryland Road Willow Grove, PA 19090 (215) 657-7134	Joseph Tarsavage
Eder Associates, Inc.	8025 Excelsior Drive Madison, WI 53717 (608) 836-1500	Anthony Miller
First Environment, Inc.	90 Riverdale Road Riverdale, NJ 07457 (201) 616-9700	Rick Dorrler
Fluor Daniels GTI, Inc.	100 River Ridge Drive Norwood, MA 02062 (800) 635-0053	David Peterson
Groundwater Services, Inc.	2211 Norfolk, Suite 1600 Houston, TX 77098 (713) 522-6300	John Connor
International Technologies Corporation (IT)	2925 Briar Park Houston, TX 77042 (713) 784-2800	John Mastroianni
Radian International	2455 Horsepen Road, Suite 250 Herndon, VA 20171 (703) 713-6493	Christopher Koerner
Smith Environmental Technologies Corporation	One Plymouth Meeting Plymouth Meeting, PA 19462 (610) 825-3800	Dan Guest
Terra Vac Incorporated	1555 Williams Drive, Suite 102 Marietta, GA 30066-6282 (404) 421-8008	Charles Pineo
Wayne Perry, Inc.	8281 Commonwealth Avenue Buena Park, CA 90621 (714) 826-0352	Don Pinkerton

Note: This list is not inclusive of all vendors capable of providing dual-phase extraction technologies. This list reflects those vendors contacted during the preparation of this report.

CHAPTER 5.0

DIRECTIONAL DRILLING

This chapter focuses on the application of directionally-drilled horizontal wells to enhance SVE bioventing/biosparging, and air sparging technologies. Horizontal wells are gaining popularity for use in SVE and air sparging remedial systems. This is a result of recent advances in drilling mud formulation, screen design and drill rig availability. Horizontal wells are being used to remediate shallow soil and groundwater in areas where access is limited by airport tarmacs, buildings, tanks and subsurface debris. One horizontal well can take the place of as many as 20 vertical wells eliminating the need for redundant hardware for SVE and groundwater pumping.

The following sections provide an overview of directional drilling, describe conditions under which the technology is applicable, contain a detailed description of directional drilling methods, highlight performance data, list vendors that provide directional drilling services, outline the strengths and limitations of the technology, and provide recommendations for using the technology. Cited figures and tables follow references at the end of the chapter.

5.1 TECHNOLOGY OVERVIEW

The first directionally drilled horizontal wells for environmental remediation were installed in 1988 as part of horizontal extraction and injection remediation systems at the DOE Savannah River Site (SRS) Integrated Site Technology Demonstration. Seven wells were installed at the SRS to demonstrate innovative in situ remediation technologies. Between 1988 and 1993, the DOE’s Office of Science and Technology supported the development and deployment of directional drilling technology for environmental applications at the SRS. The DOE also funded the development and demonstration of directional drilling technologies at the Sandia National Laboratory in Albuquerque, New Mexico, between 1991 and 1995 (Kaback and others 1996).

Today, the use of horizontal wells for SVE and air sparging has moved into the private sector. Horizontal directional drilling is considered an acceptable technology; in appropriate geologic environments and for appropriate contaminants, it can result in better performance and lower overall cost than vertical wells.

Horizontal wells can be used to access areas generally not accessible using vertical well drilling technologies, such as under buildings and airport tarmacs. Figure 5-1 illustrates a hypothetical horizontal well network installed beneath a building to access contaminated soil and groundwater.

Two recent, large-scale applications of this technology occurred at the John F. Kennedy (JFK) Airport (Tetra Tech 1996a), where more than 50 horizontal wells totaling more than 20,000 feet in length were installed to remediate a jet fuel plume under the tarmac. Additionally, about 25 horizontal wells have been installed at a Dow Chemical Company Louisiana Division plant located in Plaquemine, Louisiana (Tetra Tech 1996b).

The number of horizontal wells installed for environmental remediation projects has increased dramatically in recent years. In 1994, there were only 55 documented horizontal wells in the U.S., and in 1995, there were 117 (Kaback and others 1996). More than 400 new horizontal wells nationwide are projected during 1996 (Wilson 1995a).

Improvements in technologies borrowed from the oil and gas industry and utility industry drilling technologies, combined with an increase in competitiveness among drilling contractors, has contributed to the increase in popularity of horizontal wells. These improvements, which have focused on downhole drilling motors, drill bit steering, accuracy in drill tool guidance systems, drilling fluids, and screen designs, are continuing to sustain a cost competitive marketplace for horizontal wells in environmental remediation.

Directional drilling employs the use of specialized drill bits to advance curved boreholes in a controlled arc (radius) for installation of horizontal wells or manifolds for SVE and sparging technologies. The borehole is initiated at a shallow angle typically 5 to 30 degrees to the ground surface. After arrival at a target depth, the drilling tool is reoriented to drill a horizontal borehole. Electronic sensors located in the drill tool guidance system provide orientation, location, and depth data to the driller. Drilling fluids are generally used to convey cuttings as well as lubricate and maintain the integrity of the borehole while enlarging its diameter or installing a well. There are two types of directionally drilled boreholes: blind and continuous. Blind boreholes terminate in the subsurface, and the well is installed from the entrance of the borehole. Figure 5-2 illustrates a blind borehole completion. Continuous boreholes are reoriented upward and return to the ground surface. In continuous boreholes, the well is installed from the exit point and pulled into the borehole by the drill rig. Figure 5-3 illustrates a continuous well completion.

An overview of a horizontal well installation is as follows:

- Advance a pilot hole
- Enlarge the hole using a reaming drill bit, by pushing or pulling the bit through the pilot hole. In a continuous borehole, the reaming drill bit tool is inserted into the borehole at the exit point and pulled back to the drill rig.
- Install the well by pushing or pulling the well casings into the borehole. In continuous boreholes, well installation generally occurs during the reaming phase (second bullet).

Figure 5-4 illustrates advancing a pilot hole, and Figure 5-5 illustrates backreaming and well casing installation.

5.2 APPLICABILITY

Directional drilling is applicable for installation of horizontal wells to enhance a variety of remedial systems. Horizontal wells have been shown to be effective for SVE, air sparging, groundwater extraction, and free product removal. Of the approximately 370 documented horizontal wells in the United States today, 35 percent were installed for SVE, 33 percent for groundwater extraction, 21 percent for air sparging remedial applications, and 11 percent for other purposes (Kaback and Oakley 1996). Horizontal wells have also been used as gravity drainage systems for groundwater extraction to allow for gravity pumping and injection, eliminating costly aboveground treatment and disposal fees (Tetra Tech 1996c).

There are several benefits to using horizontal wells. These include:

- Horizontal wells can have as much as a 50 percent larger zone of influence than vertical wells because they can provide a linear, constant, and uniform air delivery or vacuum to the formation.
- Horizontal wells can increase the performance of remedial systems (such as SVE, bioventing, and air sparging) because horizontal wells conform closer to the distribution of the contaminant than vertical wells.

- In air sparging systems, horizontal wells can be oriented perpendicular to the groundwater flow direction. In this manner, groundwater can be exposed to a curtain of oxygen as the groundwater flows by the sparge well.
- Horizontal wells can reduce the limitations of anisotropic hydraulic conductivities common in most stratified sediments by being oriented in the direction of the higher horizontal hydraulic conductivity tensor.

Horizontal wells are well suited for cleanup of soil particles, soil vapor, and groundwater using an integrated scheme in which the wells are located both above and below the water table (Downs 1996). The largest example of such an integrated remedial scheme is at New York's JFK: approximately 36 horizontal air sparging and 18 SVE wells have been installed to remediate a large plume of jet fuel in both subsurface soils and groundwater. In this system, two to three air sparging wells are located adjacent to (and below) an associated SVE well (see Section 5.4.1.4 for details).

The application of horizontal wells to extract free product in areas where the elevation of the water table is variable may be limited because the elevation of the free product plume may move above and below the elevation of the horizontal well.

5.2.1 Geologic Conditions

Horizontal wells can be installed in most geologic materials that are suitable for SVE and air sparging, including unconsolidated sands, silts, and clays, as well as bedrock. Installation in silts and clays can be difficult because of the reduction of the specific capacity of the well caused by the smearing of silts and clays against the borehole wall, which can result in lower effective permeabilities. Costs rise with increased drilling difficulty (for example, in cobble and coarse gravels).

5.2.2 Distances Achieved

Horizontal boreholes as long as 2,600 feet and to depths of 235 feet have been installed (Kaback and Oakley 1996); however, borehole lengths of between 200 and 600 feet, with depths of less than 50 feet, are most common.

5.3 ENGINEERING DESCRIPTION

Directional drilling methodologies were first developed and used by the utility industry for the installation of buried utility conduits (sewer pipes, power lines, etc.). Large, river-crossing drill rigs were developed in the 1970s for installing utility conduits underneath rivers with this technology. These large and powerful rigs can drill boreholes up to 60 inches in diameter and thousands of feet long. Approximately 25 percent of the boreholes for environmental remediation projects have been installed by directional drilling using these larger drill rigs. The remaining 75 percent of the boreholes for environmental remediation projects have been installed by directional drilling with the use of drill rigs used by the utility industry.

The following sections describe the directional drill rigs, drilling assembly, drilling fluids, guidance system, well construction materials, and design considerations for directional drilling as well as the common problems encountered during directional drilling projects.

5.3.1 Drill Rigs

Directional drill rigs typically consist of a carriage that slides on a frame holding the drill rods at an angle of 0 to 45 degrees. The rigs are generally powered by a hydraulically driven motor on the carriage which rotates the drill rods (photographs 5-1 through 5-4). A chain drive, rack and pinion drive, or hydraulic cylinder may push or pull the carriage to advance or retract the drill string. A pump on the rig capable of handling various drilling fluids is required (EPA 1994).

The drill rig provides thrust to the drilling tool, providing the force to advance the drill string the length of the borehole and providing sufficient pulling force to retract the casing into the completed borehole. Horizontal drill rigs must be anchored to the ground by staking or attaching it to a buried or surface weight. This provides an opposing force to the thrust or pull-back. The drill rig must also provide torque to the drill strings. Most drilling methods require that the drill string be rotated while it is advanced into the borehole to reduce drag friction on the drill string.

Drill rigs are available in a range of sizes. They are classified according to their torque and force they push and pull with. Mini and midi type drill rigs are most commonly used for shallow SVE boreholes.

Mini and midi drill rigs (photographs 5-1 through 5-3) can be very compact (for example, a typical gasoline station can remain open during drilling operations). Maxi rigs, on the other hand, take up considerable space and require several large trucks to mobilize and setup on the site. Photograph 5-4 shows a maxi rig.

Mini drill rigs are mounted on a trailer, a truck, or a self-propelled tracked vehicle. The drilling fluid system is limited; water or a dilute bentonite based fluid are commonly used. A mini drill rig's maximum thrust force is less than 40,000 pounds. Their use is limited to small diameter (4-inch range) pipe installations at depths of less than 30 feet in semiconsolidated sediments.

Midi drill rigs are mounted on a trailer or a self-propelled tracked vehicle. These rigs have a maximum thrust force of less than 80,000 pounds. They are used to drill continuous or blind boreholes and install pipes up to 8 inches in diameter. The drilling fluid systems are larger and can accommodate all types of drilling fluids.

Maxi drill rigs are mounted on trailers. These rigs have a maximum thrust force of up to 800,000 pounds. Maxi rigs can accommodate any type of drilling fluid, have been used to drill up to 60-inch boreholes, and can be used to install pipes of up to 14 inches in diameter. The large river crossing drill rigs fall into this category (May 1994).

5.3.2 Drilling Assembly

The drilling assembly used during horizontal drilling consists of a drilling tool, a bent subassembly, and a guidance system. The drilling tool is preferentially oriented in the borehole by the bent subassembly to drill in the desired direction. The guidance system provides the orientation and location of the drill string to the driller. There are three kinds of drilling tools, namely tri-cone type drilling tool, hydraulically assisted, job-style drilling tool, and compaction tools. These drilling tools are described below.

5.3.2.1 Tri-Cone Type Drilling Tools

A tri-cone type drilling tool uses a downhole mud motor (tri-cone type drill bit), a water jet, a compaction hammer, or a combination of these to drill a borehole by cutting the formation. The trajectory is curved by using a tool (the bent subassembly) that is eccentric relative to the drill rod or has a bevel in the drilling tool face itself. Figure 5-6 shows typical drilling assembly for the different drilling phases. Downhole mud motors (or tri-cone type drill bits) are powered by drilling fluid that is pumped down the drill pipe. The drilling fluid (either a bentonite or organic polymer-based drilling fluid) facilitates the turning of the drill bit. The drilling fluid is removed by development and using sodium hypochlorite. Downhole mud motors and water are the most commonly used tools in the environmental drilling industry.

5.3.2.2 Hydraulically Assisted, Jet-Style Drilling Tools

Hydraulically assisted, jet-style (slant head fluid-assisted drill bit) drilling tools are the most commonly used drill tools today. Hydraulically assisted, jet-style drilling tools use hydraulic pressure to cut the geologic formation. The hydraulic jet is directed from a bent housing or from a drilling fluid port on a drill bit attached to a bent subassembly. To drill the curved section, the bent subassembly and the hydraulic jet are placed in the direction of the borehole deviation. To drill the straight segment, the drill string is rotated by the driller. The rotation prevents the hydraulic jet from having a preferred orientation.

5.3.2.3 Compaction Tools

Compaction tools work on the same principle as wood chisels. Compaction tools are wedge-shaped and move in the direction of the slant on the face of the wedge. The drill string is pushed if the borehole direction is to be changed and rotated and pushed if the borehole direction is to be straight. Compaction tools are restricted to unconsolidated materials and to boreholes that are less than 50 feet deep. Compaction tools can press cuttings into the side of the borehole and damage formation permeability.

5.3.3 Drilling Fluids

Drilling fluids are used to clean cuttings from the drill bit, to suspend cuttings for transport to the surface, to lubricate the drill string, to cool the drill bit, and to prevent the loss of drilling fluids to the formation.

Drilling fluids are either bentonite clay based, or synthetic or natural polymer based. Selection of the proper drilling fluid is essential for a successful drilling project. Recent advances in drilling fluid formulations have resulted in mixed metal hydroxide bentonite fluids and xantham polymer systems that have a high gel strength to carry drill cuttings and filtration control to seal the borehole.

Special well development fluids are used to remove the drilling fluids from the well (for example, mixed metal hydroxide drilling fluids require well development using sodium acid polyphosphate to flocculate the bentonite and clean the well). Xantham polymer-based drilling fluid breaks down and is easily removed using sodium hypochlorite during well development. Xantham polymer-based drilling fluid also breaks down over time. This type of drilling fluid has been shown to increase the success rate of horizontal wells by reducing borehole damage (reduced borehole wall permeability) that can be caused by bentonite based drilling fluids. It can also lower well installation costs by reducing well development time.

5.3.4 Guidance Systems

The guidance system allows the driller to control the orientation, pitch, and depth of the drilling tool. It is located in the downhole assembly behind the drilling tool and the bent subassembly. There are three common types of guidance systems as follows:

- Radio beacon-receiver systems
- Magnetometer-accelerometer systems
- Inertial (gyroscopic) systems

Each system provides location and depth data. The radio beacon method uses a surface tool to “walk along” the ground surface while following the drilling tool during drilling. It is limited to depths of up to 25 feet. The magnetometer-accelerometer system orients using a surface imposed magnetic field and a computer to navigate. The inertial system uses gyroscopes to orient with the earth’s magnetic north and a computer to interpret navigational data.

5.3.5 Directionally Drilled Well Installation

Directionally drilled well materials, screens, casing, and installation steps are described in the following subsections.

5.3.5.1 Well Materials

The well screen and riser pipe design for a horizontal well is similar to that of a vertical well with the exception that horizontal wells require materials with higher tensile strength while maintaining flexibility. Horizontal well materials are subject to high tensile stresses resulting from skin friction along the borehole wall, particularly at curved sections of the borehole. Selection of riser pipe and well screen material depends on the soil characteristics, contaminant type, and radius of the curvature of the borehole. HDPE and fiberglass/epoxy resin are well suited to short radius boreholes because of their flexibility. Stainless steel and carbon steel can also be used in boreholes with medium and large radii. PVC is not well suited for use in horizontal wells because it has neither the high tensile strength nor the flexibility necessary (Mast and Koerner 1996).

5.3.5.2 Well Screens

Traditional prepacked dual well screens, single well screens enveloped in a geotextile filter material, and porous polyethylene pipes are commonly used. Filter packs are generally impractical in horizontal wells because of the difficulties of installation. Other screen designs such as wire-wrapped screens, geotextile fabric wrapping and louvered stainless steel, multilayered stainless steel and sintered HDPE and stainless steel have been used. Wire-wrapped screens are only available in PVC and steel. Wire-wrapped screens are not made from HDPE because of the low melting point of the material. A porous HDPE screen is fairly new on the market and is designed specifically for horizontal well installations. The screen consists of pure spherical shaped polyethylene beads that are heated and molded into a pipe. The heating process does not melt the spheres completely, allowing the pipe to be porous. By controlling the size of the polyethylene beads, the permeability can be varied. The open area of this material averages 30 percent and has 3 times the collapse strength of HDPE slotted screen (Bardsley 1995).

5.3.5.3 Well Casings

Carrying casings are commonly used to install the screens and riser pipes. Carrying casings are installed after the pilot hole is advanced by pulling it into the borehole during the reaming phase of the drilling. The well materials are placed into the carrying casing during installation or afterwards. Once the screen and riser are placed into the borehole, the carrying casing is withdrawn from the well, leaving the well screen and riser pipe in place.

5.3.5.4 Well Installation

The steps of installation of directionally drilled horizontal wells are as follows:

- Installation of the pilot hole and exit trenches. The pilot holes are generally drilled with an approach angle of less than 25 degrees (Wilson 1995b). Figure 5-4 illustrates the installation of the pilot hole.

- Continuous Boreholes: switch drill bits at the exit point and enlarge the borehole using a reaming tool. A carrier casing is generally pulled into the borehole with the reaming drill bit.

  Blind Boreholes: washover pipe equipped with a reaming bit is advanced over the pilot hole drill string. This step helps clean the borehole wall and enlarges the hole to allow casing installation. The pilot hole drill string is removed, and the washover casing remains to be used to install the well materials. Figure 5-5 illustrates the backreaming and casing installation process.

- The screen and riser are installed in the carrier casing or washover pipe

- The casing is removed, and the well material is left in the formation

- The well is developed with water and special drilling mud removal solutions

- Install SVE and air sparging system components

5.3.6 Design Considerations

The important design considerations for directional drilling are described below.

5.3.6.1 Radius of Curvature

The radius of curvature is an important design consideration in horizontal wells. Medium and long radii of curvature boreholes are preferable over shorter radii because of the reduced drilling and installation stress on the drill string and casing. Longer radii can be drilled by a variety of drill rigs. However, longer radii increase the drilling footage and increases cost. The “step off distance,” or the distance required to accommodate the angle of entry and achieve the desired depth, should also be considered. Generally, a minimum of a three to one ratio of horizontal distance to depth (approximately 18 degrees) is required (Tetra Tech 1996d). The design process must consider space availability, drill rig capabilities, well materials, and cost to arrive at the approach angle and radius of curvature.

5.3.6.2 Air Flow Patterns

A common problem with horizontal vapor extraction and air sparging wells is that the air delivery may not be uniform throughout the screen interval. Nonuniform airflow will result from permeability variations within the formation surrounding the screen interval, faulty well installation, or poor well screen design. Preferential exit of air at the blower-end of the well can occur if there is excessive pressure drop along the screen interval, or if there is failure in the annular seal. Excessive pressure drop within the screen interval can occur if the slot size is too large or if the open area is too great. Research conducted during the preparation of this report indicate that the use of a uniform slot size will likely result in nonuniform air flow. Designing the well screen to correct for nonuniform air flow is one of the most important factors in well screen design.

Lundegard and others (1996) conducted an air sparging pilot test using horizontal wells at the Guadalupe Oil Field in California. A careful screen design resulted in uniform air flow patterns. These investigators estimated air flow rates for a well in the design phase using the model TETRAD (Vinsome and Shook 1993; Lundegard and Andersen 1996). Using the derived flow rates from TETRAD, applicable pipe size and hole spacing were calculated for a well design. The hole sizes and spacings were designed using sparger design equations and guidance described by Perry and Chilton (1975) and Knaebel (1981).

5.3.7 Common Problems

Common problems in directional drilling projects result primarily from poor planning by the engineering contractor, and a lack of experience and preparation by the drilling contractor. Historical problems have occurred for various reasons as follows (Wilson 1995b):

- Not fully characterizing the horizontal well site geology and geochemistry
- Not fully researching the credentials of the drilling company
- Not planning and researching the drilling fluid and screen materials and design carefully
- Not developing the well adequately
- Not evaluating carefully the potential for pressure drops due to slope, geology or well loss
- Not using a contractor experienced in planning, procuring, and implementing a horizontal well installation program
- Not retaining a driller who understands the intricacies of drilling in the specific geologic environment
- Not providing close oversight to the drilling contractor
- Drilling contractors providing undersized and undermaintained equipment for the job
- Drilling contractors drilling the pilot hole too quickly and not creating a smooth uniform curvature to the borehole
- Not maintaining a consistent pressure along the length of the horizontal well

Two solutions to the problem of inconsistent pressure are to reduce the diameter of the well screen toward the exhaust end of the screen or to use a sintered HDPE screen that can be custom made to have varying pore size while maintaining the same open area along its length.

5.4 PERFORMANCE AND COST ANALYSIS

Performance and cost data are presented in this section for four case studies. These are SRS, Alberta Gas Plant, Hastings East Industrial Park, and JFK. The JFK case study presents the most ambitious and up-to-date information regarding the use of horizontal wells for SVE and air sparging.

5.4.1 Performance

The availability of data comparing the performance of horizontal to that of vertical wells are limited. The majority of work with this technology is being conducted at confidential private industrial and Department of Defense facilities. Because of the relative newness and proprietary nature of this technology, the bulk of the performance data are contained in pilot study, installation, and performance monitoring reports prepared by contractors. Contractor reports were difficult to obtain. Only a few of the available references contained performance data. These are presented as case studies below.

Personal communication with several experts in the field was conducted as part of this analysis. These individuals are listed in Section 5.8.2. A unanimous consensus by these individuals indicated that horizontal wells can have as much as a 50 percent larger zone of influence than vertical wells because they can provide a linear, constant, and uniform air delivery or vacuum to the formation. Performance of remedial systems (such as SVE, bioventing, and air sparging) with the use of horizontal wells increases because horizontal wells can be installed more precisely in the contaminant plume than vertical wells. In addition, horizontal wells can optimize typical anisotropic hydraulic conductivities common in most stratified sediments by being oriented in the direction of the higher horizontal hydraulic conductivity tensor.

5.4.1.1 U.S. Department of Energy Savannah River Site Integrated Demonstration Site

DOE pioneered the use of horizontal wells at the SRS for environmental remediation purposes for their Integrated Site Technology Demonstration program. An abandoned process sewer line at the SRS leaked approximately 2.2 million pounds of TCE and PCE into the soil and groundwater between 1958 and 1985 (DOE 1995). A pump and treat groundwater extraction and treatment system in operation since 1984 removed approximately 230,000 pounds of solvents from the groundwater. However, solvents have continued to leach into the groundwater from the vadose zone. The depth to groundwater is 135 feet. Extensive site characterization (geology, geochemistry, and bioavailability) has been conducted at this site (Kaback and others 1991).

Air injection, SVE, and ISB using horizontal wells have been demonstrated at this site. The in situ AS/SVE strategy involved the installation of two parallel horizontal wells. These wells were aligned with the orientation of the process sewer line.

The two horizontal wells were installed in 1989 using technology borrowed from the petroleum industry. One 300-foot-long air sparging well was installed below the water table at a depth of 150 to 175 feet. The 200-foot-long SVE well was installed to a depth of 75 feet.

A 20-week pilot test was conducted. During the pilot test, the two wells operated concurrently. Three different air injection rates at two different temperatures were used. Helium tracer tests were also conducted to evaluate vapor flow pathways and aquifer heterogeneities. The SVE wells operated at 580 scfm during the test. The air sparging wells operated at a range of 170 to 270 scfm.

Almost 16,000 pounds of solvents was removed during the pilot test (Kaback and others 1996; Looney and others 1991).

The VOC extraction rate averaged 110 pounds of VOCs per day when the SVE well operated alone. Extraction rates increased to 130 pounds per day when both wells operated concurrently. The concentration of TCE at the two wells decreased from 1,600 and 1,800 μg/L to 200 and 300 μg/L, respectively. Additionally, the activity of indigenous microorganisms increased during the pilot test by an order of magnitude. These same horizontal wells were also used to evaluate ISB. The results of this study are presented by DOE (1995), and discussed in Chapter 3 of this report. The SVE well capture zone within the vadose zone was 200 by 300 feet.

5.4.1.2 Alberta Gas Plant

Armstrong and others (1995) conducted a comparison of the performance of horizontal versus vertical wells. These investigators used a numerical model (Mendoza 1992) calibrated against existing horizontal wells to evaluate well performance. Two cases were evaluated; a horizontal well installed using trenching and a horizontal well installed using drilling. The performance of the horizontal drilling case is presented here. This case evaluated the zone of influence of a 275-foot-long well with a 190-foot-long screen, installed at depths ranging from 6 to 13 feet bgs, in a silty sand to sandy silt soil. Air flow tests were conducted at the horizontal well and at a vertical air extraction well using air monitoring points within the formation to collect pressure and flow data for use in the model. Air permeabilities were back calculated. The model was then used to calculate the theoretical zone of influence of the vertical and horizontal wells.

The modeling results showed that the zone of influence of the vertical and horizontal wells at a vacuum pressure of 25 Pascal were 4.7 and 12.3 meters, respectively, indicating that one 60-meter, horizontal well could provide the same areal coverage as 22 vertical wells. A cost evaluation indicated that, based on well installation costs alone, a 60-meter-long well would cost the same as 15 to 20 vertical wells. This cost evaluation only considered well installation and did not consider surface equipment associated with each well such as blowers, manifolding, and piping. When these costs are factored in, the cost effectiveness of horizontal wells would be realized.

5.4.1.3 Hastings East Industrial Park

Wade and others (1996), under direction of the U.S. Army Corps of Engineers, conducted a 1-year pilot study of an air sparging system with one horizontal and one vertical sparging well at the Hastings East Industrial Park near Hastings, Nebraska. The site is part of a former naval ammunition depot that was decommissioned in 1967. The agency responsible for the pilot study was the U.S. Army Corps of Engineers. Widespread soil and groundwater contamination exists at the site. The contaminants of concern at this facility are chlorinated solvents, primarily TCE at concentrations as high as 16,000 μg/L in groundwater. A full-scale remedial system, incorporating air sparging using both horizontal and vertical wells, was designed, installed, and extensively tested over a period of 1 year. Figure 5-7 presents the site plan showing the zone of contamination, the locations of monitoring points, and vertical and horizontal air sparging wells.

The system installed at this site is a deep system by most standards. The depth to groundwater at this facility is 100 to 130 feet bgs. The geology includes deposits of silty clay loess, sand, and gravel with interbeds of silt and clay to the water table. The geology of the aquifer includes sand and gravel. The aquifer is anisotropic, and the horizontal and vertical hydraulic conductivities are estimated at 7×10^{-2} cm/s and at 1×10^{-7} cm/s, respectively.

This system was designed as an integrated approach using the horizontal well as both a method of containment and a device for contaminant mass removal by installing it perpendicular to the groundwater gradient across the width of the contaminant plume. With this orientation, a vertical curtain of sparged air aligned perpendicular to the groundwater flow direction was created so the air can strip the TCE from the groundwater as it flows by the horizontal well.

The horizontal well was placed approximately 370 feet downgradient from the source of the plume. The borehole for the well was drilled with a 600-foot-radius of curvature (considered to be a large radius). No information regarding drill rig type or other specifics of the drilling phase was available. The horizontal well has a 6-inch diameter and a 200-foot-long well screen, and it was drilled to a depth of 125 feet (13 feet below the water table). The total length of the well is 600 feet. A standard, continuously wound, stainless steel, prepacked well screen was used. The slot size was selected using standard water well industry screen design criteria. An air diffuser pipe was installed within the screen to help distribute the air evenly along the screen. A blower capable of injecting air at approximately 320 scfm while maintaining a wellhead pressure of 11 psi was installed. The well was developed by jetting, pumping, and surging the screen. In addition, phosphates were jetted through the screen to destroy the gel properties of the bentonite-based drilling mud. The well was then videotaped to confirm adequate development.

The vertical well was installed at the center of the contaminant plume in the same stratigraphic horizon as the horizontal well. This well has a 4-inch diameter and a 5-foot-long, continuously wound, stainless steel screen.

In addition to the sparging wells, the system design incorporated SVE wells screened in the vadose zone. These wells served a dual purpose of capturing the sparged gas and remediating the vadose zone sands and gravel. A total of 24 vertical SVE wells, 15 vertical vadose zone monitoring wells, and 22 vertical groundwater monitoring wells were installed.

The system was operated in five phases for a period of 1 year during the pilot test. The first two phases operated using a constant air injection, and the last three phases at cycled air flow. The goal of the pilot test was to optimize groundwater cleanup and prevent the plume from spreading around the zone of sparging. There was a concern that long periods of sparging at a high flow rate at the horizontal well could spread the plume because of the reduction of water hydraulic conductivity within the sparge zone. The horizontal well operated at flow rates of 160 to 320 scfm, and the vertical well operated at flow rates of 15 to 30 scfm. Extensive soil vapor and groundwater sampling during the course of the year was conducted to measure the performance of the system.

The zone of sparging around each well was determined by observing air in the groundwater monitoring wells, TCE concentration in monitoring wells, and changes in TCE concentrations in the SVE wells. The zone of influence was about twice as large around the horizontal well as the vertical well. The zone of sparging was 60 feet around the horizontal well and 26 feet around the vertical well at the maximum air flow rates.

The effectiveness of each well in reducing TCE in the groundwater was also evaluated. Groundwater quality data from nearby downgradient groundwater monitoring wells were used to evaluate the performance of the horizontal and vertical air sparging well; these data are shown on Figures 5-8 and 5-9, respectively. TCE concentrations were reduced by more than 90 percent at the groundwater monitoring wells screened at the top of the water table. Wells screened toward the bottom of the 15-foot-thick aquifer showed much less TCE reduction; water moving below the horizontal well was not exposed to the sparge curtain. The groundwater sampling results showed that the plume did not spread around the sparging curtain.

TCE concentrations were reduced in the groundwater monitoring wells adjacent to the vertical sparging well; groundwater cleanup resulting from the vertical well was much less significant than groundwater cleanup resulting from the horizontal well. However, it does not appear that those wells are located directly downgradient from the sparging well. Direct comparison with the horizontal well may not be an accurate representation of the well efficiencies immediately downgradient of the sparge well.

Wade and others (1996) cited that the horizontal well created a uniform sparge curtain that would be unlikely with vertical wells. They noted that the horizontal well had a sparging capacity of more than 10 times that of the vertical well under the same injection pressure. The zone of influence around the horizontal well was greater than the vertical well by a factor of 2 under maximum injection rates. Cost effectiveness was not evaluated in literature cited.

5.4.1.4 John F. Kennedy Airport

The Port Authority of New York and New Jersey has installed the most ambitious AS/SVE project to date using horizontal wells at the JFK airport. More than 50 horizontal wells, to lengths reaching more than 600 feet, have been installed in two separate areas. The system combines about 36 air sparging wells and 18 SVE wells. Figures 5-10 and 5-11 illustrate the layout of the system. The system uses approximately 13,000 feet of horizontal SVE wells and 7,000 feet of horizontal air sparging wells. The design of the horizontal SVE and horizontal air sparging wells was based on a pilot study and was followed by a full-scale test. The system is augmented by 28 vertical air sparging and 15 vertical SVE wells. The SVE and air sparging wells will operate continuously while the groundwater is being intermittently sparged, extracted, and treated by liquid phase activated carbon and discharged into the storm water. Postinstallation monitoring for soil and groundwater is also underway as a part of this system design.

The soil and groundwater at JFK are contaminated with jet fuel that spilled and/or leaked from the hydrant fueling system. A small fraction of the contamination is also from USTs that leaked motor oil, heating oil, or ethylene glycol. The compounds of concern at JFK are VOCs (ethylbenzene and toluene), and SVOCs (primarily base neutral compounds). The concentrations of VOCs and SVOCs in soil ranged from nondetected to 148,000 mg/kg and nondetected to 584,000 mg/kg, respectively. The concentration of BTEX and SVOCs in groundwater ranged from nondetected to 6,000 μg/L and nondetected to 4,000 μg/L, respectively (Roth and Pressly 1996).

The geology at JFK includes hydraulic fill consisting of fine to medium sand with trace silt to depths of 10 to 16 feet bgs. The fill is underlain by a thin, low permeability, clayey-peat layer. The depth to groundwater ranges from 6 to 8 feet bgs (Roth and Pressly 1996).

The remedial system was a result of intensive laboratory and field studies by the Port Authority of New York and New Jersey. Two pilot studies were used to collect predesign data. The first pilot test used a 260-foot long horizontal SVE well constructed with 3-inch diameter HDPE. The horizontal SVE well was installed about 3.5 feet bgs and has a varying slot size of 160 feet of 0.01 inch and 100 feet of 0.020 inch slot opening. The horizontal air sparging well was 190 feet long with 80 feet of screen installed at 12 feet bgs. A pilot test for each well was conducted independently to determine the zone of influence, air flow rates, and distribution of air flow rates. Figures 5-12 and 5-13 show results from the air sparging and SVE pilot tests, respectively. The results of these pilot tests were evaluated to look at the relationships between vacuum pressure and flow and the resulting geometric distribution of pressure vacuum as measured by pressure and vacuum monitoring points around the wells. Horizontal SVE air flow versus vacuum data were plotted and linearly regressed to solve for flow per foot of screen interval as a function of vacuum at the center of the screen. Vacuum line loss versus flow were also plotted and linearly regressed to solve for the change in vacuum as a function of flow. These evaluations were used to design the screen slot size and distance between the horizontal SVE and horizontal air sparging wells in the full-scale pilot test and remediation system.

The objective for the full-scale test was to affect a 150-foot radius with the horizontal SVE well having 1 to 2 scfm per foot of well screen with an air pressure at the well end equivalent to 10 inches of water. For the full scale horizontal air sparging well, the objective was to affect a 50-foot zone of influence with a 0.4 to 0.8 scfm per foot of well screen having a pressure of 3.89 psi at the well end.

A full-scale pilot test was conducted to verify the findings of the pilot test and collect additional data for the design of the remediation system. The horizontal SVE well used in the full-scale test was installed to a depth of 3.5 feet with a total length of 660 feet and a 530-foot long well screen. The screen used a 0.25-inch slotted well screen with the distance between slots varying from 0.25 to 0.875 inch with the larger spacing being located nearer the blower end of the well. The horizontal air sparging well had a total length of 680 feet with a screen length of 480 feet installed 12 feet bgs. Pressure and vapor monitoring points were installed on either side of the wells to determine zone of influence. Figures 5-12 and 5-13 illustrate the soil vacuum and sparge pressure at the maximum blower rates.

Results of the full-scale pilot test showed that the maximum zone of influence for SVE ranged from 250 feet at the beginning of the screen (closest to the blower) to 120 feet at the middle and 185 feet at the end of the screen. The flow rate from the horizontal SVE well ranged from 220 to 720 cfm. The SVE air flow per foot of screen length ratio was 0.42 to 1.37 cubic feet per minute per foot (cfm/ft). The goal of 1.13 cfm/ft along the entire length of screen was not realized. The investigators determined the air flow rate per section of screen using the streamline and equipotential distribution of vacuum and pressure for each test.

The zone of influence for the air sparging well was a maximum of 52 feet. The distribution of air sparging pressure was elliptical as in the horizontal SVE well test. The maximum zone of influence observed was 52, 30, and 10 feet at the beginning, middle, and end of the screen, respectively. The air sparging flow rate ranged from 60 to 480 cfm, and air flow per foot of screen length ratio was 0.13 to 1.01 cfm/ft. The goal for zone of influence of the air sparging well was 40 feet with an air flow per foot of screen length ration of 0.9.

The flow rate in the screen portion of the well closest to the SVE blower was 3 times greater than the flow rate further from the blower. This information was used to design the screen for the remediation system. The goal of the final design was to have even air flow along the length of the horizontal SVE and horizontal air sparging well. To compensate for this air flow variation along the screen section, the screens for the full-scale remediation were designed to have the open area of the screens toward the end of the well. The open area is approximately 2 times greater than the area at the beginning of the well.

The pilot test also demonstrated reduction of significant concentrations of VOCs in groundwater as well as VOC extraction rates within the soil vapor.

The full system of the horizontal SVE and horizontal air sparging wells were installed over a 3-month period at the International Arrivals Building. Logistical considerations were intensive at an active airport with the requirements of minimal disruption of traffic at the tarmac and at the gates. A 2-month reconnaissance and scheduling effort was undertaken just to locate the borehole paths. Fifteen horizontal SVE wells were installed to screen depths of about 3.5 to 5 feet bgs. Twenty seven horizontal air sparging wells were installed with screen depths at about 12 feet bgs. More than 3,700 feet of interconnecting subsurface manifolds and piping was installed to connect the well fields to the three treatment system buildings constructed for the project. In addition, 15 vertical SVE and 28 vertical air sparging wells were installed.

The results of the remediation during the first 2 months of operation show that the systems have extracted about 18,600 pounds of vapor phase VOCs. The concentration of VOCs and methane have steadily decreased with time, indicating the system effectiveness. Several wells within the system have air flow per foot of screen rates within the design specifications. However, several wells are operating with air flow per foot of screen rates below design specification. In addition, many wells have pressure and air flow drops from the blower to the ends of the screen lengths. It is anticipated that these rates will increase as the residual drilling fluid in the wells biodegrade and pore water in the vadose zone evaporates.

5.4.2 Cost Analysis

Obtaining cost data from vendors was difficult. In general, they would not release specific information on their cost structure. Cost information based on interview responses obtained from the vendors and experts seem to agree on a price range of 100 to 150 dollars per foot for an installation of horizontal wells using HDPE well materials. This compares to a price range of 30 to 50 dollars per foot for a vertical well. This cost would be representative of a turnkey installation including all well installation materials, surface completions, and development. Using stainless steel or prepack screens can increase this cost by 100 dollars per foot.

When comparing the cost of horizontal to vertical well installations, it is important to consider the entire system costs and not just well installation. Horizontal wells can be shown to be more efficientfrom a performance standpoint and less costly to install and operate than vertical wells when the costs of blowers, downhole pumps, manifolding and piping and surface treatments units are considered.

5.5 VENDORS

Table 5-1 presents a list of vendors that were identified and contacted as part of this investigation. The vendors presented here represent a list of vendors who supply directional drilling services for the environmental community. This list is likely a subset of vendors with the capability to install a horizontal well for environmental purposes. Additionally, with recent advancements in drilling mud formulations and screen design plus a training program recently developed by Ditch Witch, Inc., in Perry, Oklahoma, drilling companies that currently provide directional drilling services to the utility industry are expected to emerge as having the capability to conduct environmental drilling services. When seeking a directional drilling contractor, it is important to conduct a search for contractors who have experience in drilling boreholes in the local geologic framework. In doing so, a project team has a greater level of confidence that the drilling contractor will install the well to meet the project specifications.

5.6 STRENGTHS AND LIMITATIONS

The following list outlines some of the strengths of using horizontal well technology for environmental remediation:

- Boreholes can follow the geometric trend of the contaminant plume since the boreholes can be guided in the horizontal plane. One horizontal well can remediate a surface area many times that of a single vertical well because contaminant plumes are generally vertically thin and horizontally extensive. This is because horizontal hydraulic conductivities are generally several times those of vertical hydraulic conductivities.

- Horizontal wells can access contaminated areas that cannot be reached by conventional remedial methods.

- Horizontal wells cause minimal impact to activities at the ground surface such as vehicle traffic, plant operations, and flight lines.

- Horizontal wells technology is nondestructive in that it does not damage existing land improvements.

- Horizontal wells can be completed in most geologic environments by the use of alternative drilling mud fluids.

- Although installation costs are more expensive on a per footage basis, a network of horizontal wells can be more cost effective when indirect factors are considered (for example, surface piping networks, downhole pump requirements, and effective area of influence of the well). Pilot testing at the DOE SRS demonstrated that horizontal wells for vapor extraction can be up to 5 times more efficient than vertical wells because of a larger effective zone of influence (Looney and others 1991).

The following list outlines some of the limitations of using horizontal well technology for environmental remediation:

- The vertical capture zone of a horizontal well is limited by the vertical hydraulic conductivity of the formation. If the contamination is distributed across several geologic strata, the effectiveness of horizontal wells may be reduced.

- Areas with highly fluctuating water tables can cause problems with SVE systems if the water table variability is not fully understood.

- Drilling fluids can disturb and alter the borehole surface and reduce the effective permeability of the geologic formation, limiting the zone of influence of the well.

- Installation of horizontal wells is several times more expensive than installation of vertical wells. A careful cost analysis must be conducted to determine the feasibility of a horizontal well drilling program.

- Installation of horizontal wells requires knowledge of all potential subsurface obstacles along its path. Detailed mapping along the borehole path may be required.

- Others limitations and considerations include: impacts of drilling fluids on SVE well efficiency, difficulties in well development, uniform air delivery/recovery, drilling fluid breakout, and potential drainage to surface features (invasion).

5.7 RECOMMENDATIONS

Air sparging and SVE horizontal wells are most applicable to conducting remedial activities in the following situations: in areas where access is limited to install a vertical well network; where the contaminant zone is less than 80 bgs (due to high costs associated with deeper installations); where the contaminant has a linear/ellipsoid geometry; and where the contaminant is located within a single stratigraphic horizon. Horizontal wells are best suited to be installed in silty sand, sand and fine gravel lithologies. The costs increase dramatically in geologic environments that include bedrock, clay, glacial till, cobbles, and boulders. In remedial systems which specify a trench or cut off wall as the preferred alternative, a horizontal well may be able to create a permeable zone when used with sparging. Horizontal wells can eliminate the need for excavation in areas where space is limited.

5.8 REFERENCES

This section includes a list of references cited in Chapter 5 (Subsection 5.8.1) and a table presenting professional contacts (Subsection 5.8.2). A comprehensive bibliography is provided in Appendix B.

5.8.1 Cited References

Armstrong, J.E., C.A. Mendoza, B.J. Moore, and P.E. Hardisty. 1995. A Comparison of Horizontal Versus Vertical Wells for Soil Vapour Extraction. Presented at Solutions ‘95, International Association of Hydrogeologist Congress XXVI. Edmonton, Alberta. June 4 - 10.

Bardsley, D.S. 1995. Horizontal Well Materials. World Wide Web Home Page (http//:www.horizontalwell.com). Environmental Consultants LLC.

Downs, C.E. 1996. Multimedia Remediation Applications of Horizontal Wells. In: Proceedings of the Tenth National Outdoor Action Conference and Exposition, Las Vegas, Nevada. National Ground Water Association. Las Vegas, Nevada. Pages 237-243. May 13-15.

Kaback, D.D., B.B. Looney, C.A. Eddy, and T.C. Hazen 1991. Innovative Ground Water and Soil Remediation: In Situ Air Stripping Using Horizontal Wells, Westinghouse Savannah River Company, Savannah River Site, Aiken South Carolina. In Proceedings of the Fifth National Outdoor Action Conference and Exposition. Las Vegas, Nevada. National Ground Water Association.

Kaback, D.D., and D. Oakley. 1996. Horizontal Environmental Wells in the United States: A Catalogue. Colorado Center for Environmental Management. 999 18th Street, Suite 2750, Denver, Colorado 80202. (303) 297-0180. April.

Knaebel, K.S. 1981. Simplified Sparger Design. Chemical Engineering. March 9. Pages 116-117.

Looney, B.B., T. Hazen, D. Kaback, and C. Eddy. 1991. Full-Scale Field Test of the In Situ Air Stripping Process at the Savannah River Integrated Demonstration Test Site. WSRC-RD-91-22. Aiken, South Carolina. Westinghouse Savannah River Company. July 29.

Lundegard, P.D., and G. Anderson. 1996. Multi-Phase Numerical Simulation of Air Sparging Performance: Groundwater. Volume 34(3). Pages 451-460.

Lundegard, P.D., Chaffee, B. and D. LaBrecque. 1996. Effective Design of a Horizontal Air Sparging Well. Presented at the St. International Conference on Air Sparging, International Network of Environmental Training, Inc. October 24.

Mast, V.A., and C.E. Koerner. 1996. Environmental Horizontal Directional Drilling Technology. No-Dig Engineering, Volume 3, Number 2. Pages 17-21. March and April.

May, D.W. 1994. The Use of Horizontal Wells for Subsurface Soil and Aquifer Restoration, Drilling Technology. In: J.P. Vozniak, ed,. American Society of Mechanical Engineers, New York, New York. PD-Volume 56. Pages 227-239.

Mendoza, C.A. 1992. VapourT Users Guide. Department of Geology, University of Alberta, Edmonton.

Perry, R.H., and C.H. Chilton, ed. 1975. Chemical Engineers Handbook. Fifth Edition. McGraw Hill. New York.

Tetra Tech EM Inc. (Tetra Tech) 1996a. Personal Communication between Paul Frankel, Hydrogeologist, and Marvin Kirshner, Chief Environmental Engineer, Port Authority of NY and NJ. September.

Tetra Tech. 1996b. Personal Communication between Paul Frankel, Hydrogeologist, and Eric Meyer, Design Engineer, Radian Corporation. September.

Tetra Tech. 1996c. Personal Communication between Paul Frankel, Hydrogeologist, and Charlie Downs, Design Engineer, Pollution Prevention Associates. September.

Tetra Tech. 1996d. Personal Communication between Paul Frankel, Hydrogeologist, and Michael Lubrecht, Marketing Director, Directed Technologies Drilling, Inc. September.

Roth, R.J., and N.C. Pressly. 1996. Remediation of Jet-Fuel-Contaminated Soil and Groundwater at JFK International Airport Using Horizontal Air Sparging and Soil Vapor Extraction. Presented at the First International Conference on Air Sparging. International Network of Environmental Training, Inc. October 24.

U.S. Department of Energy. 1995. In Situ Bioremediation Using Horizontal Wells, Innovative Technology Summary Report. Prepared by Colorado Center for Environmental Management. Denver, CO.

U.S. Environmental Protection Agency. 1994. Alternative Methods for Fluid Delivery and Recovery. EPA/625/R-94/003.

Vinsome, P.D.W., and G.M. Shook. 1993. Multi-Purpose Simulation. Journal of Petroleum Science and Engineering. Volume 9. Pages 29-38.

Wade, A., G.W. Wallace, S.F. Siegwald, W.A. Lee, and K.C. McKinney. 1996. Performance Comparison Between a Horizontal and a Vertical Air Sparging Well: A Full-Scale One-Year Pilot Study. In: Proceedings of the Tenth National Outdoor Action Conference and Exposition, Las Vegas, Nevada. National Ground Water Association. Pages 189-206. May 13-15.

Wilson, D. D. 1995a. Introduction to 1995 NGWA Environmental Horizontal Well Seminar. World Wide Web Home Page (http//:www.horizontalwell.com). October.

Wilson, D.D. 1995b. Environmental Horizontal Well Drilling and Installation Methods. World Wide Web Home Page (http//:www.horizontalwell.com), by Environmental Consultants, LLC.

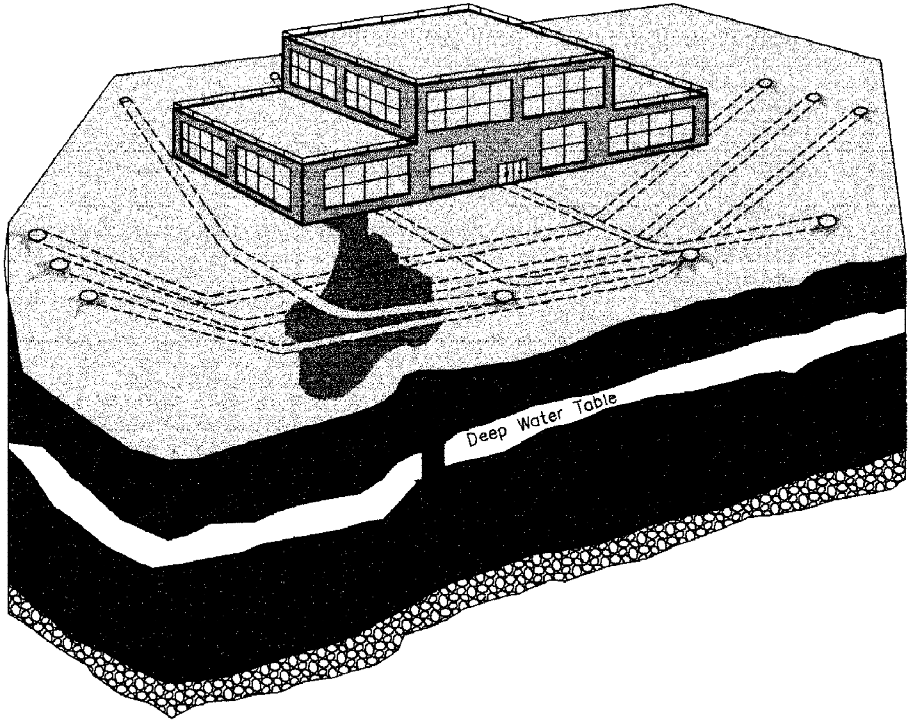
5.8.2 Professional Contacts

Name	Affiliation
Armstrong, James (403) 247-0200	Komex International, Ltd.
Birdwell, Dale (405) 235-3371	Genesis Environmental
Cox, Bob (510) 227-1105 x420	OHM, Inc.
Downs, Charlie, Ph.D. (303) 936-4002	Private Consultant, Pollution Prevention Associates
Fournier, Louis B. (610) 558-2121	STAR Environmental
Kaback, Dawn (303) 297-0180 x111	Colorado Center for Environmental Management
Kirshner, Marv Ph: (212) 435-8255 Fx: (212) 435-8276 Alt Ph: (201) 961-6600 x8255	Port Authority of New York and New Jersey
Layne, Roger 1-800-654-6481	Ditch Witch, Inc., The Charles Machine Works, Inc.
Meyer, Eric (504) 922-4450	Radian Corporation, Baton Rouge
Pressly, Nick (516) 286-5890	Pressly & Associates, Inc.
Wilson, David D. (303) 422-1302	Horizontal Well and Environmental Consultants, Inc.

INFORMATION CENTERS

Organization	Contact Name	Services
National Ground Water Association 1-800-551-7379	Mark Shepherd x. 594	Provide database search for issues related to groundwater
Remedial Action Program Information Center (423) 241-3098	Mary Bales	Collect documentation on issues related to decontamination, decommissioning, and remediation of sites

FIGURE 5-1
HORIZONTAL WELL NETWORK INSTALLED BENEATH A BUILDING TO REMEDIATE SOIL AND GROUNDWATER



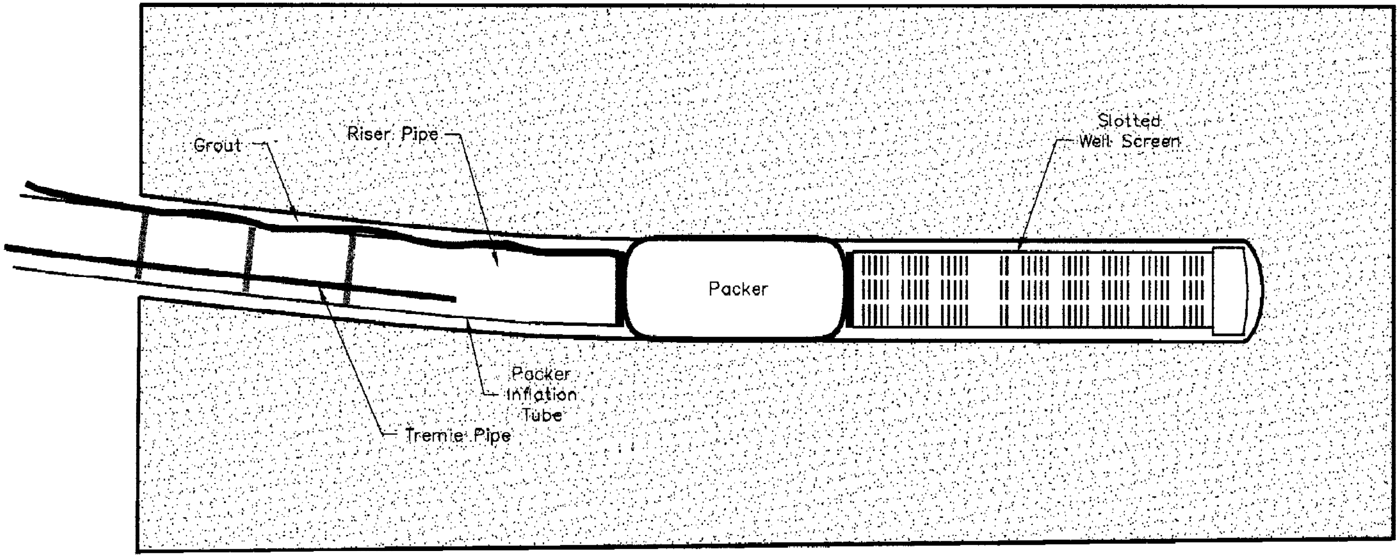
SOURCE: MODIFIED FROM WEMPLE AND OTHERS 1994

HORIZONTAL WELL NETWORK INSTALLED BENEATH A BUILDING TO REMEDIATE SOIL AND GROUNDWATER

FIGURE

5-1

FIGURE 5-2
BLIND BOREHOLE COMPLETION

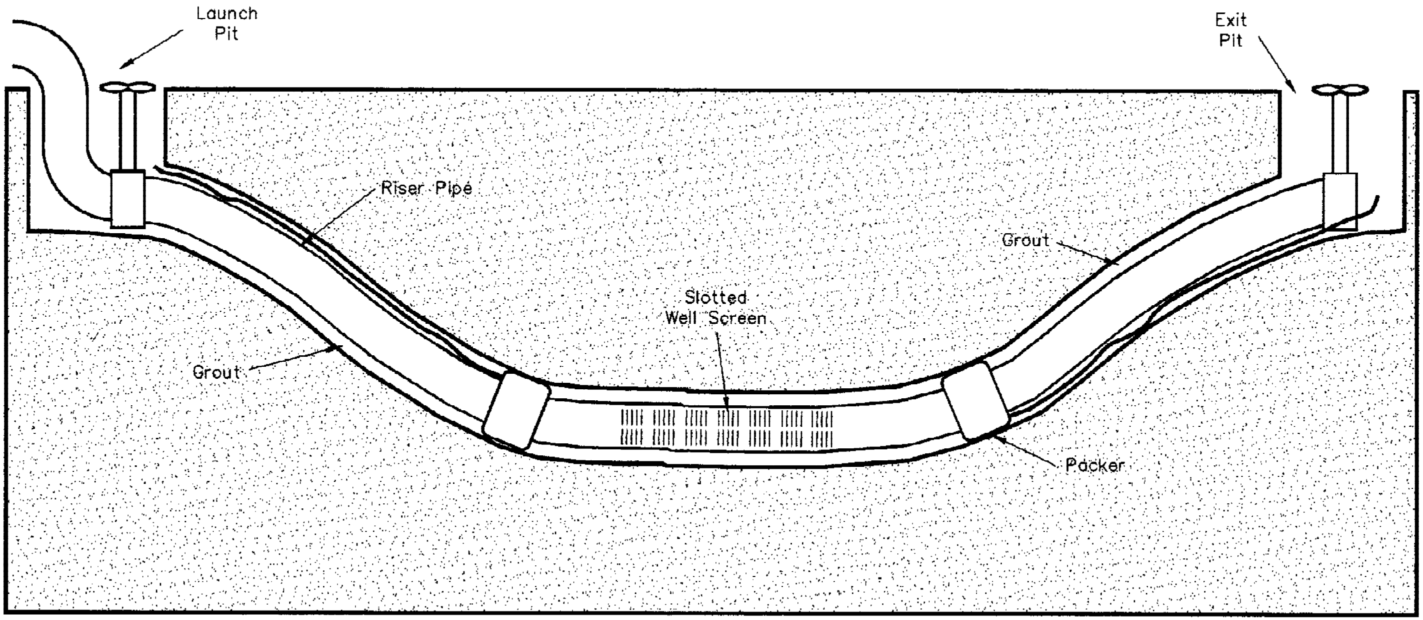


SOURCE: MODIFIED FROM DIRECTED TECHNOLOGIES DRILLING, INC. 1996

BLIND BOREHOLE COMPLETION

FIGURE
5-2

FIGURE 5-3
CONTINUOUS WELL COMPLETION

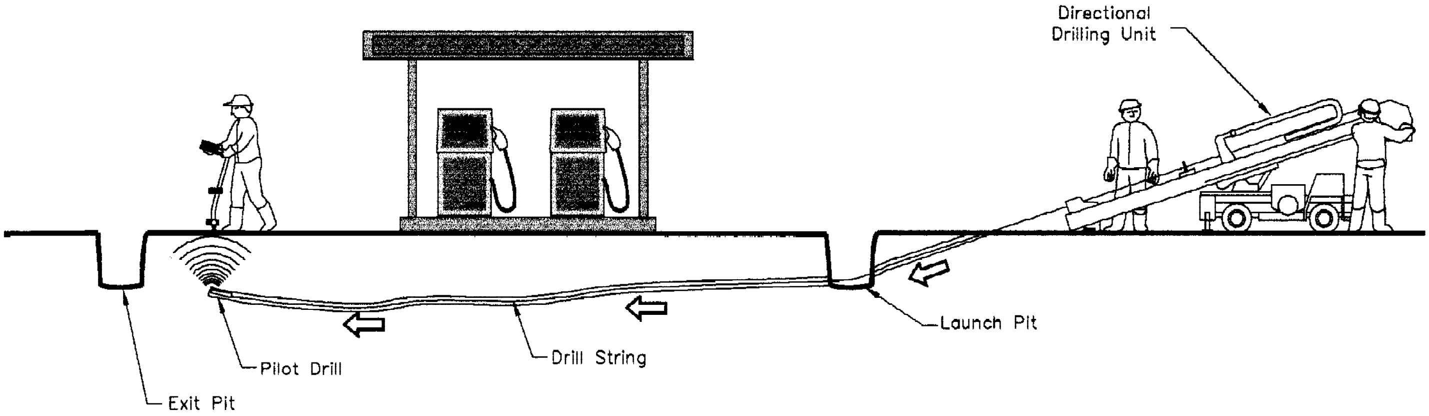


SOURCE: MODIFIED FROM DIRECTED TECHNOLOGIES DRILLING, INC. 1996

CONTINUOUS WELL COMPLETION

FIGURE
5-3

FIGURE 5-4
PILOT HOLE ADVANCEMENT

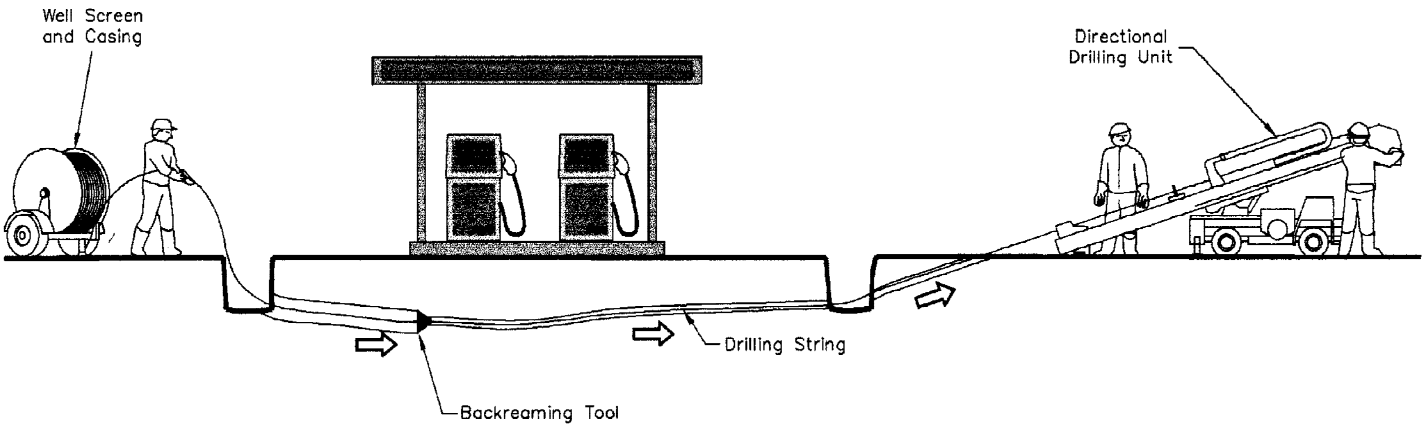


SOURCE: MODIFIED FROM DIRECTED TECHNOLOGIES DRILLING, INC. 1996

PILOT HOLE ADVANCEMENT

FIGURE
5-4

FIGURE 5-5
BACK REAMING AND WELL CASING INSTALLATION

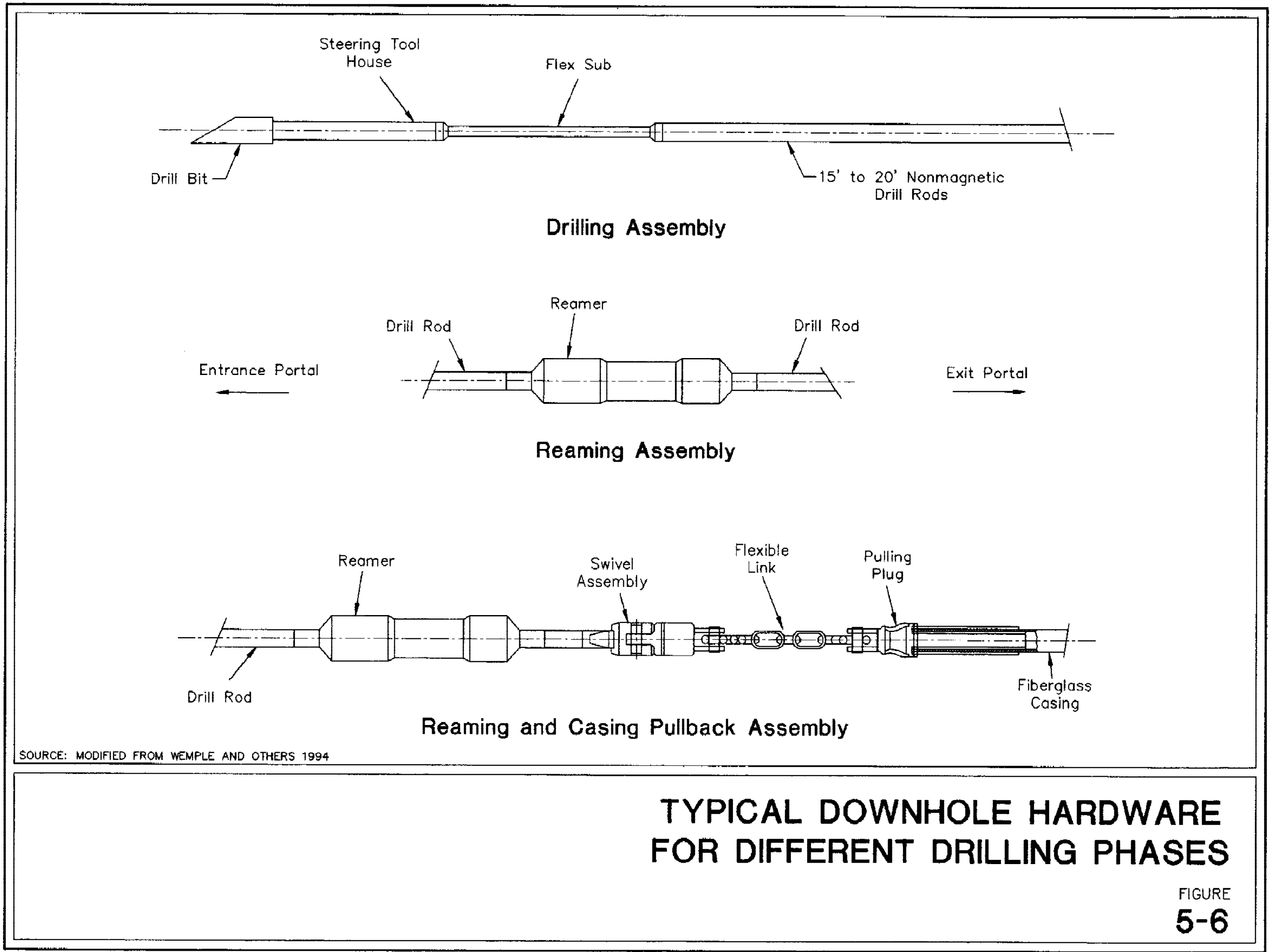


SOURCE: MODIFIED FROM DIRECTED TECHNOLOGIES DRILLING, INC. 1996

BACKREAMING AND WELL CASING INSTALLATION

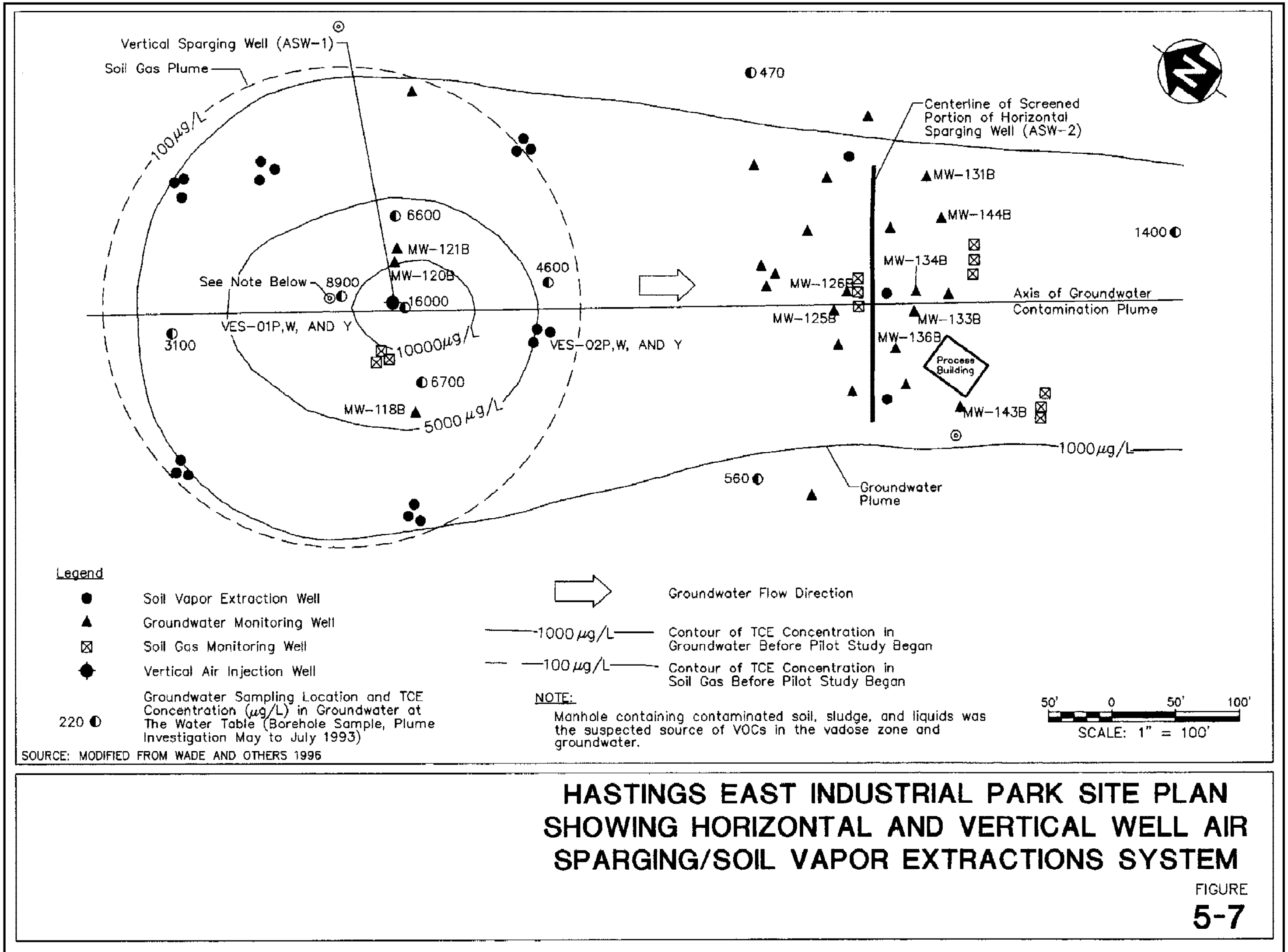
FIGURE
5-5

FIGURE 5-6
TYPICAL DOWNHOLE HARDWARE FOR DIFFERENT DRILLING PHASES



SOURCE: MODIFIED FROM WEMPLE AND OTHERS 1994

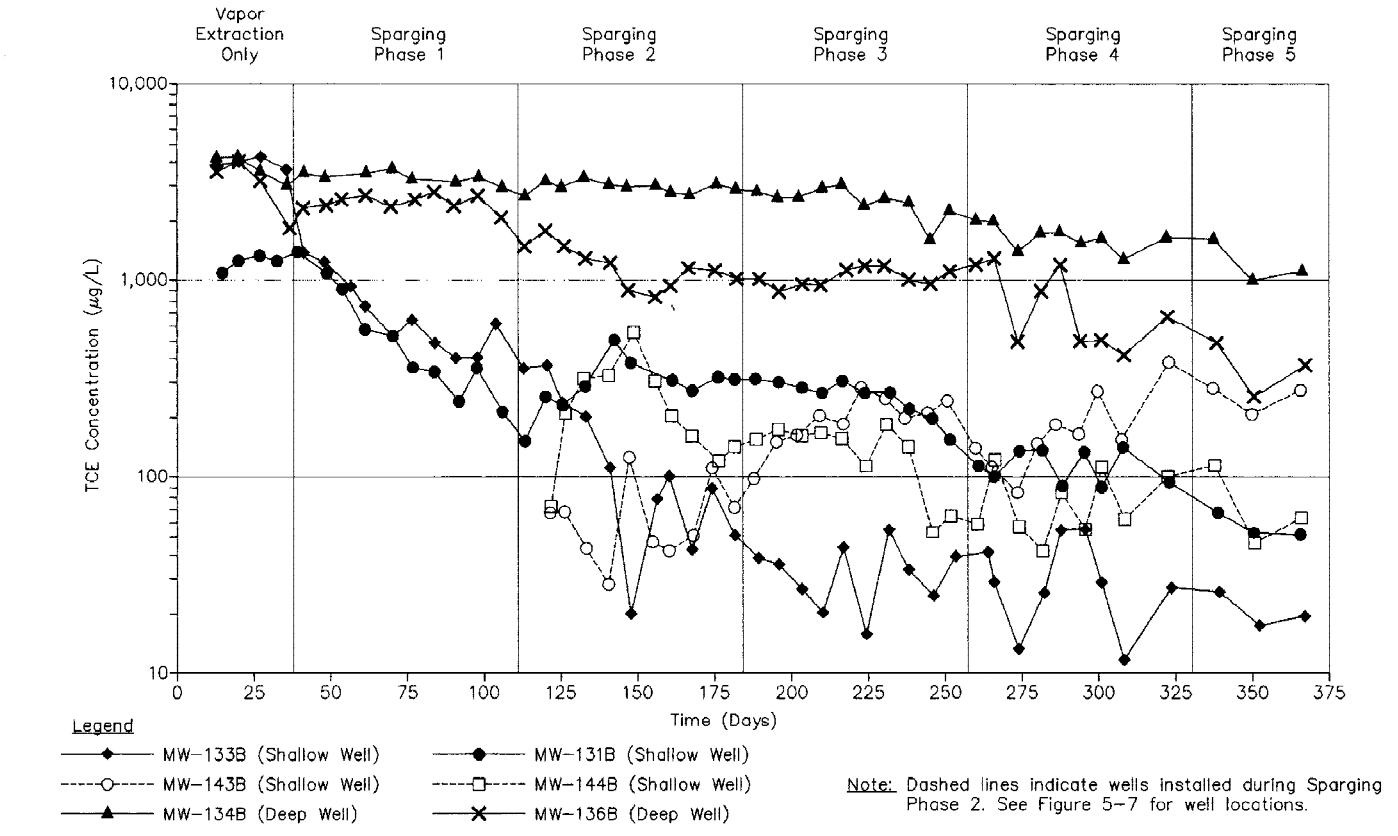
FIGURE 5-7
HASTINGS EAST INDUSTRIAL PARK SITE PLAN SHOWING HORIZONTAL AND VERTICAL WELL AIR SPARGING/SOIL VAPOR EXTRACTION SYSTEM



NOTE: Manhole containing contaminated soil, sludge, and liquids was the suspected source of VOCs in the vadose zone and groundwater.

SOURCE: MODIFIED FROM WADE AND OTHERS 1996

FIGURE 5-8
TCE CONCENTRATIONS IN SIX GROUNDWATER MONITORING WELLS DOWNGRADIENT FROM THE HORIZONTAL SPARGING WELL



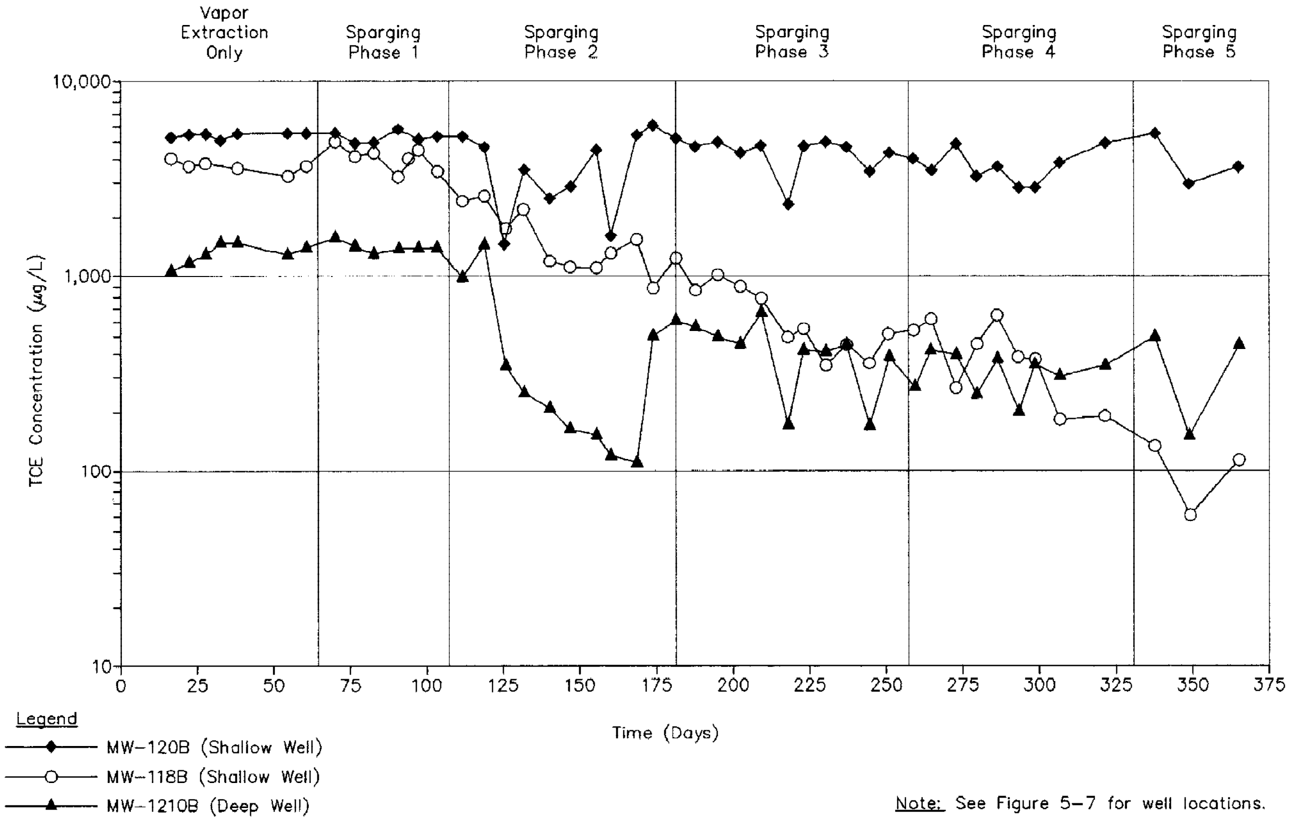
Note: Dashed lines indicate wells installed during Sparging Phase 2. See Figure 5-7 for well locations.

SOURCE: MODIFIED FROM WADE AND OTHERS 1996

TCE CONCENTRATIONS IN SIX GROUNDWATER MONITORING WELLS DOWNGRADIENT FROM THE HORIZONTAL SPARGING WELL

FIGURE
5-8

FIGURE 5-9
TCE CONCENTRATIONS IN THREE GROUNDWATER MONITORING WELLS NEAR THE VERTICAL SPARGING WELL



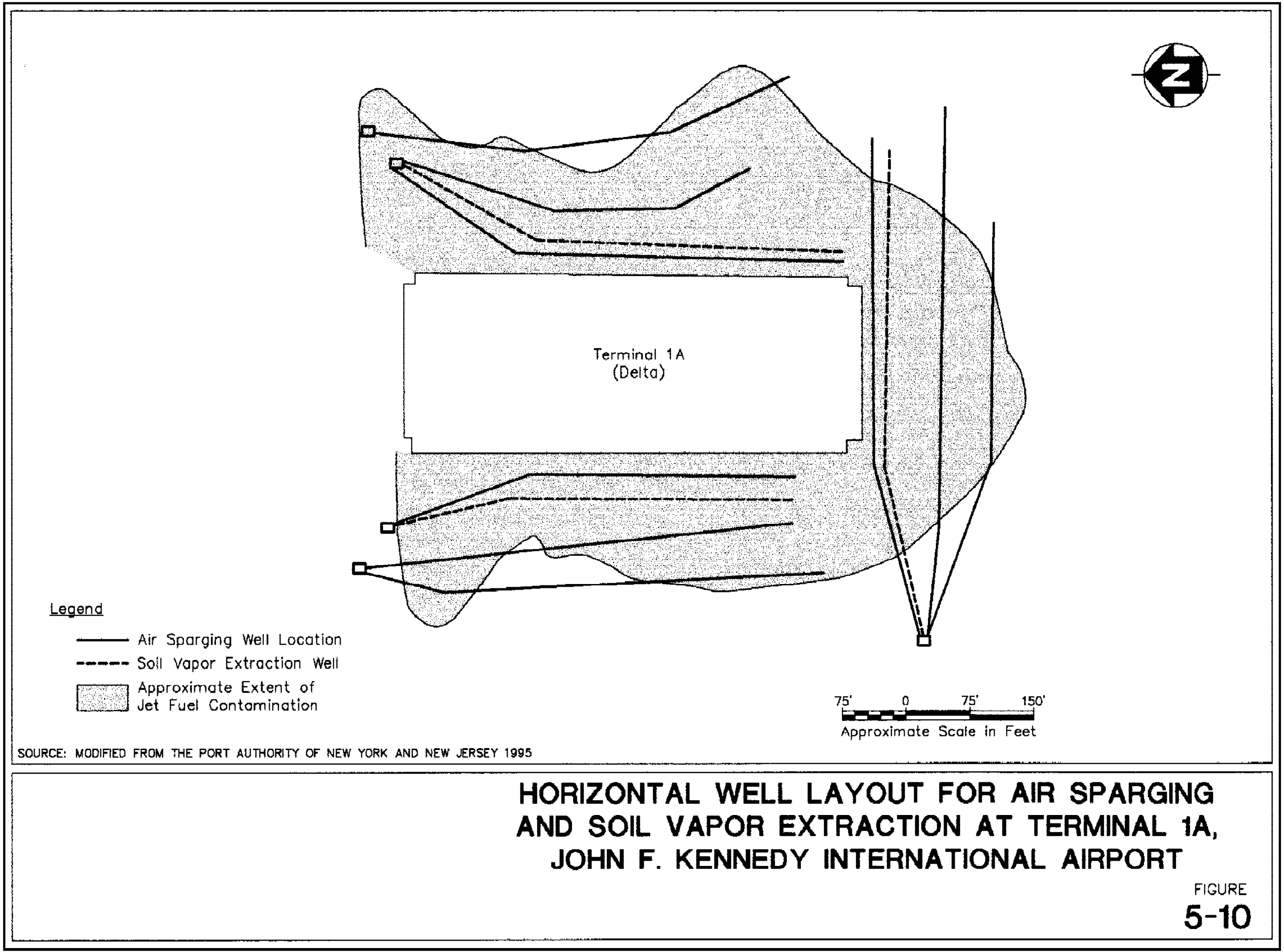
Note: See Figure 5-7 for well locations.

SOURCE: MODIFIED FROM WADE AND OTHERS 1996

TCE CONCENTRATIONS IN THREE GROUNDWATER MONITORING WELLS NEAR THE VERTICAL SPARGING WELL

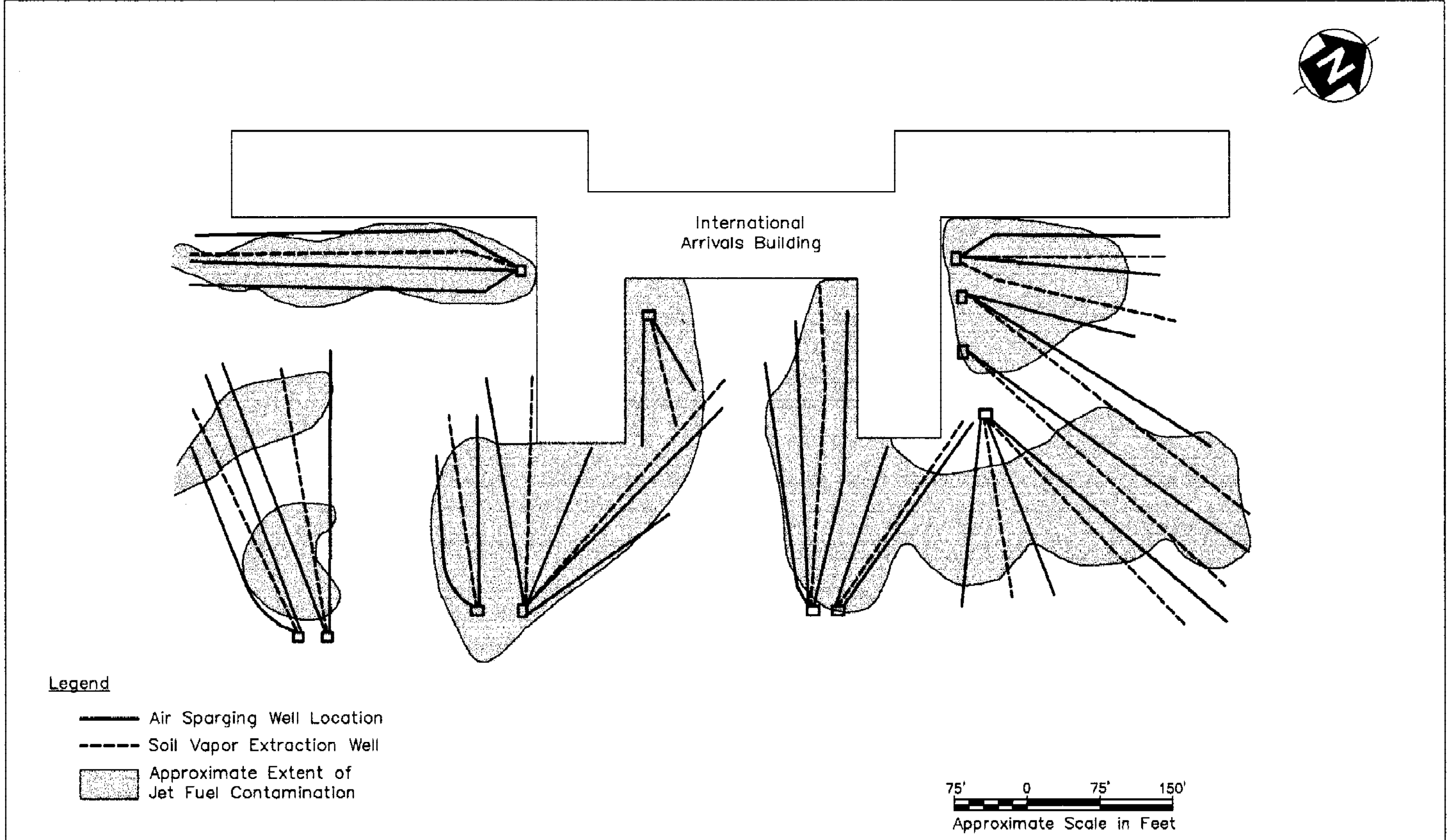
FIGURE
5-9

FIGURE 5-10
HORIZONTAL WELL LAYOUT FOR AIR SPARGING AND SOIL VAPOR EXTRACTION AT TERMINAL 1A, JOHN F. KENNEDY INTERNATIONAL AIRPORT



SOURCE: MODIFIED FROM THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY 1995

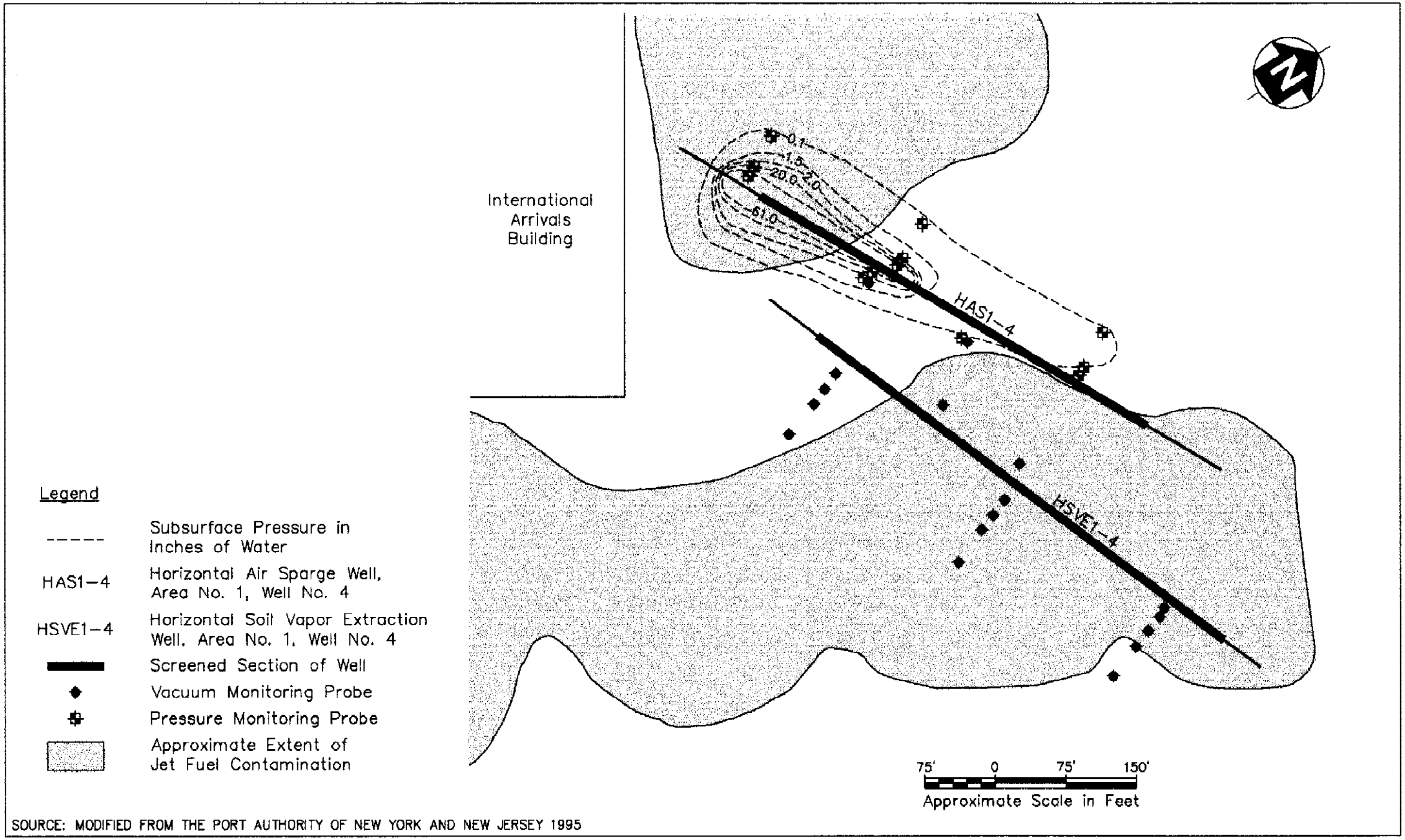
FIGURE 5-11
HORIZONTAL WELL LAYOUT FOR AIR SPARGING AND SOIL VAPOR EXTRACTION AT THE INTERNATIONAL ARRIVALS BUILDING, JOHN F. KENNEDY INTERNATIONAL AIRPORT



SOURCE: MODIFIED FROM THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY 1995

HORIZONTAL WELL LAYOUT FOR AIR SPARGING
AND SOIL VAPOR EXTRACTION AT THE INTERNATIONAL
ARRIVALS BUILDING, JOHN F. KENNEDY INTERNATIONAL AIRPORT
FIGURE
5-11

FIGURE 5-12
AIR SPARGING PILOT TEST, NOVEMBER 1995 AT THE INTERNATIONAL ARRIVALS BUILDING, JOHN F. KENNEDY INTERNATIONAL AIRPORT



SOURCE: MODIFIED FROM THE PORT AUTHORITY OF NEW YORK AND NEW JERSEY 1995

AIR SPARGING PILOT TEST, NOVEMBER 1995
AT THE INTERNATIONAL ARRIVALS BUILDING,
JOHN F. KENNEDY INTERNATIONAL AIRPORT

FIGURE
5-12

FIGURE 5-13
SOIL VAPOR EXTRACTION PILOT TEST NOVEMBER 1995 AT THE INTERNATIONAL ARRIVALS BUILDING, JOHN F. KENNEDY INTERNATIONAL AIRPORT

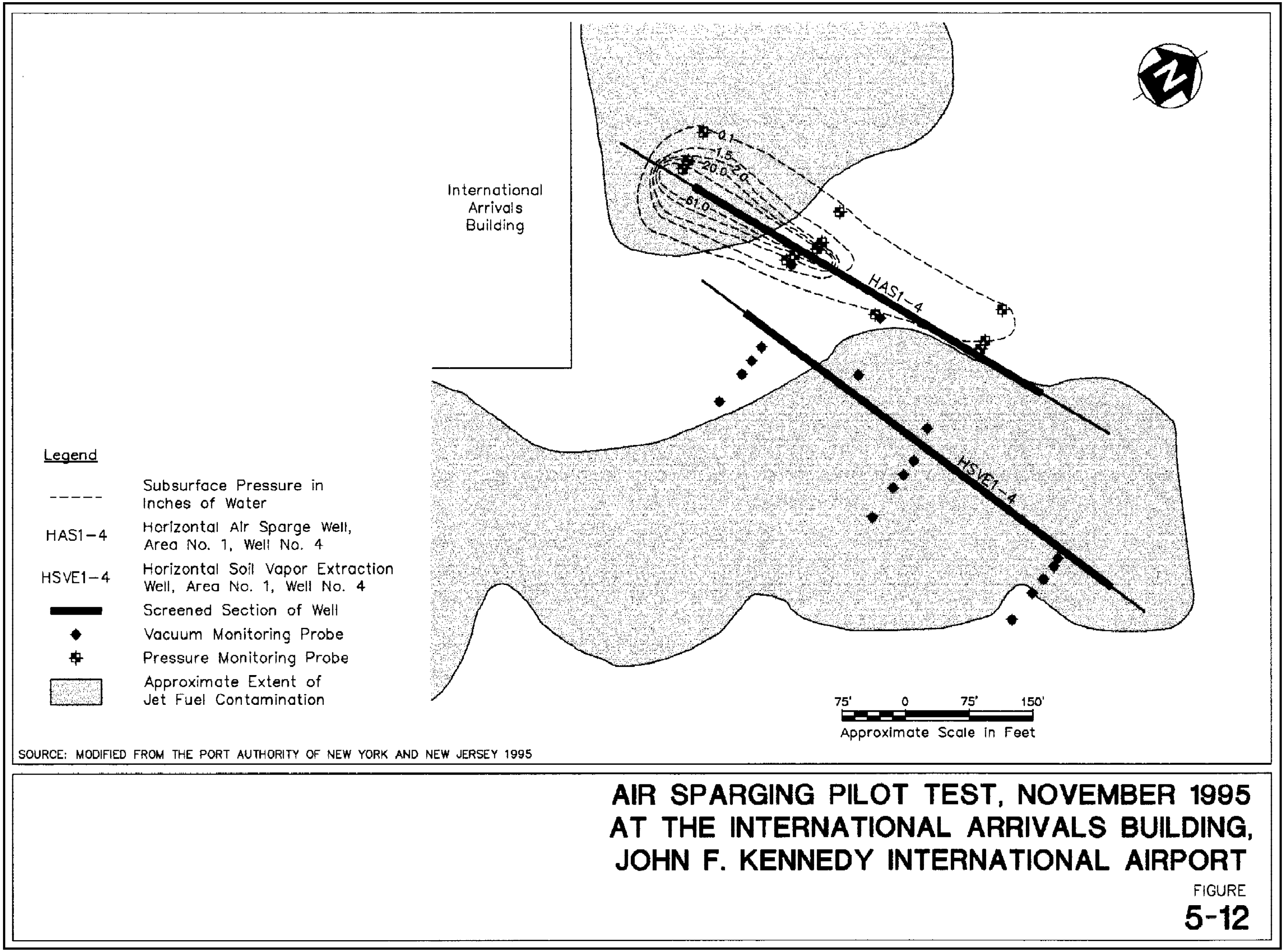


TABLE 5-1

VENDORS OF HORIZONTAL WELLS AND DIRECTIONAL DRILLING TECHNOLOGY[a]
(Page 1 of 3)

Name of Vendor	Address, Phone, Fax	Point of Contact
American Augers, Inc. (Drill Rig Manufacturer)	135 U.S. Route 42 P.O. Box 814 West Salem, OH 44287 Ph: (419) 869-7107 Fx: (419) 869-7425 1-800-324-4930	Gary Stewart
Davis Horizontal Drilling, Inc.	7204 Timberlake Mustang, OK 73064 Ph: (405) 376-2702 Fx: (405) 376-3807	Roland Davis
Directed Technologies Drilling, Inc.	1315 South Central Ave, Suite G Kent, WA 98032 1-800-239-5950 Ph: (206) 850-2848 Fx: (206) 850-2824 mlubrecht@accessone.com	Michael Lubrecht
Directional Drilling, Inc.	P.O. Box 159 Oakwood, GA 30566 *or* 3536 Atlanta Highway Flowery Branch, GA 30542 Ph: (770) 534-0083 Fx: (770)531-9553	Jim McEntire
Ditch Witch, Inc., The Charles Machine Works, Inc. (Drill Rig Manufacturer)	P.O. Box 66 Perry, OK 73077 Ph: (405) 336-4402 1-800-654-6481 Fx: (405) 336-3458	Roger Layne
Drilex Inc.	15151 Sommermeyer Houston, TX 77041 Ph: (713) 957-5470 Fx: (713) 957-5483	David Bardsley
Fishburn Environmental Drilling	5013 State Route 229 P.O. Box 278 Marengo, OH 43334	Stuart Brown

TABLE 5-1

VENDORS OF HORIZONTAL WELLS AND DIRECTIONAL DRILLING TECHNOLOGY[a]
(Page 2 of 3)

Name of Vendor	Address, Phone, Fax	Point of Contact
GTS Horizontal Drilling Co.	1231 B East Main Street, Suite 189 Meriden, CT 06450 1-800-239-8079	Tom Bryant
Horizontal Drilling Technologies	2414 S. Hoover Road Wichita, KS 67215 Ph: (316) 942-3031	Mark Mesner
Horizontal Subsurface Technologies, Inc.	634 West Clarks Landing Road Egg Harbor, NJ 08215 1-800-965-0024	
Horizontal Technologies, Inc.	2309 Hancock Bridge Parkway P.O. Box 150820 Cape Coral, FL 33915	Donald Justice
Kelly Corp.	Ph: (204) 544-9462	Ken Kelly
KVA Slantwell Installations/KVA Analytical Systems	15 Carlson Lane Falmouth, MA 02540 Ph: (508) 540-0561 Fx: (508) 457-4810	Steve or Pat
Mears/HDD, Inc.	4500 North Mission Road Rosebush, MI 48878-0055 1-800-632-7727 Fx: (517) 433-5433	Dick Gibbs
Michels Environmental Services	817 West Main Street (main office) Brownsville, WI 53006 Ph: (414) 583-3132 Fx: (414) 583-3429	Tim McGuire Ph: (303) 423-5761 Fx: (303) 423-1947
OHM Remediation Services Group	5731 W. Las Positas Blvd Pleasanton, CA 94588 Ph: (510) 227-1105	Robert Cox
Pledger, Inc.	12848 SE Suzanne Drive Hobe Sound, FL 33455 Ph: (407) 546-4848 Fx: (407) 546-3211	Steve McLaughlin

TABLE 5-1

VENDORS OF HORIZONTAL WELLS AND DIRECTIONAL DRILLING TECHNOLOGY[a]
(Page 3 of 3)

Name of Vendor	Address, Phone, Fax	Point of Contact
SCHUMASOIL® Schumacher Filters America, Inc.	P.O. Box 8040 Asheville, NC 28814 Ph: (704) 252-9000 Fx: (704) 253-7773	Anne Ogg
Stearns Drilling	6974 Hammond S.E. Dutton, MI 49316 Ph: (616) 698-7770 Fx: (616) 698-9886	Roland Clapp
Trenchless Technology Center	Department of Civil Engineering P.O. Box 10348 Louisiana Technical University Ruston, LA 71272	
Vermeer Manufacturing (Drill Rig Manufacturer)	Route 1 P.O. Box 200 Pella, IA 50219 Ph: (515) 628-3141	David Whampler

Note: a This list is not inclusive of all vendors capable of providing horizontal wells and directional drilling technologies. This list reflects vendors identified who provided horizontal drilling and support services during the preparation of this report.

CHAPTER 6.0

PNEUMATIC AND HYDRAULIC FRACTURING

This chapter discusses pneumatic and hydraulic fracturing technologies used to enhance SVE, as well as other remediation technologies. Environmental applications of blast fracturing techniques have to date only been used to enhance a limited number of pump-and-treat methods (Miller 1996) and, therefore, will not be included in this discussion on SVE enhancement technologies. Interested readers are referred to the literature citations in the bibliography section for more information on this topic. The following sections provide an overview of pneumatic and hydraulic fracturing, describe conditions under which the technology is applicable, contain a detailed description of fracturing methods, highlight performance data, list vendors that provide pneumatic and hydraulic fracturing services, outline the strengths and limitations of the technology, and provide recommendations for using the technology.

6.1 TECHNOLOGY OVERVIEW

Pneumatic and hydraulic fracturing are recognized methods adapted from the petroleum industry to induce fractures to improve the performance of extraction or injection wells. The two enhancement technologies involve the injection of either gases (typically air) or fluids (either water or slurries) to increase the permeability of the area around an injection well, thereby allowing increased removal or degradation rates of contaminants and potentially more cost-effective remediation.

Pneumatic fracturing typically involves the injection of highly pressurized air into soil, sediments, or bedrock to extend existing fractures and create a secondary network of conductive subsurface fissures and channels. The enhanced network of fractures increases the exposed surface area of the contaminated soil, as well as its permeability to liquids and vapors. The pore gas exchange rate, often a limiting factor during vapor extraction, can be increased significantly as a result of pneumatic fracturing, thereby allowing accelerated removal of contaminants. Figure 6-1 illustrates in a cross section the effects of pneumatic fracturing enhanced vapor extraction (EPA 1993a).

In hydraulic fracturing, water or a slurry of water, sand, and a thick gel is used to create distinct, subsurface fractures that may be filled with sand or other granular material. The fractures are created through the use of fluid pressure to dilate a well borehole and open adjacent cracks. Once fluid pressure exceeds a critical value, a fracture begins to propagate. The fracture continues to grow until injection ceases or pressure dissipates, the fracture intersects a barrier, a permeable channel or the ground surface, or the injected fluid leaks out through the boundary walls of the formation being fractured. Fractures may remain open naturally, or they may be held open by permeable materials, known as “proppants” (typically sand), injected during fracture propagation. The resultant fracture interval is designed to be more permeable than the adjacent geologic formation. Figure 6-2 illustrates the shape of hydraulic fracture in three dimensions and in cross section, as inferred from exposures of fracture created beneath level ground (Murdoch and others 1990).

Pneumatic and hydraulic fracturing enhancement technologies are most applicable to low-permeability geologic materials, such as fine-grained soils and over consolidated sediments, including silts and clays, as well as bedrock. Both technologies can enhance the in situ remediation of any chemical contaminants usually treated by the specific technology with which fracturing is combined. Pneumatic and hydraulic fracturing are being developed and used to enhance such remediation technologies as SVE, DPE, in situ bioremediation including bioventing, oxidation, thermal treatment including hot gas injection, in situ vitrification, and free product recovery, as well as groundwater pump-and-treat systems.

In general, the costs of pneumatic and hydraulic fracturing are estimated to be roughly equal, although pneumatic fracturing may be less expensive in some cases since it does not require the added capital costs of equipment for mixing injection slurries. Unpropped fractures may, however, close with time. In making price comparisons, users should make certain that vendors provide cost estimates that are based on comparable remediation activities and include all costs including mobilization. Typically, the factors that have the most significant effect on the unit price of fracturing are such site-specific factors as characteristics of the soil, depth of contamination, depth to groundwater, and size of the area of contamination.

6.2 APPLICABILITY

The primary application of pneumatic and hydraulic fracturing technologies is to improve the performance of wells by increasing the flow of air or fluids into or out of the area affected by a well. Pneumatic and hydraulic fracturing techniques can improve the performance of most in situ remedial technologies that involve fluid flow. The following subsections describe the applicability of fracturing to various geologic conditions, the contaminants of concern, and remediation technologies that can be enhanced through the use of pneumatic or hydraulic fracturing.

6.2.1 Geologic Conditions

Pneumatic and hydraulic fractures can be created in most naturally occurring materials, from rock to unlithified sediments or soil. Fracturing techniques have been developed to increase the permeability of fine-grained soils and rocks, such as silts, clays, and shales, because in situ remediation technologies are not usually applicable when hydraulic conductivities are less than 1 x 10^{-4} cm/s or pneumatic conductivities are less than 1 x 10^{-5} cm/s (Schuring and others 1995). Figure 6-3 shows general guidelines for the application of pneumatic fracturing in various geologic materials (Schuring and others 1995). In formations that have moderate permeabilities, pneumatic fracturing may be useful for rapid aeration and delivery of supplemental liquids or dry media, though it may not be cost-effective.

To a great extent, geologic conditions control the effectiveness of fractures, which must be significantly more permeable than the enveloping geologic formation to have a major effect on well discharge or injection. Therefore, the relative improvement resulting from pneumatic and hydraulic fractures increases as the hydraulic conductivity or permeability of the geologic formation decreases. Pneumatic and hydraulic fracturing are most effective in geologic formations containing abundant silt and clay because they have the lowest initial hydraulic conductivities or permeabilities (EPA 1994; Frank and Barkley 1995).

The state of stress in a geologic formation will affect the orientation of a fracture once it has propagated from the borehole. Fracturing is particularly suited to sites underlain by soils in which the lateral component of stress exceeds the vertical stress applied by the weight of the overburden (such soils are termed "over consolidated"). Fractures are usually flat-lying if horizontal formation stresses are greater than vertical stresses, and they tend to be steeply dipping if vertical stresses are greatest. The state of stress of soils and unlithified sediments depends on several factors, including history of consolidation and history of wetting and drying. The effect of bedding within a geologic formation can be unpredictable;

fractures follow contacts along interbedded sediments or partings between rock beds in some cases and crosscut beds in others.

The strength of the geologic formation plays an important role in determining whether fractures will stay open naturally or whether they should be filled, or propped, with a granular material, such as sand (Murdoch and others 1991; EPA 1994; Schuring and others 1995). In general, the strength of fine-grained soil decreases with increasing water content or decreasing consolidation. Therefore, fractures may stay open in dry soils but may close when the soil becomes saturated. The stress driving closure of a fracture is the stress that the geologic formation applies (for a horizontal fracture, the unit weight of the geologic formation times the depth), plus the amount of suction applied to the fracture during vapor extraction. Fractures may be propped naturally when soil or rock is strong relative to the closure stress. However, if strength decreases, depth increases, or suction increases past a critical value, fractures should be propped with granular materials.

6.2.2 Contaminants

Because pneumatic and hydraulic fracturing technologies are not in themselves remediation technologies, they are applicable to a wide range of contaminant groups, with no particular target group (Frank and Barkley 1995; EPA 1994; Schuring and others 1995). The types of treatable contaminants will depend on the primary technologies used. For example, SVE is applicable to VOCs and SVOCs, and bioremediation theoretically is capable of degrading any organic compound. Integrating pneumatic and hydraulic fracturing with those technologies will not change the basic applicability of the technologies, but it can extend the areal range of treatable contamination. For example, fracturing may make thermal injection feasible at an SVE site by improving the heat flow and transfer characteristics of the geologic formation. As a result, SVE could be used to treat compounds with lower vapor pressures that would otherwise not be suitable for such treatment. Similarly, the ability to inject biological solutions containing microbes and nutrients directly into a geologic formation may increase the biodegradation rate and the number of organic compounds that are treatable with bioremediation.

Contaminants that form complexes with the soil matrix are not always remediated effectively with the aid of enhancement fracturing; however, researchers and developers in both pneumatic and hydraulic fracturing technologies are rapidly expanding their research efforts to enhance the in situ remediation of inorganic and non-VOCs. The use of pneumatic or hydraulic fracturing to enhance the remediation of contaminants from the production of explosives remains inconclusive.

6.2.3 Technologies Enhanced by Fracturing

The typical application of pneumatic and hydraulic fractures is to improve the performance of wells used in remediation. Table 6-1 presents examples of in situ remediation technologies that can be enhanced by fracturing and the benefits of creating fractures (Frac Rite Environmental, Ltd [Frac] 1996). Currently, enhancement of SVE is the most common environmental application of pneumatic or hydraulic fracturing. Fracturing also can increase the recovery of free-phase fluids, such as LNAPLs and DNAPLs, by increasing the discharge of recovery wells. Such applications closely resemble the recovery of oil from petroleum reservoirs. DPE is the simultaneous recovery of vapor and liquid from wells with induced fractures near saturated zones. Other common applications of pneumatic and hydraulic fracturing enhancement include the injection of nutrients or oxygen-bearing fluids into the subsurface to promote bioremediation.

In addition, the application of pneumatic and hydraulic fracturing as an enhancement for remediation using electroosmosis is currently under investigation. Injection of graphite into the subsurface can create fractures that are electrically conductive. This process is similar to maintaining a pressure difference between two fractures to drive flow except that in fine-grained soils, migration by electroosmosis can be faster than migration by hydraulic flow. Research currently is also underway to combine fracturing with in situ vitrification, soil washing, and thermal treatment technologies. The development of such diverse in situ treatment methods, within targeted zones or specific geologic formations and horizons, may provide low-maintenance systems that offer major cost reductions, compared with current methods (Accutech Remedial Systems, Inc. [Accutech] 1996; Frac 1996; FRX Inc. [FRX] 1996).

6.3 ENGINEERING DESCRIPTION

For pneumatic and hydraulic fracturing technologies, the fundamentals of inducing fractures by injecting gases or fluids into the subsurface are similar (EPA 1994). The following subsections discuss the major factors that affect the creation of subsurface fractures by injection and provide detailed descriptions of the specific processes involved in the application of pneumatic and hydraulic fracturing.

6.3.1 Injection Media

The major considerations that affect the choice of injection media for creating fractures include the equipment required for injection, safety concerns, the potential to mobilize contaminants, and the ability to transport solid grains into the fracture.

Air is the primary gas used in creating pneumatic fractures, although other gases have applications under specific conditions, such as cases in which anaerobic conditions are desired. Air injection requires relatively simple equipment (EPA 1993a; EPA 1993b). High injection pressures, however, demand special safety precautions. With air injection, there is relatively little possibility of mobilizing liquid phases, but there is a strong possibility of mobilizing vapor phases. Local governments may regulate injection of air into the subsurface. Fine-grained particles or powders can be transported into fractures by injecting air. However, the ability to transport particles decreases with increasing grain size and density, an effect that limits the capability to inject significant volumes of coarse-grained materials. Through research efforts, development of specialized equipment and proppants is currently underway to improve the transport of proppant, such as sand and other materials, during air injection (EPA 1994; Accutech 1996).

Creating fractures with water requires relatively simple pumps, although pressures in excess of 700 psi may be needed to initiate the fracture (EPA 1994). Safety precautions are required because of such potentially high pressures. In some locations, injection of water is restricted by regulations. Injected water will have limited effect on the mobilization of vapors, although it may mobilize fluids. In most cases, the injected water and any fluids mobilized as a result of the injection should be recovered through the resulting fractures. Water can be used to transport solid grains into a fracture; however, the best results are achieved through the use of plastic particles that have a density similar to that of water (EPA 1994).

Guar gum gel is a viscous fluid commonly used in creating hydraulic fractures (Murdoch and others 1991; Frank and Barkley 1995). Guar gum, a food additive derived from the guar bean, is mixed with water to form a short-chain polymer with the consistency of mineral oil. Adding a cross linker causes the guar gum polymer chains to link and form a thick gel capable of suspending high concentrations of coarse-grained sand. That property makes guar gum gel ideal for filling fractures with solid material. An enzyme added to the gel breaks the polymer chains, allowing recovery of the thinned fluid from the fracture.

Hydraulic fracturing with guar gum requires several specialized pieces of equipment (EPA 1993c). A mixer is required to blend the gel, cross linker, and enzyme, as well as sand or other solids. The method also requires a pump capable of handling a slurry that contains high concentrations of granular material. The safety precautions necessary are similar to those for cases in which pressurized water is used. Injection of guar gum gel does not affect the mobilization of vapors significantly, but liquids may be slightly mobilized after the gel breaks down. The fracture confines the gel during injection; therefore, prompt recovery of the gel should eliminate interaction with pore fluids. Local authorities that regulate subsurface injection may regulate the injection of guar gum gel, as well. Because in situ organisms metabolize the organic components of guar gum gel, its use commonly is avoided when fractures are created to enhance discharge from drinking-water wells. The major benefit of the use of guar gum gel is its capability to suspend a high concentration of coarse-grained materials, such as sand (10 to 15 pounds of sand per gallon of gel), as a slurry in the gel (EPA 1994).

6.3.2 Fracturing Equipment

The equipment used to create fractures consists of both an aboveground system that must be capable of injecting the desired fracture medium at the required pressures and rates and a below-ground system that must be capable of isolating the zone where injection will take place. The type of medium to be injected largely determines the specifications of the aboveground equipment. Sections 6.3.8 and 6.3.9 discuss specific requirements for aboveground equipment for pneumatic and hydraulic fracturing. Both pneumatic and hydraulic fracturing can use straddle packers that allow spacing of fractures approximately every 1.5 feet along an open borehole. Straddle packers are appropriate in rock and in some unlithified sediments.

An alternative to the use of straddle packers during hydraulic fracturing of unlithified sediments is the driving of a casing with an inner pointed rod to the specified depth (Murdoch and others 1990). After the rod is removed, a high-pressure pump injects a water jet to cut a notch in the sediments at the bottom of the borehole. The notch reduces the pressure required to start propagation and ensures that the fracture starts in a horizontal plane at the bottom of the casing. A fracture can be created at the bottom of the casing by injecting a liquid or slurry. After the fracture is created, the rod can be reinserted and driven to greater depths to create another fracture, or the casing can be left in place for access to the fracture during recovery. Use of this approach in unlithified sediments allows advancement of the casing by either hammering (with a drop weight, pneumatic, or hydraulic hammer) or direct pushing (using the weight of a drill rig or cone penetrometer).

6.3.3 Injection Pressure and Rate

The pressure required to initiate a fracture in a borehole depends on several factors, including confining stresses, toughness of the enveloping geologic formation, initial rate of injection, size of incipient or existing fractures, and the presence of pores or defects in the borehole wall. In general, the injection pressure increases with increasing depth, injection rate, and fluid viscosity. For example, propagating a fracture by injecting a liquid into soil at 20 gallons per minute and at a 6-foot depth requires approximately 8 to 12 psi of pressure, the pressure required increases approximately 1 psi for each additional foot of depth. In contrast, the pressure required to create a fracture by injecting air, with injection rates of 700 to 1,000 cfm, is in the range of 70 to 150 psi (EPA 1994). The pressure during propagation decreases in most operations; however, the specifics of the pressure history depend on a variety of factors. For example, slight increases in pressure may occur because of an increase in the concentration of sand in the slurry during injection.

6.3.4 Fracture Size and Shape

The effectiveness of pneumatic and hydraulic fractures largely depends on the size and shape of the fracture with respect to the borehole. Propagation could continue indefinitely if the fracture were created in infinitely impermeable material, but, in real materials, several factors limit the size and shape of fractures. The volume of injected fluids and the rate at which they are injected are the primary controllable variables that affect the size of the fracture.

Some of the injected fluid flows out through the walls of the fractures and into the pores of enveloping soil or rock, a process known as "leakoff" (EPA 1994). The rate of leakoff increases as the fracture grows and offers more surface area through which the injected fluid can flow. Other factors that affect the leakoff rate include the relative permeability of the geologic formation and the viscosity and pressure of the fluid. The rate of fracture propagation decreases as the rate of leakoff increases, and horizontal propagation ceases entirely when the leakoff rate equals the rate of injection.

Leakoff generally controls the size of pneumatic fractures. For example, injecting gas at 800 to 1,800 cfm into sandstone for approximately 20 seconds typically results in fractures approximately 20 to 70 feet in maximum dimension (EPA 1994). A longer injection period does not greatly affect the dimensions of the fracture; however, increasing the rate of injection will generally increase the size of the fracture. Therefore, in pneumatic fracturing, the rate of injection is a critical design variable that affects the size of the fracture.

The volume of injected fluid determines the size of the resulting fracture. Maximum dimensions of fractures created by gases (air) or liquids are limited by the tendency of the fracture to climb and intersect the ground surface or by the loss of fluid through the fracture walls. The maximum horizontal dimension of a fracture also increases with increasing depth and decreasing permeability of the formation. At a depth in the range of 5 to 16 feet in over consolidated silty clay, the typical maximum dimension of a fracture is approximately 3 to 4 times its depth (EPA 1994).

The shape of a fracture created by pneumatic and hydraulic fracturing largely depends on the fracturing technique, including the type of fluid used during injection, the rate and pressure of injection, and the configuration of the borehole, as well as the site conditions (Murdoch and others 1990; Murdoch and others 1991; EPA 1994; Schuring and others 1995). Critical site conditions that affect the shape of a fracture include loading at the ground surface from structures, such as buildings, reservoirs, landfills, or heavy equipment; the permeability and heterogeneity of the geologic formation; and the presence of subsurface borings. In general, fractures range in shape from steeply dipping, elongated fractures to flat-lying circular or disk-shaped fractures. The flat-lying fractures are most useful in many environmental applications because such fractures can grow to significant size without intersecting the ground surface.

6.3.5 Site Conditions

In addition to geological conditions at a specific site, as discussed in Section 6.2.1, surface and subsurface structures, such as buildings, pavement, buried utilities, other wells in the vicinity, and backfilled excavations, must be considered in the design and creation of effective pneumatic or hydraulic fractures (EPA 1994; Frank and Barkley 1995; Schuring and others 1995). Inducing fractures beneath such structures may cause vertical displacement of these structures. Fracturing typically results in ground surface elevation increases or "heaving" of up to 1 centimeter or more. In cases in which surface displacements are not desired, real-time monitoring of ground surface elevations is advisable so that the procedure can be terminated before the structures are significantly displaced.

Surface structures also may affect the propagation of fractures by loading the ground surface. Fractures created adjacent to buildings most likely will propagate away from the buildings in response to the surface loading by the structure. Propagation of a fracture may change dramatically or terminate altogether if the fracture intersects a backfilled excavation or other deep features, such as wells, piezometers, or grouted sampling holes. The severity of such effects depends on individual site conditions and can be evaluated only after those specific conditions are known.

6.3.6 Monitoring the Formation of Fractures

The most widely used method of monitoring the location of fractures in the subsurface is measurement of the vertical displacement of the ground surface (Murdoch and others 1991). Net displacements can be determined by surveying a field of measuring staffs with finely graduated scales, before and after fracturing. This method is inexpensive and provides reliable data on final displacements.

As an alternative, tilt sensors that detect changes in electrical resistivity can measure extremely gentle slopes of the ground surface in real time, while a fracture is being created. Although a complete description of the deformation includes strain, displacement, and tilt fields, measurements of the tilt field are the easiest to perform at the very high levels of resolution necessary to provide useful information. Resistivity measurements and calculation of displacement fields are seldom better than parts per million, while calculated strain measurements are reliable to parts per 100 million, and tilt can be monitored routinely at parts per billion (Echo-Scan Corporation [Echo] 1996).

6.3.7 Well Completion

The type of post fracture well completion affects the flexibility of subsurface control, versatility in creating additional fractures, and cost. Some methods of completion provide access to each fracture or group of fractures, while others simultaneously access all the fractures in a well. Individual completions provide versatility by allowing the use of each fracture or set of fractures for either injection or recovery of fluids. For example, this method can allow alternating between air inlet and suction of adjacent fractures or can provide the capabilities of dewatering from lower fractures and vapor recovery from upper fractures (EPA 1994). The method also can improve recovery of NAPL because it allows the user to direct aqueous and nonaqueous phases to separate pumps.

Completion techniques that access all fractures simultaneously resemble standard well completion methods (Clark 1988). To provide individual access, a grouted zone along the borehole can isolate each fracture or set of fractures. Individual completions, however, are more costly than simultaneous continuous screening of all fractures. As an alternative, casings driven to create fractures in unlithified sediments can be left in place to allow access to the fracture during recovery. In certain cases, it may be necessary to return to a well to create additional fractures. Additional fractures can be created in wells that consist of open boreholes, and fracture size can be increased when completions consist of driven casing. It is difficult to use wells that have already been completed with a screen and gravel pack to create fractures.

6.3.8 Pneumatic Fracturing

During pneumatic fracturing, wells are typically drilled into the contaminated vadose zone and left uncased (EPA 1993b; Frank and Barkley 1995). Each well is divided into several small intervals of about 2 feet using a straddle packer system, as described in Section 6.3.2. Short bursts (about 20 seconds in duration) of compressed air are injected sequentially into each interval to fracture the adjacent geologic formation. The fracturing extends and enlarges existing fissures, primarily in the horizontal direction, and may induce new fractures. Figure 6-4 illustrates the effects of pneumatic fracturing on two different geologic formations (Schuring and others 1995).

Pneumatic fracturing requires equipment that rapidly delivers air to the subsurface. Injecting air directly from a compressor may induce fractures under some circumstances; however, filters or specialized compressors may be required to eliminate traces of oil in the air stream. In addition, compressors typically cannot supply the pressure or the rate that pressurized gas cylinders are capable of. Therefore, the applicability of such equipment may be limited to relatively permeable formations in which leakoff limits the size of the fractures created by injection at moderate rates. The most versatile equipment developed to date employs a series of high-pressure gas cylinders with a pressure regulator to control injection. Air is injected into the subsurface at rates of approximately 800 to 1,800 cfm and at pressures of 70 to 300 psi. The process can be tailored to site conditions and is particularly suitable for delivering air at high rates. Moreover, the method can use gases other than air to create fractures (EPA 1994).

Recent application to saturated zones has provided evidence that the process can also effectively enhance remediation of saturated zones (Keffer and others, 1996). The characteristics that are changed include an aquifer's transmissivity, hydraulic conductivity, and relative storage function. When pneumatic fracturing has been applied to saturated zones containing significant volumes of free product, the magnitude of the change in product recovery rates has been observed to be several orders of magnitude.

6.3.9 Hydraulic Fracturing

Figure 6-5 illustrates the steps necessary to create hydraulic fractures (EPA 1993c); 6- or 8-inch hollow-stem augers are used to drill an initial borehole to just above the fracture interval. Individual segments of steel rod and casing are threaded together, as required for the depth of the fracture. The tip of a fracturing lance is driven through the casing to a depth at which the fracture is to be located. Only the lance is removed, leaving soil exposed just below the bottom of the casing. Water under high pressure is injected through the casing to cut a disk-shaped notch 6 inches outward from the lanced borehole. The notch serves as the starting point for the fracture. Water is injected into the notch until a critical pressure is attained and a fracture is created. If the fracture is to be propped, a slurry of water, sand, guar gum gel, cross linker, and an enzyme breaker is pumped at high pressure into the borehole to propagate the fracture.

The residual gel biodegrades, and the resultant fracture is a highly permeable sand-filled lens. The process is repeated at varying depths, typically from 5 to 30 feet, to create a stack of sand-filled hydraulic fractures. Fractures are created in a radius of 10 to 60 feet of the borehole and up to 1 inch in thickness. The sand-filled fractures serve as avenues for the extraction of soil vapors, injection of air, or recovery of groundwater and contaminants. These fractures also can improve pumping efficiency and the delivery efficiency for other in situ processes. Various granular materials, such as graphite, may be used instead of sand to create fractures that have different properties than sand within the surrounding formation. Hydraulic fractures injected beneath the water table have shown to effectively enhance remediation of saturated zones.

The equipment required for hydraulic fractures created by injecting water alone consists primarily of a high-pressure, positive displacement pump with pressure relief devices (EPA 1994). For hydraulic fractures filled with sand or other granular proppant, a mixer is needed to create the slurry. Batch mixers consisting of one or two open tanks fitted with agitators or continuous mixers that blend metered streams of guar gum gel, cross linker, enzyme breaker, water, and sand can be used to create the slurry. Continuous mixers require a larger capital investment than batch mixers; however, continuous mixers reduce the time and labor required to create fractures, thereby reducing the cost. Positive displacement pumps and duplex and triplex piston pumps, as well as progressive cavity pumps, are used widely to inject slurries into boreholes.

6.4 PERFORMANCE AND COST ANALYSIS

This section provides recent performance and cost data for remediation technologies enhanced by pneumatic and hydraulic fracturing during field demonstrations.

6.4.1 Performance

Table 6-2 summarizes selected remediation technologies, technology developers and vendors, site locations and geologic formation types, contaminants treated, and the results of field performance tests. Four of these field demonstrations are discussed as case studies in greater detail below.

6.4.1.1 Pneumatic Fracturing Enhancement of SVE and Hot Gas Injection in Shale

Pneumatic fracturing combined with SVE and hot gas injection was evaluated under EPA's SITE demonstration program as a means of remediating a contaminated vadose zone overlying contaminated groundwater at an industrial park in Somerville, New Jersey (EPA 1993a; EPA 1993b; EPA 1995; Accutech 1996). The geologic formation consists of 4 to 6 feet of weathered shale overlying fractured shale bedrock. Contaminants of concern are VOCs and SVOCs, including TCE, PCE, and benzene.

The remedial action objectives of this demonstration were to increase the permeability of the vadose zone formations by creating new horizontal fractures or enlarging existing fractures, determine the effect of fracturing on the rate of removal of VOCs, and evaluate the effects of hot gas injection on the transfer of heat through the formation and on the rate of removal of VOCs through vapor extraction. Fracture wells were drilled into the contaminated vadose zone to a depth of approximately 20 feet. To create an intensely fractured vadose zone, short bursts of air were injected at successive intervals of depth of the fracture wells. Each injection extended and enlarged existing fractures in the formation and created new fractures, primarily in the horizontal direction.

Pneumatic fracturing increased the flow of extracted air by 400 to 700 percent compared with rates achieved before fracturing. Even greater increases in the rate of extracted air flow (190 times) were observed when one or more of the monitoring wells were opened to serve as passive air inlets to the formation. The effective area of influence was observed to increase from approximately 380 square feet to at least 1,250 square feet, more than a threefold increase. Pressure data, collected at perimeter monitoring wells and measurements of surface heave indicate that the propagation of fractures extended past the most distant monitoring wells to at least 35 feet.

Figure 6-6 compares TCE mass flow rates over a 4-hour test before and after pneumatic fracturing. Even though concentrations of TCE in the air stream remained approximately constant before and after fracturing at approximately 50 mg/kg, the increased rate of air flow resulted in an increase in TCE mass removal of 675 percent (EPA 1993a). When wells were opened to passive air inflow, the increase in TCE mass removal was 23,000 percent after pneumatic fracturing. In addition, chemical analysis of the extracted air during post-fracturing tests showed high concentrations of organic compounds that had been detected in only trace amounts before fracturing. Therefore, pneumatic fracturing effectively opened access to pockets of VOCs that previously had been trapped.

The effect of the injection of hot gas into the fractured formation, in terms of heat transfer, air flow, volatilization, and TCE mass removal, were inconclusive. In one experiment, increases in well temperature (to approximately 65 to 85° Fahrenheit) were observed, but TCE mass removal decreased. A second experiment provided contradictory results: increased TCE mass removal rates at increased injected (and extracted) air flow rates were observed, but no elevated temperatures were measured in the extraction wells. The presence of perched water in the wells may explain some of the inconsistencies in the air flow rate and temperature results from the hot gas injection experiments conducted during the demonstration.

6.4.1.2 Pneumatic Fracturing Enhancement of SVE in Clay

Pneumatic fracturing combined with SVE was demonstrated at an abandoned tank farm in Richmond, Virginia (EPA 1993a; Schuring and others 1995). The geologic formation at the site consisted of highly over consolidated clays overlain by clayey silts. The aboveground tanks had been removed, and only a 6-inch-thick slab of concrete remained. Soil samples from the vadose zone beneath the slab showed two principal VOCs in the clay: methylene chloride and trichloroethane (TCA). VOC concentrations, as determined by headspace analysis of spoon samples and gas chromatograph analysis of soil samples, ranged up to 8,500 mg/kg and 485 mg/kg, respectively. An adjacent sump appeared to be the source of the contamination.

The remedial action objectives for this demonstration were to increase the permeability of the clay formation and to evaluate the effects of the enhancement on the removal of VOCs by SVE. Baseline conditions were established for flow rates of air extraction and removal of contaminants. Initial flow rates were less than 0.00071 cubic feet per minute. Figure 6-7 shows that removal concentrations for both contaminants peaked at approximately 23 mg/kg and neared nondetectable levels after 35 minutes (EPA 1993a) before pneumatic fracturing.

All fracture injections were made between 5 and 10 feet below the surface of the concrete slab within the clay horizon. During pneumatic injection, surface heave was measured at more than 1 inch in some areas.

Although the concrete slab did deflect some of the injection influence, fractures were detected beneath the concrete slab using surface measurements. Following the pneumatic fracture injections, the permeability of the formation increased substantially, as indicated by a 4,900 percent increase in flow rates of extracted air. Post fracture concentrations of contaminants extracted peaked at 8,677 mg/kg for methylene chloride and 4,050 mg/kg for TCA, as Figure 6-8 shows. The concentration of methylene chloride leveled off to approximately 200 mg/kg, which remains far higher than the concentrations detected before pneumatic fracturing (EPA 1993a). The results indicated that pneumatic fracturing significantly increased the removal rate of contaminants in low permeability soils.

6.4.1.3 Hydraulic Fracturing Enhancement of DPE in Clayey Silts

Hydraulic fracturing was used to enhance the extraction of hydrocarbon condensate using pneumatic pumps and free-phase hydrocarbons from contaminated groundwater underlying a former gas plant and compressor station in northwestern Alberta, Canada (Frac 1996). Condensate discharged to a flare pit at the facility had contaminated soil and groundwater, both on site and a considerable distance beyond the property boundary. Contaminated soils consist of clayey silts and silty, fine sands at a depth of approximately 20 to 40 feet. The groundwater table is located at 30 feet bgs. Free-phase hydrocarbon condensate was identified on the groundwater surface at apparent thicknesses greater than 10 feet.

The remedial action objectives for this project were to mitigate further contaminant migration and recover the hydrocarbon condensate and free-phase hydrocarbons in a cost-effective manner and thereby reduce the risks to an acceptable level. Forty-eight fractures (six fractures per well) were created at the site. A surfactant was incorporated into the sand-laden fracture fluid to assist in the mobilization of hydrocarbons to the extraction wells by improving its relative permeability to water.

Echo of North Carolina provided noninvasive, near-real-time monitoring and mapping of the hydraulic fracturing process with surface sensors. Maps of 30 hydraulic fractures over a 72-hour period were provided shortly after the fractures were created. Maps of the induced fractures provided the basis for optimizing the number and pattern of wells and the fracture design and execution for the remainder of the contaminated area (Echo 1996).

Table 6-3 compares average permeability (K values), zone of influence, and hydrocarbon condensate recovery rates in gallons per day before and after fracturing. Hydraulic conductivity before fracturing was calculated from an average of results of rising head and aquifer pumping tests, and hydraulic conductivity after fracturing was calculated from an average of values from aquifer pumping and recharge tests.

The hydraulic fracturing program at this site successfully induced fractures 0.02 to 0.07 inches in thickness and improved the zone of influence by a factor of four. After fracturing, the hydraulic conductivity increased by 1 order of magnitude, and the volumetric rate of hydrocarbon condensate recovered increased by a factor of approximately seven. Liquid recovery rates were approximately 6 times greater after fracturing, and the proportion of hydrocarbon condensate removed increased from 18 to 77 percent in the fractured wells. Another result was the relatively rapid rate of postpumping recharge of the hydrocarbon condensate in the fractured wells, compared with that for a nonfractured well. For example, within 24 hours of the time the pump was turned off at a fractured well, the thickness of condensate had returned to approximately 50 percent of the original thickness, while the condensate in a nonfractured well recovered only 25 percent of its original thickness over the same period.

Using a high-suction MPE system, the rate of removal of hydrocarbon vapor was improved from 2.9 kg/day to more than 200 kg/day in the fractured well, and the radius of vacuum influence typically doubled from 7 to 13 meters (23 to 43 feet). The hydraulic gradient and drawdown measured in one area of the facility indicate that plume capture in that area has been reasonably effective as a result of the remediation efforts. The influence of SVE was much greater when applied at fractured wells than at unfractured wells, and MPE was much more efficient than SVE or conventional pumping in removing condensate.

6.4.1.4 Pilot-Scale Testing of Hydraulic Fracturing at Linemaster Switch Superfund Site

Pilot-scale testing of hydraulic fracturing at the Linemaster Switch Superfund Site in Woodstock, Connecticut, was conducted to assess the capability of fracturing to enhance SVE and groundwater extraction (FRX 1996; Fuss and O’Neill, Inc. 1996). The site is contaminated with TCE, paint thinner, and other VOCs used at the facility. The contaminants penetrated the underlying 40 feet of clay soil and entered a weathered bedrock system that serves as a drinking-water aquifer for the area. Pump-and-treat operations have stabilized the contaminant plume in the aquifer, but the contaminated clay soils are a persistent source of groundwater contamination.

The objectives for this pilot-scale study included demonstrating the ability to propagate fractures, estimating the effect of fracture heave on the facility, evaluating fluid recovery rates before and after fracturing, and evaluating the full-scale feasibility of hydraulic fracturing at the site.

Two hydraulically fractured recovery wells were installed, with four fractures in one well and eight in the other. Fractures were spaced at approximately 10-foot increments, beginning at 8 feet bgs for the first well, and at 5-foot increments for the second well, also beginning at 8 feet bgs. The fractures were propped with a guar gum gel and sand slurry.

The feasibility of propagating the fractures was demonstrated through the use of uplift maps and the detection of sand in split-spoon samples. Field tests before and after fracturing, as well as modeling of groundwater and air flow rates, showed that post-fracture groundwater extraction rates were approximately 4 to 6 times greater than those in conventional wells at the site. Figure 6-9 shows the cumulative amount of groundwater removed in gallons before fracturing, and Figure 6-10 shows the total flow after hydraulic fracturing. The results indicate that hydraulic fracturing increased the groundwater extraction rate by approximately 10 times. In addition, extracted air flow rates were higher than expected.

6.4.2 Cost Analysis

This section provides data on the cost of pneumatic and hydraulic fracturing and describes how those costs are determined so that reasonable cost estimates can be made for similar contaminated sites. Two cost scenarios are presented below, one for pneumatic fracturing and the other for hydraulic fracturing.

6.4.2.1 Costs of Pneumatic Fracturing

Since pneumatic fracturing has been commercialized only recently, data on production costs are limited. The costs presented here are drawn from the SITE demonstration project conducted by Accutech in Somerville, New Jersey. An economic analysis of the costs of the demonstration enabled the projection of annual operating costs for a full-scale remediation effort under similar conditions. Table 6-4 summarizes the cost categories that were considered and the percentage of the total cost that each subcategory represents (EPA 1993a). The three major factors in determining costs were labor, capital equipment, and emissions control. The cost figures include several assumptions that were made regarding TCE removal rates at the Somerville site; the reader is advised to refer to vendors and the literature cited for an in-depth analysis of the cost projections for specific sites.

For Accutech's pneumatic fracturing and vapor extraction process, the cost for 1 year of operation, during which 2,660 pounds of TCE were removed, is estimated at $371,364, or approximately $140 per pound of TCE removed (EPA 1993a). A direct comparison with conventional vapor extraction was not made because conventional vapor extraction would not have been possible at the site without fracturing. In cases like this, potential cost savings can be weighed against the cost of excavating the site and hauling away the contaminated soil or rock. Present costs of excavation and hauling range from $200 to $800 per yd^3 (Schuring and others 1995).

In general, the cost of pneumatic fracturing will vary with the size of the project and the conditions at the site. On the basis of 1995 projections, the incremental production cost of pneumatic fracturing in excess of primary remediation is expected to range from $8 to $20 per yd^3 of soil or rock fractured (Schuring and others 1995). Volume measurements are made by multiplying the treatment area by the height of the actual fracture zone. For example, if a 500-foot by 500-foot site is to be fractured, starting at a depth of 10 feet and extending down to a depth of 20 feet, the volume and cost would be:

$$\text{Volume} = [500\text{ ft} \times 500\text{ ft} \times (20\text{ ft}-10\text{ ft})]/27\text{ ft}^3\text{ per yd}^3 = 92{,}593\text{ yd}^3$$

$$\text{Cost range} = 92{,}593\text{ yd}^3 \times \$8\text{ to }\$20 = \$740{,}740\text{ to }\$1{,}851{,}852.$$

The cost of applying pneumatic fracturing to a site must be weighed against the potential cost savings and other factors. The use of pneumatic fracturing reduces both the capital costs and the operating costs of remediation projects, primarily because the technology enhances formation permeability. Because the zone of influence of each extraction well is increased, the well spacings can be increased and thus, the number of wells required for remediation is reduced. For example, at a site that has an initial low permeability, wells for standard vapor extraction may be spaced on a grid of 10 feet. With fracturing, the spacing probably could be increased to as much as 20 to 25 feet. At a spacing of 20 feet, a savings of as much as 75 percent in the cost of drilling wells could be realized. At a spacing of 25 feet, the savings would range as high as 84 percent (Schuring and others 1995).

The direct application of pneumatic fracturing to the zones of contamination speeds up the rate of mass removal, typically reducing the time required for remediation. A savings in operation costs therefore, can be realized. For example, if the treatment time is reduced from 10 years to 5, potential savings in operation costs, in present dollars, are 36 percent (calculated at a compound annual interest rate of 12 percent). If the remediation time is reduced to 3 years, potential savings in operation costs increase to 57 percent. Therefore, although annual costs may be slightly higher with some pneumatic fracturing systems, the removal efficiencies result in life-cycle costs that are 2 to 3 times lower than conventional remediation technologies, such as pump-and-treat (Green and Dorrler 1996).

6.4.2.2 Costs of Hydraulic Fracturing

Economic data for hydraulic fracturing are even more limited than those for pneumatic fracturing; however, many of the principles discussed above also apply to hydraulic fracturing. Table 6-5 shows cost data obtained from EPA's SITE demonstration of hydraulic fracturing conducted at Oak Brook, Illinois, in 1993 and used to determine estimated costs of hydraulic fracturing at other hazardous waste sites (EPA 1993c). Again, the reader is cautioned to keep in mind the implications of the assumptions made in the SITE demonstration report when applying the cost figures to other remediation sites. The reason to be cautious is because five cost categories out of the 12 typically associated with cleanup activities at Superfund and RCRA-corrective action sites were not applicable to the hydraulic fracturing technology demonstration. The cost categories included start-up costs, utility costs, effluent and treatment disposal, residuals and waste shipping and handling, equipment maintenance, and modifications.

Capital equipment costs for this project included the costs for an equipment trailer on which the slurry mixer, pumps, tanks, and hoses were mounted; a fracturing lance with a wellhead assembly; a pressure transducer and display; and uplift survey instruments. The total capital equipment cost was $92,900. The cost of rental of capital equipment assumes 30 rentals per year and depreciation of the capital costs over

3 years. Supplies and consumables include sand, guar gum gel, enzyme, and diesel fuel or gasoline for operating the pumps. The total cost per fracture was estimated at approximately $950 to $1,425.

Other factors that influence the cost of hydraulic fracturing include preferences of the client and mobilization charges that will vary depending on the scale of the remediation project. In general, in 1996, the cost of hydraulic fracturing ranges from $1,500 to more than $2,500 per fracture (FRX 1996; Frac 1996). That cost may be small in light of the benefits of enhanced remediation and the reduction in the number of wells needed to complete remediation.

6.5 VENDORS

Many companies are involved in various aspects of pneumatic and hydraulic fracturing, including equipment, installation, and operation. Vendors of pneumatic and hydraulic fracturing used for the development of this report are identified in Tables 6-6 and 6-7.

6.6 STRENGTHS AND LIMITATIONS

The following list outlines some of the strengths of using pneumatic and hydraulic fracturing technologies for environmental remediation:

- Pneumatic and hydraulic fracturing can increase well discharge many times over discharge rates achieved with conventional, unfractured wells.

- The relative increase in performance is greatest in the tightest formations, where the performance of conventional wells is poorest.

- In low-permeability formations, pneumatic and hydraulic fractures can improve the performance of hydraulic control and containment at a site, or they can be combined with other remediation technologies to accelerate recovery.

- Solid compounds that improve the remedial process, such as nutrients or electrically conductive compounds, can be delivered to the subsurface.

- In SVE applications, changes in soil vacuum applied to horizontal fractures can induce controlled communication between horizontal fractures, by creating vertical or inclined fractures between the horizontal ones.

The following list outlines some of the limitations of using pneumatic and hydraulic fracturing technologies for environmental remediation:

- Pneumatic and hydraulic fracturing may not solve all the problems of remediation in tight formations.
- Fracturing is ineffective in normally consolidated soils and sediments in which the horizontal stress is less than the vertical stress.
- The presence of water decreases the efficiency of SVE; therefore, fracturing to enhance SVE is best suited to unsaturated, over-consolidated geologic formations that have low permeabilities.

Table 6-7 compares pneumatic and hydraulic fracturing (FRX 1996; Keffer and others 1996).

6.7 RECOMMENDATIONS

To apply pneumatic and hydraulic fracturing effectively, a good understanding of the basic principles of fracturing is helpful (see Sections 6.2 and 6.3). Pressures required to initiate and sustain subsurface fractures are difficult to predict because they are a complex function of depth of overburden, tensile strength of the soil matrix, fluid pore pressure, and matrix stresses in the soil. Therefore, thorough site characterization is necessary since fracturing may be an unnecessary step at sites with high natural permeabilities. In addition, because of the great variability of geologic materials, the conduct of pilot-scale field tests is advisable before implementation of full-scale fracturing installations.

Specific variables to consider when implementing fracturing to enhance fluid flow will vary depending on the intended application of the pneumatic or hydraulic fractures to be created (EPA 1994). For example, when fractures are to be induced for SVE remediation, design variables that must be considered are the selection of proppants and well completion specifications. In addition, simultaneous recovery of vapor and liquid is inevitable when extracting near-saturated zones and may occur when accelerating the recovery of liquids by placing a vacuum on a well. Such a dual-phase recovery approach requires the use of a well that has an inner tube attached to the vacuum pump so that the system induces vapor flow during normal operations and also aspirates and removes any liquid that enters the well. For steam injection applications, wells require steel rather than plastic casing because of the high temperature of the steam. For the enhancement of bioremediation, the rate of injection of nutrients, oxygen-bearing fluids, or simply ambient air must be considered to optimize the performance of the treatment.

The effects of pneumatic and hydraulic fracturing on nearby structures and utilities depend on the type of construction and on the amount of deformation of the ground. Experience with fracturing in the vicinity of structures is limited; therefore, caution is recommended when fracturing in close proximity to structures. Geotechnical analyses should be performed to establish tolerable movements for a particular project, and the fracture injections should be designed appropriately (Schuring and others 1995).

For hydraulic fracturing, design considerations must ensure that fractures are not spaced vertically so close to one another that adjacent fractures intersect. Likewise, the fracture wells must be spaced sufficiently far apart laterally to prevent the intersection of fractures from adjacent wells. The sand in a fracture should be thick enough to provide a large contrast with the permeability of the geologic formation. However, once the sand in a fracture is several millimeters thick, creating a thicker sand pack to obtain additional contrast provides only minor improvement in well performance. Therefore, a decision must be made whether the cost of additional sand is worth the incremental benefit achieved by a thicker fracture (EPA 1994).

6.8 REFERENCES

This section includes references cited in Chapter 6 (Subsection 6.8.1) and a list of professional experts in the fields of pneumatic and hydraulic fracturing (Subsection 6.8.2), while a comprehensive bibliography is included in Appendix B.

6.8.1 Cited References

Accutech Remedial Systems, Inc. 1996. Pneumatic Fracturing Project Summaries and Photographs Submitted by Mike Galbraith. Keyport, NJ. August 5.

Clark, L.J. 1988. The Field Guide to Water Wells and Boreholes. John Wiley and Sons, Inc., New York. Page 155.

Echo-Scan Corporation. 1996. Fracture Monitoring and Mapping Project Summaries Submitted by M. Deryl Wood. Cary, NC. August 16.

Frac Rite Environmental Ltd. 1996. Hydraulic Fracturing Project Summaries Submitted by Gordon H. Bures. Calgary, Canada. July 31.

Frank, U. and N. Barkley. 1995. Remediation of Low-permeability Subsurface Formations by Fracturing Enhancement of Soil Vapor Extraction. Journal of Hazardous Materials, Volume 40. Pages 191-201.

FRX Inc. 1996. Hydraulic Fracturing Project Summaries and Photographs Submitted by William W. Slack and Larry C. Murdoch. Cincinnati, OH. July 24.

Fuss and O'Neill, Inc. 1996. Hydraulic Fracturing Project Summary Submitted by David L. Bramley. Manchester, CT. July 12.

Green, S.R. and R.C. Dorrler. 1996. Four Bullets Shoot down Costs: Combined Technology Approach Cleans up Faster and Cheaper than Pump-and-Treat. Soil and Groundwater Cleanup. March.

Keffer, E.B., J.J. Liskowitz, and C.D. Fitzgerald. 1996. The Effect of Pneumatic Fracturing When Applied to Groundwater Aquifers. In: Proceedings of the Sixth West Coast Conference on Contaminated Soils and Groundwater. Pages 1-21.

Miller, R.R. 1996. Blast-Enhanced Fracturing. Technology Summary Report. TS-96-01. Ground-Water Remediation Technologies Analysis Center. Pittsburgh, PA.

Murdoch, L.C., G. Losonsky, I. Klich, and P. Cluxton. 1990. Hydraulic Fracturing to Increase Fluid Flow. In: F. Arendt and Others, eds. Contaminated Soil. Kluwer Academic Publishers, Netherlands. Pages 1087-1094.

Murdoch, L.C., G. Losonsky, P. Cluxton, B. Patterson, I. Klich, and B. Braswell. 1991. Feasibility of Hydraulic Fracturing of Soil to Improve Remedial Actions. Project Summary. EPA/600/S2-91/012.

Schuring, J.R., P.C. Chan, and T.M. Boland. 1995. Using Pneumatic Fracturing for In-situ Remediation of Contaminated Sites. Remediation. Spring. Pages 77-89.

U.S. Environmental Protection Agency (EPA). 1993a. Accutech Pneumatic Fracturing and Hot Gas Injection, Phase 1. Application Analysis Report. EPA/540/AR-93/509. Office of Research and Development, Washington, DC.

EPA. 1993b. Technology Evaluation Report: Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase 1. Volume 1. EPA/540/R-93/509. Office of Research and Development, Cincinnati, OH.

EPA. 1993c. Applications Analysis and Technology Evaluation Report. Hydraulic Fracturing Technology. EPA/540/R-93/505. Office of Research and Development, Washington, DC.

EPA. 1994. Alternative Methods for Fluid Delivery and Recovery. Manual. EPA/625/R-94/003. Office of Research and Development, Washington, DC.

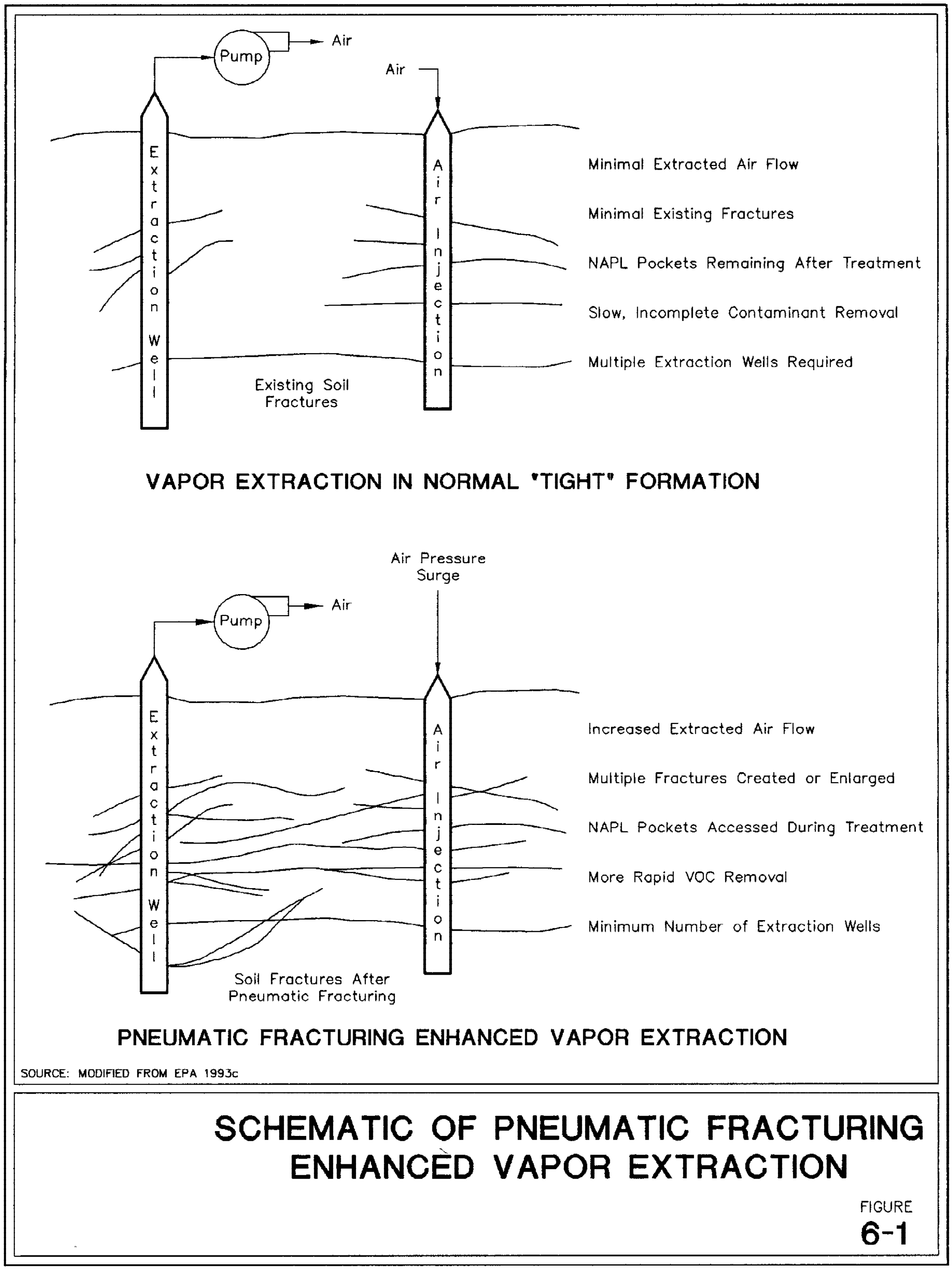
EPA. 1995. In Situ Remediation Technology Status Report: Hydraulic and Pneumatic Fracturing. EPA-542-K-94-005. Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington, DC.

6.8.2 Professional Contacts

Table 6-6 presents information that is useful in determining the capabilities of vendors in enhancing SVE, as well as other remediation technologies using pneumatic and hydraulic fracturing technologies. Listed below are the names and telephone numbers of well-known experts and developers in pneumatic and hydraulic fracturing technologies, respectively.

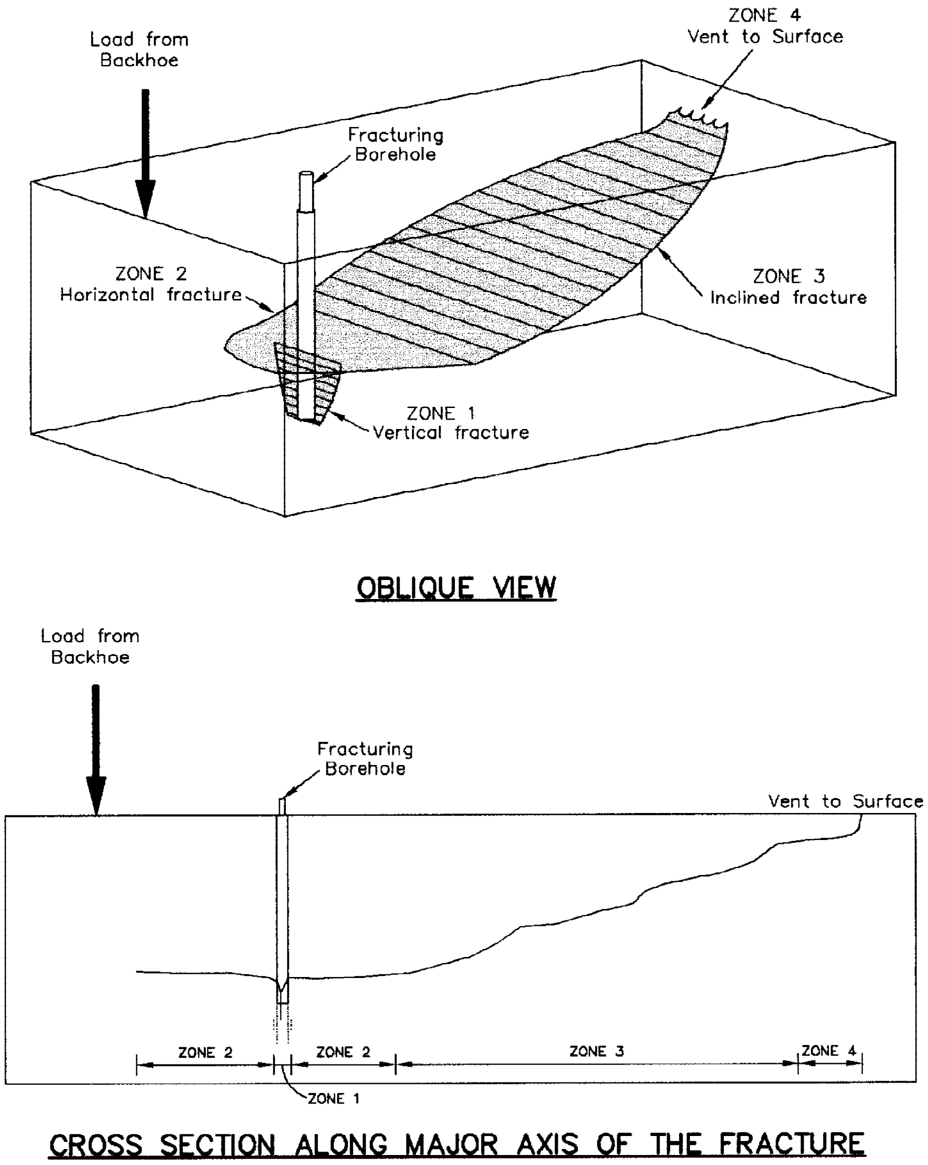
Name	Affiliation
Pneumatic Fracturing	
Uwe Frank (908) 321-6626	U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory
John Schuring, Ph.D. (201) 596-5849	Hazardous Substance Management Research Center New Jersey Institute of Technology
David Kosson, Ph.D. (908) 445-4346	Department of Chemical and Biological Engineering Rutgers, The State University of New Jersey
Hydraulic Fracturing	
Michael Roulier, Ph.D. (513) 569-7796	U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory
Larry C. Murdoch, Ph.D. (864) 656-2597	Department of Geology Clemson University
William W. Slack, Ph.D. (513) 556-2526	Center for Geo-Environmental Science and Technology University of Cincinnati, Engineering Research Division

FIGURE 6-1
SCHEMATIC OF PNEUMATIC FRACTURING FOR ENHANCED VAPOR EXTRACTION



SOURCE: MODIFIED FROM EPA 1993c

FIGURE 6-2
CONCEPTUAL SCHEMATIC OF HYDRAULIC FRACTURING



SOURCE: MODIFIED FROM MURDOCH AND OTHERS 1990

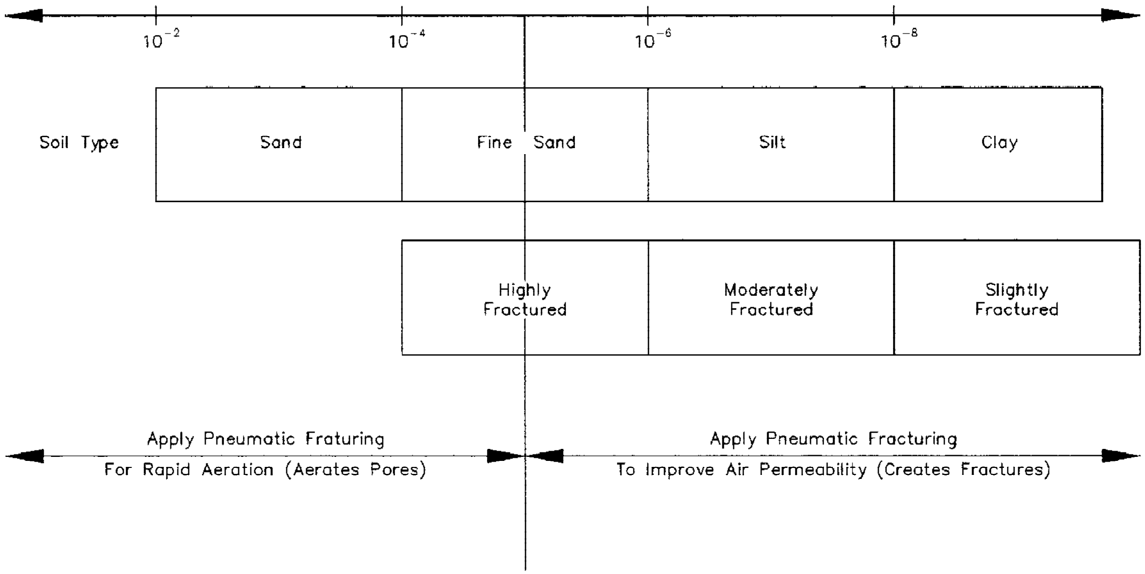
SCHEMATIC OF HYDRAULIC FRACTURING

FIGURE 6-2

FIGURE 6-3
APPLICATION GUIDELINES FOR PNEUMATIC FRACTURING

TYPES OF TREATABLE SOIL AND ROCK

Natural Pneumatic Conductivity (cm/sec)



Note:
To convert from pneumatic conductivity to hydraulic conductivity, multiply by 30. For example, if $K_p = 1.0 \times 10^{-5}$ cm/sec, the corresponding $K_h = 3.0 \times 10^{-4}$ cm/sec.

SOURCE: MODIFIED FROM SCHURING AND OTHERS 1995

APPLICATION GUIDELINES FOR
PNEUMATIC FRACTURING

FIGURE
6-3

FIGURE 6-4
EFFECTS OF PNEUMATIC FRACTURING

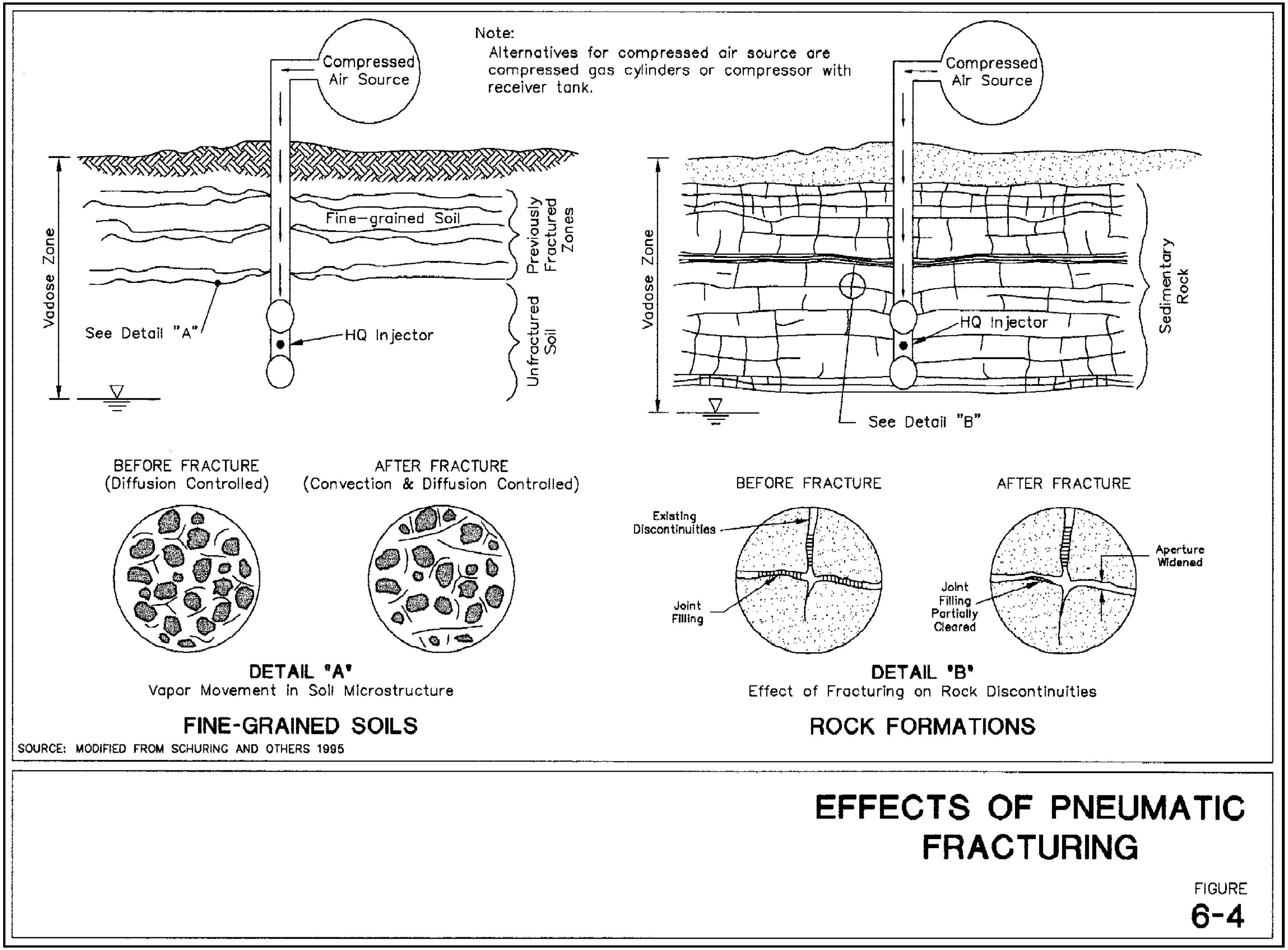
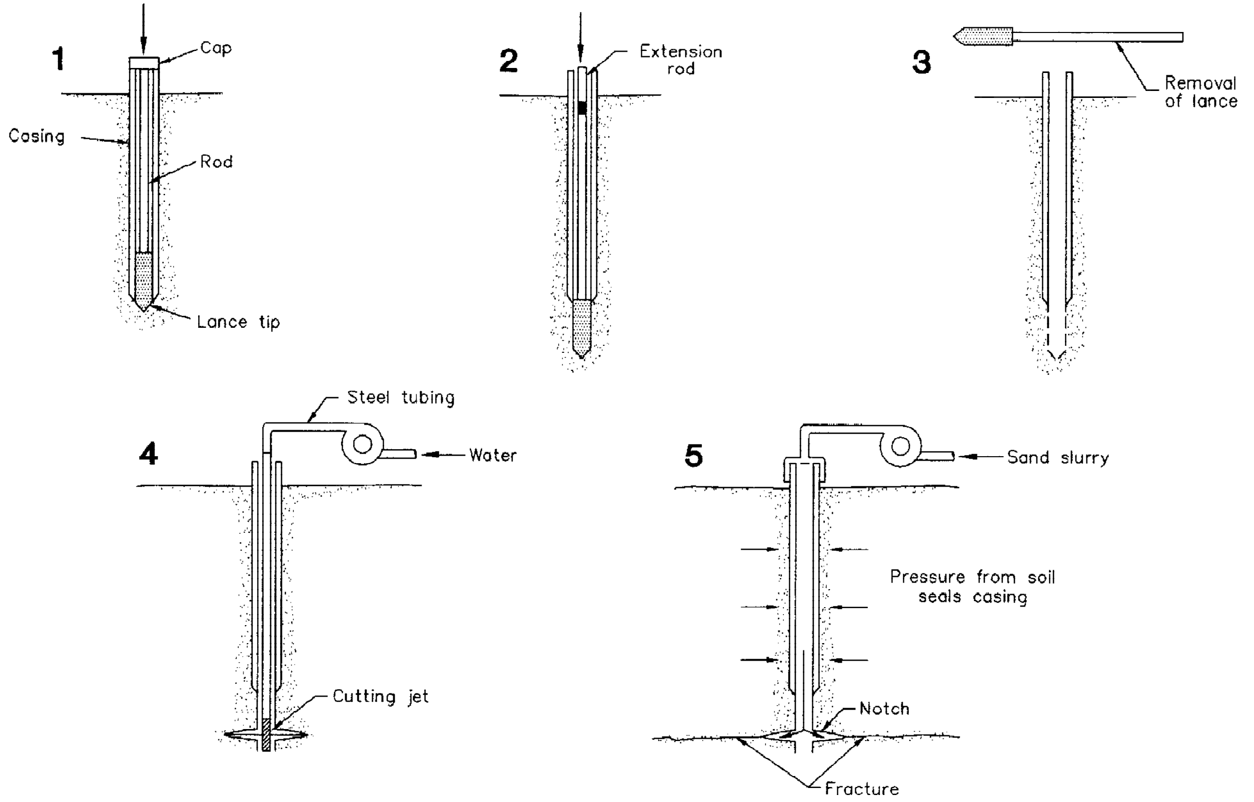


FIGURE 6-5
SEQUENCE OF OPERATIONS FOR CREATING HYDRAULIC FRACTURES

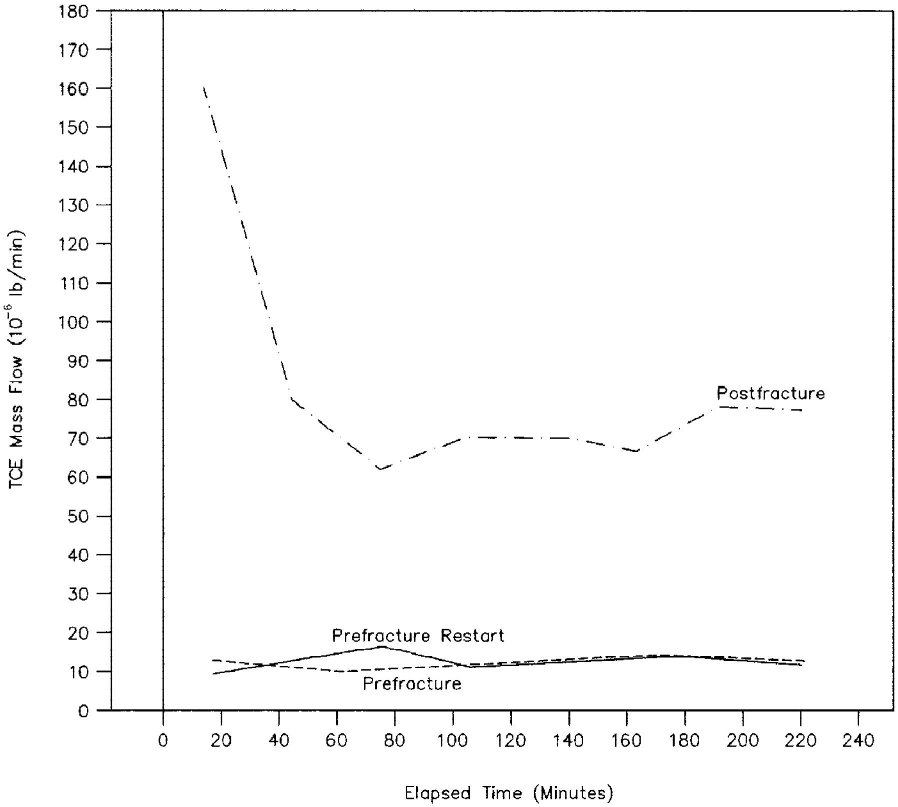


SOURCE: MODIFIED FROM EPA 1993b

SEQUENCE OF OPERATIONS FOR CREATING HYDRAULIC FRACTURES

FIGURE
6-5

FIGURE 6-6
COMPARISON OF TCE MASS REMOVAL ENHANCED BY PNEUMATIC FRACTURING

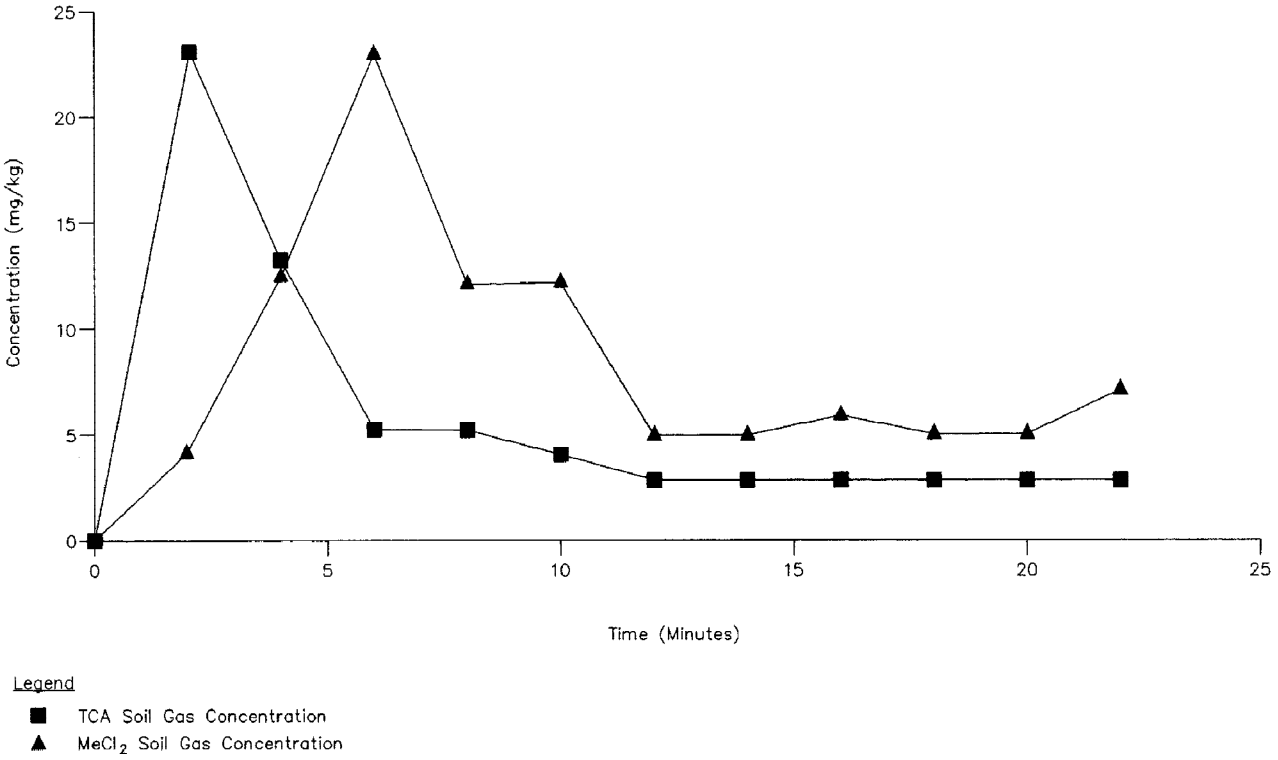


SOURCE: MODIFIED FROM EPA 1993a

COMPARISION OF TCE MASS REMOVAL ENHANCED BY PNEUMATIC FRACTURING

FIGURE
6-6

FIGURE 6-7
PREFRACTURE CONTAMINANT REMOVAL CONCENTRATIONS

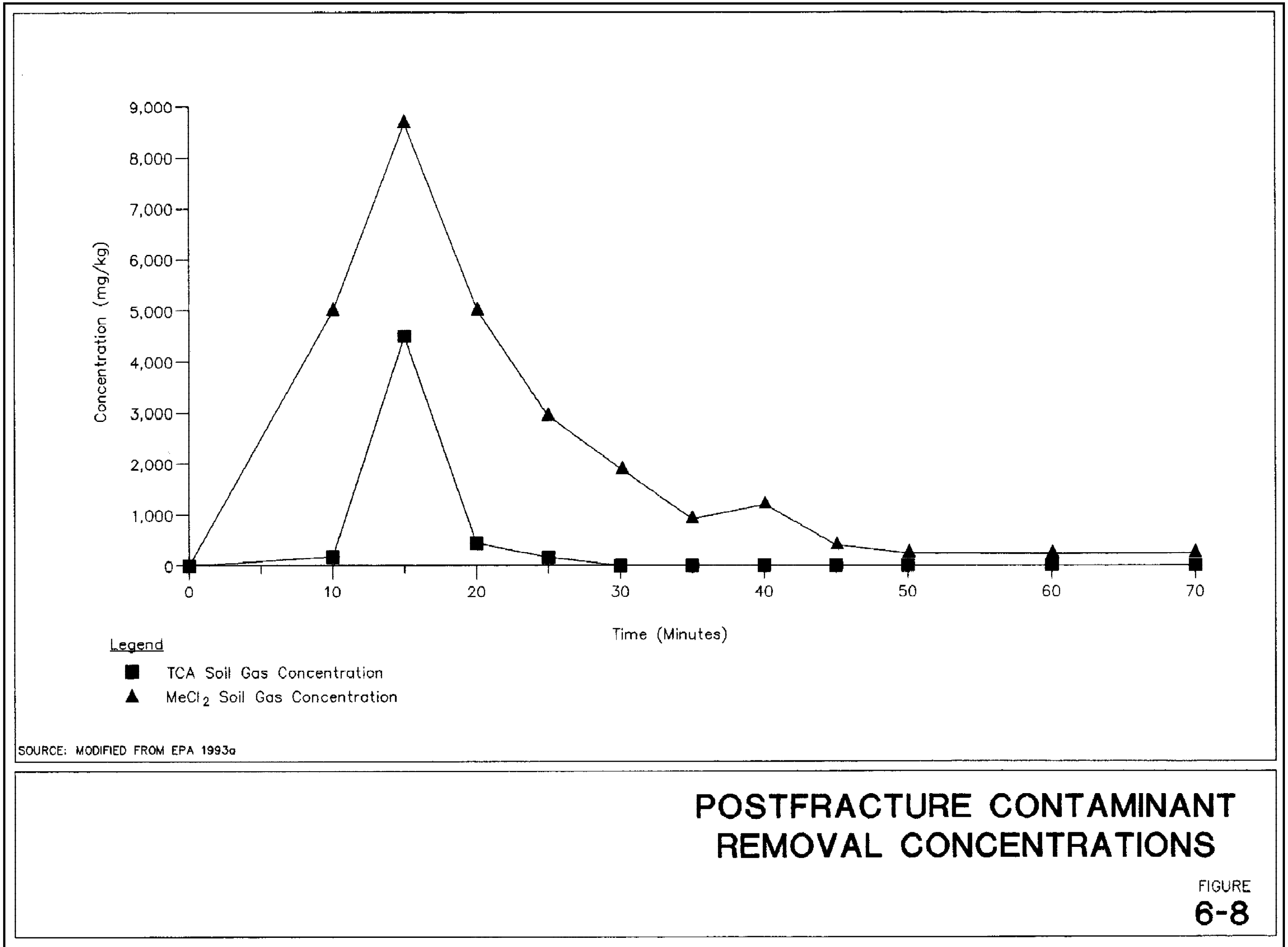


SOURCE: MODIFIED FROM EPA 1993a

PREFRACTURE CONTAMINANT REMOVAL CONCENTRATIONS

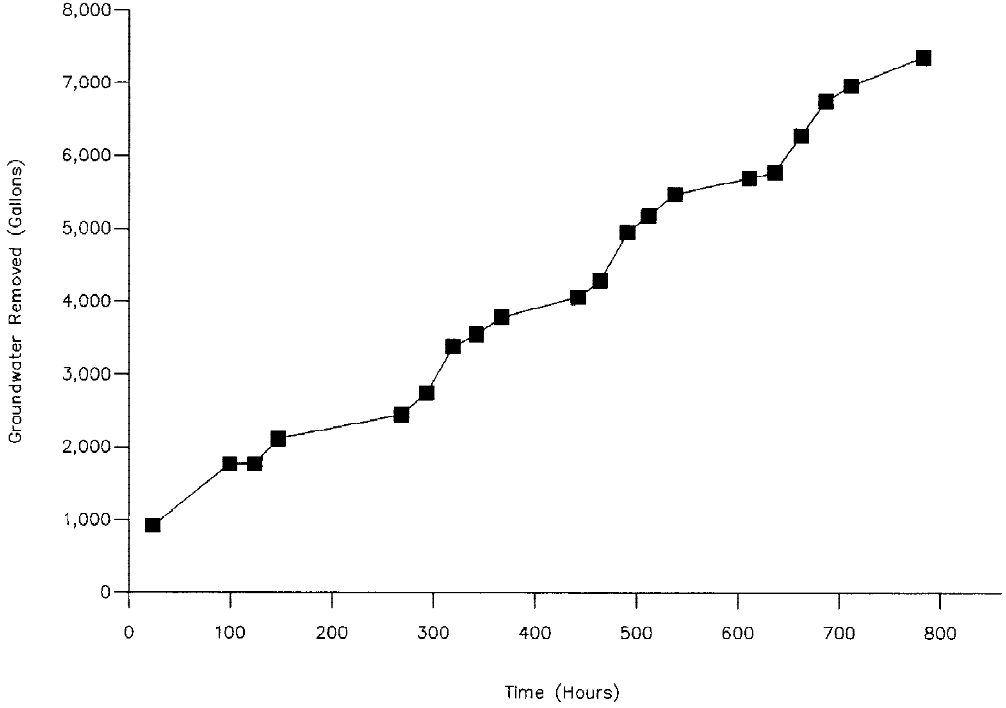
FIGURE
6-7

FIGURE 6-8
POSTFRACTURE CONTAMINANT REMOVAL CONCENTRATIONS



SOURCE: MODIFIED FROM EPA 1993a

FIGURE 6-9
CUMULATIVE GROUNDWATER REMOVAL BEFORE HYDRAULIC FRACTURING

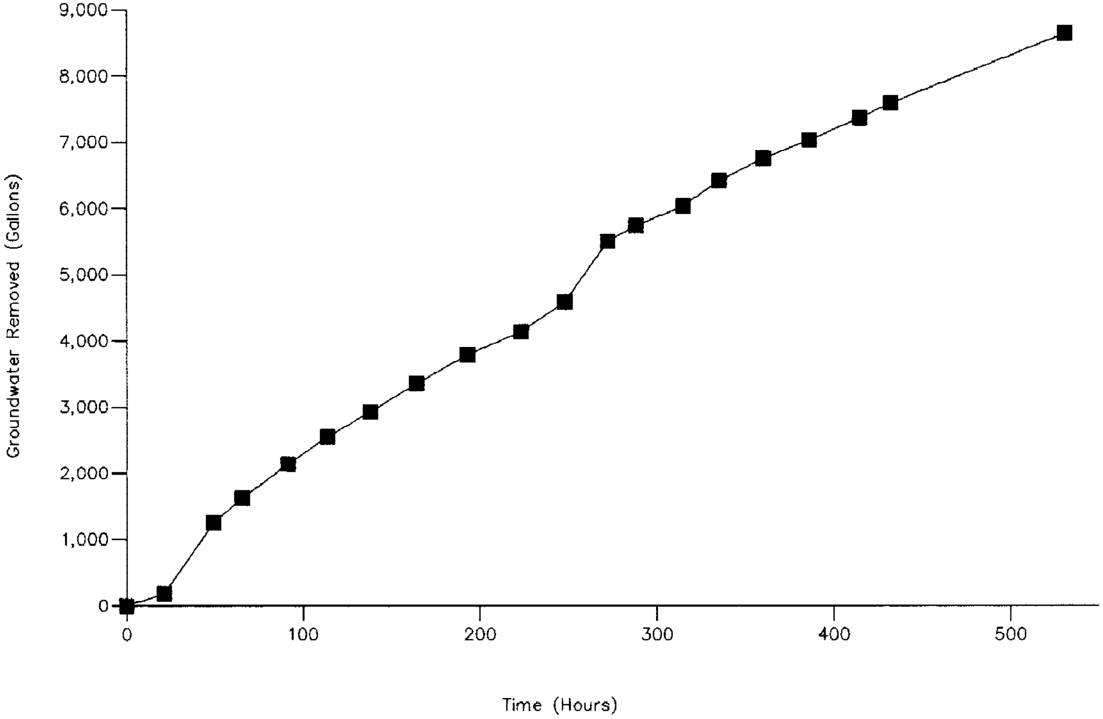


SOURCE: MODIFIED FROM FUSS AND O'NEILL, INC. 1996

CUMULATIVE GROUNDWATER REMOVAL BEFORE HYDRAULIC FRACTURING

FIGURE
6-9

FIGURE 6-10
CUMULATIVE GROUNDWATER REMOVAL AFTER HYDRAULIC FRACTURING



SOURCE: MODIFIED FROM FUSS AND O'NEILL, INC. 1996

CUMULATIVE GROUNDWATER REMOVAL AFTER HYDRAULIC FRACTURING

FIGURE
6-10

TABLE 6-1

REMEDIATION TECHNOLOGIES ENHANCED BY FRACTURING
(Page 1 of 1)

Contaminated Media	Remediation Technology	Technology Description	Benefits of Fracturing
Soil	Soil vapor extraction	Removal of VOCs from unsaturated zone soils using subsurface air flow	Greater access to contaminants, increased removal rates, and fewer wells
	Dual vapor-phase extraction	Removal of VOCs simultaneously from both soils in the saturated and the unsaturated zones	Greater access to contaminants, increased removal rates, and fewer wells
	Bioremediation	Injection and infiltration of fluids, including air, into soils to enhance biodegradation of subsurface residual contaminants	Improved fluid injection and infiltration rates, as well as improved access of microbes to contaminants
	Soil flushing	Injection and infiltration of solutions such as solvents or surfactants to concentrate contaminants into the liquid phase to enhance pump and treat	Improved injection and infiltration, as well as improved recirculation rates
	Electroosmosis	Migration of contaminants in the subsurface through the application of an electric field	Fractures act as contaminant collection pathways
	Thermal treatment	Removal of contaminants through volatilization into the gas phase by both vapor-liquid equilibrium effects and heat	Greater permeability for heat distribution and volatilization
	Vitrification	Subsurface containment of contaminants through melting of soils to form a stable glass structure with low leaching characteristics	Greater permeability for heat distribution and melting
Groundwater	Pump and treat	Removal of contaminated groundwater or immiscible contaminants and subsequent treatment or reprocessing	Larger capture zone, greater recovery rates, and fewer wells required
	Free product recovery	Removal of free-phase contaminants from an aquifer	Larger capture zone, greater recovery rates, and fewer wells required
	Bioremediation	Injection and infiltration of fluids into the saturated zone to enhance biodegradation of dissolved contaminants	Improved fluid injection and infiltration rates, as well as improved access of microbes to contaminants
	Air sparging	Injection of air into the saturated zone to remove organic contaminants by volatilization and biodegradation	Increased delivery of air, greater rates of biodegradation and removal of volatile compounds, and fewer injection wells required
	Chemical treatment	Injection of chemical reagents to the saturated zone to enhance the chemical treatment of contaminants, for example, oxidation/reduction	Improved access to contaminants and greater injection rates
	Physical treatment	Injection of hot air or steam to enhance the physical treatment of contaminants, for example in situ heating and air stripping	Greater in situ flow rates

Source: Modified from Frac Rite Environmental, Ltd. 1996.

TABLE 6-2

SELECTED EXAMPLES OF REMEDIATION TECHNOLOGIES ENHANCED BY PNEUMATIC AND HYDRAULIC FRACTURING
(Page 1 of 4)

Technology	Developer or Vendor	Site Location	Geologic Formation Type	Contaminants Treated	Technology Performance After Fracturing
Pneumatic Fracturing and SVE with Hot Gas Injection	Accutech Remedial Systems, Inc.	Somerville, New Jersey	Shale	VOCs, primarily TCE	Rate of air flow increased by more than 600 percent. Rate of TCE mass removal increased by approximately 675 percent.
Pneumatic Fracturing and SVE	Accutech Remedial Systems, Inc.	Santa Clara, California	Silty clay, sandy silts, and clays	VOCs, primarily TCE	Rate of air flow increased 3.5 times. Permeability increased as much as 510 times. Rate of TCE mass removal in clay zones increased as much as 46,000 times.
Pneumatic Fracturing and DPE	Accutech Remedial Systems, Inc.	Highland Park, New Jersey	Shale	VOCs, primarily TCE	TCE mass removal increased 3 times.
Pneumatic Fracturing and Fuel Recovery	Accutech Remedial Systems, Inc.	Oklahoma City, Oklahoma	Shale and sandstone	No. 2 Fuel oil as free product	Rate of recovery of free product increased by approximately 1,600 percent.
Pneumatic Fracturing and In Situ Bioremediation	Accutech Remedial Systems, Inc.	Oklahoma City, Oklahoma	Sandy, silty shale, and clay stone	VOCs, primarily BTEX and TCE	Transmissivity increased by approximately 400 percent.
Pneumatic Fracturing and In Situ Bioremediation	Accutech Remedial Systems, Inc.	Flemington, New Jersey	Shale	VOCs, primarily TCE	Transmissivity increased by 85 percent.
Pneumatic Fracturing and SVE	Accutech Remedial Systems, Inc.	Columbia City, Indiana	Clay	VOCs, including TCE, DCE, and vinyl chloride	Rate of air flow increased 2 times.
Pneumatic Fracturing and SVE	Accutech Remedial Systems, Inc.	Coffeyville, Kansas	Silty clay	VOCs, primarily TCE	Rate of air flow increased more than 5 times.

TABLE 6-2

SELECTED EXAMPLES OF REMEDIATION TECHNOLOGIES ENHANCED BY PNEUMATIC AND HYDRAULIC FRACTURING

(Page 2 of 4)

Technology	Developer or Vendor	Site Location	Geologic Formation Type	Contaminants Treated	Technology Performance After Fracturing
Pneumatic Fracturing and DPE	Terra Vac, Inc.	New York, New York	Clay soils	TCE, PCE, BTEX, and other VOCs	Rate of air flow did not increase appreciably. Concentration of VOCs in the extracted air stream increased 10 times.
Pneumatic Fracturing and DPE	Terra Vac, Inc.	Monroe, Louisiana	Clay soils	TCE, PCE, BTEX, and other VOCs	Rate of air flow increased by 6 to 8 standard cubic feet per minute. Rate of extraction of VOCs more than doubled.
Pneumatic Fracturing and In Situ Bioremediation	New Jersey Institute of Technology	Marcus Hook, Pennsylvania	Clay soils	BTEX	Soil permeability increased 40 times. Rate of removal of BTEX increased by more than 82 percent.
Pneumatic Fracturing and SVE	New Jersey Institute of Technology	Richmond, Virginia	Clay	VOCs, primarily methylene chloride and TCA	Rate of air flow increased 1,000 times. Concentration of VOCs in the extracted air stream increased 200 times.
Pneumatic Fracturing and DPE	First Environment, Inc.	Greenville, South Carolina	Biotite gneiss and schist	Chlorinated solvents	Recovery rate increased as much as 10 times.
Hydraulic Fracturing and SVE	University of Cincinnati	Oak Brook, Illinois	Silty clay	TCE, TCA, DCA, and PCE	Average rate of extraction increased 15 to 20 times. Concentration of contaminants recovered increased 10 times.

TABLE 6-2

SELECTED EXAMPLES OF REMEDIATION TECHNOLOGIES ENHANCED BY PNEUMATIC AND HYDRAULIC FRACTURING
(Page 3 of 4)

Technology	Developer or Vendor	Site Location	Geologic Formation Type	Contaminants Treated	Technology Performance After Fracturing
Hydraulic Fracturing and In Situ Bioremediation	University of Cincinnati	Dayton, Ohio	Sandy and silty clay	BTEX and TPH	Rate of fluid flow increased 25 to 40 times. Level of contaminant reduction was 89 percent greater for BTEX and 77 percent greater for TPH.
Hydraulic Fracturing and SVE	University of Cincinnati	Beaumont, Texas	Clay	Gasoline and cyclohexane	Rate of recovery of LNAPL increased 10 times.
Hydraulic Fracturing and SVE	Fuss and O'Neill, Inc. and FRX Inc.	Woodstock, Connecticut	Silty clay	VOCs, primarily paint thinner	Rate of fluid flow increased as much as 6 times.
Hydraulic Fracturing and In Situ Bioremediation	FRX Inc.	Denver, Colorado	Shale and clay	TPH	Reduction of concentrations of TPH in soils was approximately 90 percent in 5 months.
Hydraulic Fracturing and SVE	FRX Inc.	Lima, Ohio	Clay and silty clay	Gasoline	Rate of fluid flow increased more than 10 times.
Hydraulic Fracturing and SVE	FRX Inc.	Oakfield, Maine	Clay and silty clay	Gasoline and diesel fuel	Rate of fluid flow increased as much as ten times.
Hydraulic Fracturing and Electroosmosis	FRX Inc.	Columbus, Ohio	Clay and silty clay	Unspecified water soluble contaminants	Graphite filled fractures created an electrical field required to induce electroosmotic migration of water and contaminants.
Hydraulic Fracturing and DPE	Golder Applied Technologies, Inc.	Atlanta, Georgia	Clay	Chlorinated solvents	Average product recovery rate increased 4 times.

TABLE 6-2

SELECTED EXAMPLES OF REMEDIATION TECHNOLOGIES ENHANCED BY PNEUMATIC AND HYDRAULIC FRACTURING
(Page 4 of 4)

Technology	Developer or Vendor	Site Location	Geologic Formation Type	Contaminants Treated	Technology Performance After Fracturing
Hydraulic Fracturing and DPE	Frac Rite Environmental, Ltd. and Echo-Scan Corporation	Alberta, Canada	Clayey silt, silty sands	Hydrocarbon condensate and Free-phase hydrocarbons	Hydraulic conductivity increased 10 times and the zone of influence increased 4 times. Volumetric rate of recovery of condensate increased approximately 7 times.
Hydraulic Fracturing and SVE	Remediation Technologies, Inc.	Bristol, Tennessee	Sedimentary bedrock	TCE	Rate of extraction increased by as much as 6 times. Rate of TCE extraction increased by as much as 700 liters per minute.

TABLE 6-3

COMPARISON OF HYDROCARBON CONDENSATE RECOVERY RATES BEFORE AND AFTER FRACTURING

Before Hydraulic Fracturing			After Hydraulic Fracturing		
K_{ave} (feet/day)	**Zone of Influence (feet)**	**Condensate Recovery (gal/day)**	**K_{ave} (feet/day)**	**Zone of Influence (feet)**	**Condensate Recovery (gal/day)**
0.1	3 to 5	13	1.1	>1.5	95

Source: Modified from Frac Rite Environmental, Ltd. 1996

Note: K_{ave} Average permeability

TABLE 6-4

COST DATA FOR SOIL VAPOR EXTRACTION ENHANCED WITH PNEUMATIC FRACTURING

Cost Item	Total Cost ($)	Cost/lb TCE ($/lb)	Percent of Total (%)
Site preparation	42,000	15.79	11.3
Permitting/regulatory requirements	1,750	0.66	0.5
Capital equipment (1.5 years)	82,074	30.85	22.1
Startup	8,200	3.08	2.2
Labor	107,640	40.47	29.0
Consumables/supplies	4,000	1.50	1.1
Utilities	17,000	6.39	4.6
Emission control	70,000	26.32	18.8
Disposal of residues (water)	37,200	13.98	10.0
Analytical services	NA	—	—
Repair/replacement	NA	—	—
Demobilization	1,500	0.56	0.4
Total	$371,364	$139.60	$100.0

Source: Modified from U.S. Environmental Protection Agency 1993a and 1993b

Note:		
	NA	Not available
	—	Not applicable
	TCE	Trichloroethene

TABLE 6-5

COST DATA FOR HYDRAULIC FRACTURING

Cost Category	Estimated Cost (1993 Dollars)
Site preparation	1,000
Permitting/regulatory requirements[a]	5,000
Capital equipment rental[b]	1,000
Startup	0
Labor	2,000
Supply and consumables	1,000
Utilities	0
Treatment and disposal effluent	0
Shipping and handling of residues and waste	0
Analytical services and monitoring	700
Maintenance and modifications	0
Demobilization[a]	400
Total one-time costs	5,400
Total daily costs	5,700
Estimated cost per fracture[c]	$950 to $1,425

Source: Modified from U.S. Environmental Protection Agency 1993c

Notes:

a One-time costs

b Capital equipment includes: equipment trailer; slurry mixer and pump; mixing pumps, tanks, and hose; fracturing lance and wellhead assembly; notching pump and accessories; pressure transducer and display; uplift survey equipment; scale; and miscellaneous tools and hardware. Rental cost is based on 30 rentals per year and a depreciation of the $92,900 capital cost over 3 years.

c Total daily costs (excluding one-time costs) divided by four or six fractures per day

TABLE 6-6

PNEUMATIC AND HYDRAULIC FRACTURING TECHNOLOGY VENDORS[a]
(Page 1 of 2)

Name of Vendor	Address and Phone Number	Point of Contact
Pneumatic Fracturers		
Accutech Remedial Systems, Inc.	Cass Street and Highway 35 Keyport, NJ 07735 Phone: 908-739-6444 Fax: 908-739-0451	John Liskowitz
First Environment, Inc.	90 Riverdale Road Riverdale, NJ 07457 Phone: 201-616-9700 Fax: 201-616-1930	Richard Dorrler
McLaren/Hart Environmental Engineers, Inc.	25 Independence Boulevard Warren, NJ 07059 Phone: 908-647-8111 Fax: 908-647-8162	James Mack
Terra Vac, Inc.	92 North Main Street Windsor, NJ 08561 Phone: 609-371-0070 Fax: 609-371-9446	Loren Martin
Hydraulic Fracturers		
EMCON	3300 North San Fernando Boulevard Burbank, CA 91504 Phone: 818-841-1160 Fax: 818-846-9280	Donald L. Marcus
ERM-Southwest, Inc.	16300 Katy Freeway - Suite 300 Houston, TX 77094-1609 Phone: 713-579-8999 Fax: 713-579-8988	H. Reiffert Hedgcoxe
Fluor Daniels GTI, Inc.	2000-200 Manner Avenue Torrance, CA 90503 Phone: 310-371-1394 Fax: 310-371-4782	John F. Dablow III

TABLE 6-6

PNEUMATIC AND HYDRAULIC FRACTURING TECHNOLOGY VENDORS[a]
(Page 2 of 2)

Name of Vendor	Address and Phone Number	Point of Contact
Frac Right Environmental, Ltd.	6 Stanley Place S.W. Calgary, Alberta Canada T2S 1B2 Phone: 403-620-5533 Fax: 403-287-7092	Gordon H. Bures
FRX Inc.	P.O. Box 37945 Cincinnati, OH 45222 Phone: 513-469-6040 Fax: 513-556-2522	Larry C. Murdoch, Ph.D. and William W. Slack, Ph.D.
Fuss and O'Neill, Inc.	146 Hartford Road Manchester, CT 06040 Phone: 203-646-2469 Fax: 203-643-6313	David L. Bramley
Golder Applied Technologies, Inc.	3730 Chamblee Tucker Road Atlanta, GA 30340 Phone: 770-496-1893 Fax: 770-934-9476	Grant Hocking
Gregg Drilling and Testing, Inc.	2475 Cerritos Avenue Signal Hill, CA 90806 Phone: 310-427-6899 Fax: 310-427-3314	John Gregg
Remediation Technologies, Inc.	23 Old Town Square - Suite 250 Fort Collins, CO 80524 Phone: 970-493-3700 Fax: 970-493-2328	Ann Colpitts

Note: a This list is not inclusive of all vendors capable of providing pneumatic and hydraulic fracturing technologies. This list reflects vendors contacted during the preparation of this report.

TABLE 6-7

COMPARISON OF PNEUMATIC FRACTURING AND HYDRAULIC FRACTURING

Features	Pneumatic Fracturing	Hydraulic Fracturing
Fracture pattern	Dense network of micro-fractures around the injection point with one or two major fractures that migrate outward into the formation per injection interval.	One or two major fractures that migrate outward into the formation per injection interval with secondary fractures in overlying formation.
Injection medium	Air or other gases with or without fine grained proppants.	Water or slurries of water, sand, and other additives.
Injection interval	2 to 3 feet	0.5 to 5 feet
Fracture aperture	0.5 to 1.0 mm	1 to 2 cm
Radial extent of fractures	20 to 70 feet	10 to 25 feet
Radial extent of influence	20 to 70 feet	10 to 70 feet
Maximum depth	At depths greater than 75 feet self-propping decreases; however, propping agents can be used.	Up to several hundred feet, with or without propping agents.
Injection time to create fracture	20 seconds	5 to 15 minutes
Well completion	Typically a single well screen across all fractures at one location. All fractures in a well either inlet or recovery.	Typically a casing for each fracture. Where well contains multiple fractures, use each fracture for either air inlet or recovery.
Geologic formations that favor successful application	Over-consolidated or bedded sediments and bedrock	Over-consolidated or bedded sediments

Source: Modified from Keffer, Liskowitz, and Fitzgerald 1996 and FRX Inc. 1996.

CHAPTER 7.0
THERMAL ENHANCEMENT

This chapter describes use of thermal enhancements for increasing overall performance of SVE systems. The following sections provide an overview of thermal enhancements, describe conditions under which the technology is applicable, contain a detailed description of thermal enhancements, highlight performance data, list vendors that provide thermal enhancement services, outline the strengths and limitations of this technology, and provide recommendations for using the technology. Cited figures and tables follow references at the end of the chapter.

7.1 TECHNOLOGY OVERVIEW

Thermal enhancements for SVE may involve a number of different technologies aimed at transferring heat to the subsurface to (1) increase the vapor pressure of VOCs or SVOCs to enhance their removal via SVE or (2) to increase air permeability. Vaporized contaminants are removed by SVE extraction wells. Thermal enhancement technologies include steam or hot air injection, ER heating, RFH, and thermal conduction heating. Past applications of steam injection technologies have focused primarily on moving and vaporizing free petroleum product in the subsurface toward extraction wells for removal. Hot air injection has been used to increase the vapor pressure of VOCs and SVOCs in the vadose zone, thus decreasing remediation time and increasing contaminant removal. Use of ER heating and RFH has primarily focused on increasing mass removal rates of contaminants in low-permeability soil. ER heating and RFH remove soil moisture, thus increasing air permeability in the soil and increasing contaminant removal in low-permeability soil formations. Thermal conduction heating enhances conventional SVE treatment by heating the soil surface to volatilize contaminants.

Steam injection technologies enhance conventional SVE treatment by injecting steam into the contaminated region. Contaminants are pushed ahead of the condensing water vapor toward the typical extraction wells. Additionally, some of the contaminants are vaporized or solubilized by the injection of steam and are moved toward the extraction wells by an applied vacuum. Three common methods of delivering the steam into the contaminated region are use of injection wells, injection through drill augers, and injection below the area of contamination. Steam injection technology is typically more applicable to regions with medium to high-permeability soils, where the condensate front can more freely move through the formation. In addition, a low-permeability surface layer may be needed to prevent steam breakthrough for shallow soil applications. The costs of steam injection applications range from \$46/yd^3 to \$166/yd^3.

Hot air technologies are similar to steam injection, but hot air is used in place of steam. The hot air can be supplied either through an injection well or by injecting hot air through a large mixing auger. The main strength of hot air injection technologies is their comparatively inexpensive cost. Hot air can be much easier to provide than high quality steam. However, hot air injection is not a very efficient means for delivering heat to the subsurface because of the relatively low heat capacity of air. Because both steam injection and hot air injection involve injecting a fluid under pressure into the subsurface, the same geological concerns apply for hot air injection as with steam injection. The costs of hot air injection application range from \$75/yd^3 to \$100/yd^3.

For RFH, energy is delivered to the contaminated region using electrodes or antennae that emit radio-frequency waves. These radio waves increase molecular motion, which heats the soil. These electrodes are either placed on the surface at the contaminated area or inserted into holes drilled into the contaminated area. The energy given off by the electrodes excites the contaminated region and raises the temperature. RFH is effective for treating VOCs in low-permeability soil in the vadose zone. The costs of RFH application range from \$195/yd^3 to \$336/yd^3.

ER heating uses the soil as a conduction path for electrical current. The energy dissipated because of resistance is transformed into heat. Past applications of ER heating have involved inserting an array of metal pipes into the contaminated region by drilling. An electrical current is then passed through these pipes to heat up the contaminated region and drive off soil moisture and target contaminants. ER heating is effective for treating VOCs in low-permeability soil in the vadose zone. The cost of a previous application of ER heating is \$100/yd^3.

In thermal conduction heating, a heat source is placed on the surface of the contamination or inserted into the formation, and heat is supplied to the contaminants by conduction. Typically, a common ER heater is used as the heat source. Thermal conduction heating can be used to remove VOCs in medium to low-permeability soil. An advantage of this technology is its ease of implementability and relatively inexpensive cost. However, heat conduction by this method is very slow and inefficient and requires a large temperature gradient to be maintained for acceptable heating rates to be achieved. Based on the limited application of thermal conduction heating, no representative costs are presented.

7.2 APPLICABILITY

In general, thermal enhancement technologies should be considered during soil remediation for one or more of the following applications:

- **Removal of sorbed organic compounds with low vapor pressures --** SVE generally is not effective for removing organic compounds whose vapor pressures are less than 0.1 mm Hg to 1.0 mm Hg at ambient temperatures. The range of applicability for SVE can be extended by employing thermal enhancement technologies. This has the effect of increasing contaminant vapor pressures, which make the contaminants more volatile and therefore, more susceptible to SVE treatment.

- **Reduction of treatment time for difficult matrices --** Some thermal enhancement technologies, such as RFH and ER heating, have been used to decrease treatment time for VOCs in clayey and silty soils. Soil heating first creates steam, which induces stripping of VOCs from soil, and then dries the soil to increase advection. Decreased treatment times can significantly decrease remediation costs, as well as allow property to be transferred more quickly.

- **Treatment of NAPL --** Some sites contain LNAPL or DNAPL that complicate remediation strategies and lengthen treatment times. Thermal enhancement technologies, especially steam stripping, may be used to solubilize or vaporize NAPL for subsequent removal by SVE.

- **Enhancement of biological activity in soil --** Increases in soil temperature may stimulate biological activity in the soil. In general, biodegradation rates are expected to double for every 10 degrees Celsius (^{o}C) rise temperature increase. Thermal enhancement technologies such as soil surface modification, fiber optic heating, and warm water injection may be used to provide relatively small (2 to 10 ^{o}C) increases in soil temperature.

7.3 ENGINEERING DESCRIPTION

Thermal enhancement technologies have been studied and developed to augment the performance of SVE systems for removing VOCs and SVOCs. The removal of VOCs and SVOCs by SVE is controlled by a number of transport and removal mechanisms which include:

- Gas advection
- Chemical partitioning to the vapor phase
- Gas-phase contaminant diffusion
- Sorption of contaminant on soil surfaces
- Chemical or biological transformation

Thermal enhancement technologies raise the soil temperature to increase the reaction kinetics for one or all of these removal and transport mechanisms. Gas advection involves the bulk movement of volatilized contaminants in the vapor phase as air is drawn through the soil. Advection through low-permeability soils is relatively slow and can be thermally enhanced by drying soil to increase the air permeability of the soil.

Thermal enhancement increases chemical partitioning from liquids to gases. As temperature increases, the vapor pressure of a pure chemical also increases, as depicted in Figure 7-1. The increased rate of vaporization at higher temperatures significantly increases the rate at which chemicals in the liquid form in soil are removed, particularly in areas that contain soil with medium to high permeabilities.

In areas where concentration gradients exist between pores being swept by the flowing air and contaminated soil not in communication with the air stream, contaminants will move by diffusion toward the flowing air. Gas-phase diffusion is typically much slower than advection in less permeable zones and will be the limiting factor for system performance in situations in which air flow does not pass sufficiently near contamination to allow advection. Therefore, the objective of an SVE system is to minimize the length of the diffusion path the volatilized contaminants must take to enter the air flow. In diffusion-limited formations, beneficial effects in addition to the vapor pressure increase result from increases in temperature. Temperature increases enhance the rate of vapor transport from low-permeability zones to regions of high-vapor flow (American Academy of Environmental Engineers [AAEE] 1994). In addition, for temperature increases above 100 ^{o}C, the steam is produced and the steam's pressure-driven flow to regions of high-vapor flow can help drive contaminant vapors out of low-permeability zones at a rate much higher than the natural contaminant diffusion rate.

When combined with conventional SVE, a variety of in situ thermal process options can enhance the removal of contaminants through the transport and removal mechanisms described above. These include steam injection and stripping, hot air injection, RFH, ER heating, and thermal conduction heating.

7.3.1 Steam Injection/Stripping

Steam injection (also called steam stripping) technology is used to enhance typical SVE treatment systems by injecting steam into the contaminated region. The steam increases chemical partitioning as the contaminants are pushed ahead of the condensing water vapor toward the typical extraction wells. Additionally, some of the contaminants are vaporized or solubilized by the injection of steam and are moved toward the extraction wells by an applied vacuum. Steam injection technology is typically more applicable to regions with medium- to high-permeability soils, where the condensate front can more freely move through the formation. Steam injection has limited applicability to sites contaminated with pesticides, dioxins, furans, and polychlorinated biphenyls (PCB). It is particularly well suited for the treatment of petroleum contaminants and NAPLs.

The typical steam injection system, as shown in Figure 7-2, delivers steam through injection wells into the contaminated region to heat up the zone and vaporize the contaminants. The steam also creates a pressure gradient that controls the movement of the contaminants and condensed steam front to a recovery well. After injection, the steam front travels some distance into the contaminated region before condensing. The increase in temperature volatilizes the contaminants (because of increased vapor pressures) or dissolves them in the condensed steam (because of increased solubilities). The flow of steam is controlled to limit the possibility of contaminant mobilization into previously uncontaminated areas.

Uniform steam distribution, control of the condensate front, and vapor containment are all desirable for steam stripping. The surface of the treatment area is often covered with an impermeable surface to help control the flow of the contaminants. There are two common methods of delivering the steam including the use of injection wells and injection through drill augers.

7.3.1.1 Steam Injection Through Injection Wells

Injection wells are drilled so the steam can be injected at or below the contaminant zone. Typically, a series of wells are drilled to evenly distribute steam to the contaminated region. The spacing of the steam injection wells is dependent on the soil permeability of the soil. The permeability of a particular formation could be increased by combining this technology with pneumatic fracturing. If such a treatment scheme was implemented, the number of delivery wells may be reduced. The vaporized contaminants are then collected using a vacuum apparatus, such as vacuum extraction wells or a vacuum bell at the soil surface.

The method of steam delivery described above can be used to target oily wastes. Injection and recovery wells are drilled to cover and treat the contaminated area. The steam is injected below the contaminated region, and the steam condenses and pushes the oily waste into a hot water stream. Alternatively, steam is injected directly into the contaminated region to move contaminants radially to extracting wells. This hot water stream is injected above impermeable barriers and is designed to mobilize the rising contaminants. The resulting hot water/oily waste mixture is then withdrawn through extraction wells for treatment.

Steam injection has been widely used in the petroleum industry and can be used to recover semivolatile and volatile compounds. The organic compounds are often collected for reprocessing and reuse. The application of steam heat places an upper temperature limit of 100 ºC and is, therefore, not as efficient for higher boiling point compounds. Steam injection might not be as effective in areas with impermeable regions because of limited flows through these regions. If the area is layered with impermeable and permeable regions, the contaminants will move along the bed, expanding the area of contamination. Heating the contaminated area with steam will reduce the treatment time, depending on site characteristics, compared to treatment at ambient temperatures.

7.3.1.2 Steam Injection Through Drill Auger

Steam may also be injected into the subsurface through drilling augers (see Figure 7-3). A process tower is used that supports cutting blades at the end of a hollow shaft. The process tower consists of five major components: a treatment shroud, kelly bars, cutter bits, and a rotary table and crowd assembly. Together, these components loosen the soil, inject the steam, and collect the stripped VOCs from the soil.

The cutter bits are attached to the end of each kelly bar. A set of mixing blades is also attached above the cutter bits. Each kelly bar is thus equipped with two sets of opposing blades (cutter bits and mixing blades) positioned at 90 degrees from each other, as shown in Figure 7-3. The cutter bits have nozzles for injection of steam into the soil. Mechanical power is provided to the kelly bars by a rotary table and crowd assembly.

The steam raises the temperature of the soil mass to between 170 and 180 degrees Fahrenheit (^{o}F), thereby increasing the vapor pressure of the VOCs, volatilizing them away from the soil particles, and allowing them to be transported to the soil surface by the action of the steam and an applied vacuum in the treatment shroud. The cutter bits are moved vertically to selectively treat areas of greater organic contamination. The treatment cycle may be repeated until the contaminant levels in the soil are satisfactorily reduced. The treatment procedure facilitates overlapping treatment of all depths of the block to ensure adequate exposure of the VOC-contaminated soil to the steam.

7.3.2 Hot Air Injection

Hot air injection is used to enhance typical SVE application through gas advection. The introduction of hot air to the contaminated region raises the ambient soil temperature and volatilizes the contaminants to a gas phase. The vapor is then mobilized to the extraction wells through the applied vacuum. The contaminants not in direct contact with the flowing vapor will undergo diffusion into the vapor phase from the soil. This is a slower transport mechanism than the advection process, but it has the same net effect. Hot air injection becomes more effective as the soil medium dries through its application. As the soil dries, soil permeability is increased, and the vapors can flow more freely. Hot air injection has limited applicability to dioxins, furans, and PCBs. It is also relatively less effective for the extraction of SVOCs as compared to steam injection because of lower temperatures. Hot air injection is particularly effective for VOCs in lower permeability soils.

Hot air injection is similar in implementation to steam injection, but hot air is used in place of steam. The hot air can be supplied either through an injection well or by injecting hot air through a large mixing auger (see Figure 7-3). The system is designed to work in a manner similar to the steam treatment; the contaminants are volatilized for removal at an extraction well. The resulting off-gas can then be treated.

Hot air injection can also be used in conjunction with other thermal enhancement technologies. Hot air injection can follow a steam injection process to keep the mobilized contaminants volatilized. One vendor uses hot air injection as a means of removing moisture from the contaminated region before treating the soil using oxidation.

Wells used in hot air injection are typically constructed of steel casing perforated at the bottom and cemented in place (EPA 1994). Heated, compressed air is injected into the wells, and the volatilized contaminants rise toward the surface, where they are trapped beneath an impermeable cover. Heating air may be provided by a burner and blower assembly, or heated air from a thermal or catalytic oxidation unit used to treat extracted soil vapors may be used. The vacuum extraction well captures the rising vapors because of the induced pressure gradient. When an auger configuration is used, the process is similar to the steam injection auger method. The hot air is injected through the auger as it penetrates and mixes the soil. A movable cover is used over the mixing area to reduce the chance of contaminant emissions. The volatilized contaminants are then collected with vapor extraction wells and treated.

The required input temperature puts constraints on the well materials that can be implemented successfully. As a result, more expensive well construction materials are typically required, since bentonite (a typical sealing material) loses its effectiveness at temperatures above 100°C (AAEE 1994). Additionally, for long pipe runs, insulation for the air delivery system would be required to minimize heat losses caused by thermal radiation. Finally, cyclical heating and cooling of the injection wells would induce expansion and contraction of the steel and could fatigue the concrete or cement seal.

7.3.3 Radio-Frequency Heating

RF heating is used to enhance the SVE application by heating the contaminated soil matrix to temperatures above those of steam injection processes and volatilizing contaminants. The heating efficiency is decreased as the soil matrix dries. The heating of the soil increases the chemical partitioning to the vapor phase enhancing the contaminant removal. The vaporized contaminants are then transported to the extraction wells by an applied vacuum. RFH is applicable to sites with low-permeability soils. It has limited applicability to dioxins, furans, and NAPLs. RFH is particularly applicable to sites contaminated with VOCs and SVOCs in soil.

RF heating has the ability to raise soil temperatures well above levels attainable by steam extraction and is more applicable to higher boiling point compounds. This fact also leads to a reduction in removal times. Typically, energy is delivered to the contaminated region using electrodes or antennae that emit radio-frequency waves. These radio waves increase molecular motion, which heats the soil.

The components of the RFH systems have two general purposes: transmission of RF energy and collection of vapors. RF energy is transmitted to the soil using an RF generator, a matching network, electrodes or applicators, temperature measuring devices, and an RF shield. These components are discussed briefly below:

- RF generator - The RF generator is designed to convert three-phase alternating current (AC) power to RF energy. The RFH generators used during several previous pilot-scale demonstrations have ranged from 25 to 125 kilowatts (kW). Trailers containing 10 kW and 20 kW RF generators are commercially available. The radio transmitter powered by the generator provides continuous RF wave at a frequency allocated for industrial, scientific, and medical equipment, including 6.78 mega-hertz (MHz), 13.56 MHz, 27.12 MHz, 40.68 MHz, and seven higher frequencies.

- Matching network - RF energy from the generator flows to the matching network, which is used to adjust the electrical characteristics of the RF energy being transmitted into the soil and maximize the fraction of power absorbed by the soil. This is important to increase energy efficiency of the system and to prevent unadsorbed power from reflecting back to the generator and other electrical components and overheating the components.

- Electrodes or applicators - RF energy is transmitted through the matching network to an electrode array or to applicators, which convey the energy into the soil. For applications using an electrode array, RH energy is transmitted to rows of copper electrodes, known as exciter electrodes. The electrodes are placed in boreholes and backfilled with material similar to the surrounding soil. Rows of aluminum electrodes, known as ground electrodes, are installed parallel to and on either side of the exciter electrode row. The electrode configuration is designed to direct the flow of RF energy through the soil and contain the energy within the treatment zone.

- For sites where applicators are used, energy from the RF generator flows through the matching network to the applicators, which convey the energy into the soil. The applicators are 3.5-inch-diameter antennae that are constructed with aluminum, stainless steel, Teflon, ceramic, brass, and copper components. The applicators are connected with rigid copper transmission lines that are pressurized with nitrogen to increase high voltage handling capability. The applicators are alternately selected with a remote-controlled coaxial switch.

- Temperature measuring devices - Temperature measuring devices such as thermocouples, fiber optic temperature probes, and infrared sensors are positioned throughout the treatment zone at various depths to ensure adequate heating of the contaminated soil.

- RF shield - If magnetic field monitoring indicates that the treatment system is not complying with all regulations concerning magnetic fields, an RF shield should be constructed over the treatment area to limit exposure to the RF energy that escapes the system. A corrugated aluminum arch or other structure has been used previously during pilot-scale studies.

RF systems require a vapor barrier and soil vapor extraction and treatment system. The vapor barrier can be designed similar to conventional SVE surface seals; however, an insulating barrier may be desired to reduce heat loss from the treatment area. Vapor treatment will depend on contaminant types and concentrations, and will typically consist of condensation and thermal or catalytic oxidation.

The electrodes or antennae used in this process are powered by a radio-frequency generator that operates in the industrial, medical, and scientific band. The frequency is chosen based on dielectric properties of the soil and area of contamination. These electrodes are either placed on the surface at the contaminated area or inserted into holes drilled into the contaminated area. The energy given off by the electrodes excites the contaminated region and raises the temperature. This heating occurs through two different mechanisms, ohmic and dielectric effects. Figure 7-4 illustrates how an RFH system was implemented at the Sandia National Laboratory in New Mexico.

The ohmic mechanism results from an induced voltage drop that causes electrons to flow up into the conduction band and through the contaminated region causing resistance heating (AAEE 1994). The most efficient and uniform heating is obtained by limiting the induced voltage drop in the contaminated region. The dielectric heating mechanism results from the interaction between the applied electric field and distortions of molecular structure. Polar substances present in the contaminated region have dipole moments that are randomly oriented. By applying an electric field, the dipole moments of the molecules begin to align, causing molecular distortions. The resistance to this distortion heats the soil.

The radio-frequency generator can be used to heat the contaminated soil up to 150 to 200 ºC. At such temperatures, the range of conventional SVE is extended to organic compounds with vapor pressures in the 5- to 10-mm Hg range. Some vendors claim this range can be extended further because the generator used in their system is capable of heating soils to 400 ºC (EPA 1995a). As the soil formation is continually heated, soil moisture is driven off, which results in a decrease in removal efficiency. This is caused by the decreased conductivity of air compared to water. The moisture content of the soil is critical to the removal efficiency and is reflected through the soil dielectric constant. To maintain adequate removal efficiencies, the frequency of the RF signal can be varied. Alternatively, if the system was combined with a steam injection system, the soil moisture content could be controlled.

7.3.4 Electrical Resistance Heating

ER heating is used to enhance SVE processes by a similar transport mechanism as RFH. However, ER heating is slightly less efficient because of uneven heating and decreased efficiency as the soil dries near the electrodes. The transport process increases the chemical partitioning to the vapor phase, enhancing the contaminant removal. The vaporized contaminants are then removed by extraction wells under an applied vacuum. ER heating is applicable to low-permeability soils contaminated primarily with VOCs. It is generally less applicable for sites contaminated with dioxins, furans, and PCBs (AAEE 1994).

ER heating uses the soil as a conduction path for electrical current. The energy dissipated because of resistance is transformed into heat. ER heating suffers the same limitation as RFH in terms of soil moisture content. As discussed above, with decreasing soil moisture, the removal efficiency is also decreased. With a constant voltage supply, the soil nearest the electrodes dries at a faster rate than the bulk of the soil, causing increased resistances and decreased removal efficiencies. This also leads to an unevenness in heating.

Past applications of ER heating have included six-phase soil heating (SPSH) or EM heating. 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. To maintain soil conduction, the electrodes are backfilled with graphite, and small amounts of water containing an electrolyte are added to maintain moisture. The rate of water addition depends on the soil type. A trailer-mounted power plant supplies three-phase power to a six-phase power transformer.

SPSH reduces the moisture content of the soil and makes the soil more permeable for gas flow. The electricity supplied is then increased to oxidize and cleave any remaining nonvolatile organic compounds. Soil moisture and volatized contaminants are collected under vacuum by an extraction well located in the center of the hexagon.

Components of EM heating are similar to RFH; however, powerline frequency (60 hertz [Hz]) energy is passed through the soil using the conductive path of the residual soil water. At the Sandia National Laboratory, EM heating was conducted using the same system configuration as RFH heating (Photographs 7-1, 7-2, and 7-3). Powerline frequency energy input is controlled through a multi-tap transformer to allow for the changing impedance of the soil as soil water is removed. Voltages begin at approximately 200 volts (V) and can be increased in steps up to 1,600 V. Water is added to the excitor electrodes to moderate the increased soil resistance caused by the removal of soil water adjacent to the electrodes. EM heating is capable of heating soil to between 80 and 90 ^{o}C.

7.3.5 Thermal Conduction Heating

Conduction heating enhances typical SVE treatment by heating the soil surface to volatilize contaminants. It uses the same transport mechanism as RFH and ER heating, namely by increasing chemical partitioning to the vapor phase, enhancing the contaminant removal. This particular enhancement would be most effective for sites with medium- to low-permeability soils contaminated with VOCs. It is a less efficient heating mechanism than those described previously; therefore, it is not applicable to higher boiling point compounds (although higher boiling point compounds such as PCBs will be mobilized in the first few feet bgs).

In conductive heating, a heat source is placed on the surface of the contamination or inserted into the formation, and heat is supplied to the contaminants by conduction. Typically, a common ER heater such as a thermal blanket is used as the heat source. The thermal blanket is placed on the contaminated soil and heat is conducted from the blanket/soil surface interface vertically into the soil, thus volatilizing organics in the soil. The blanket also acts as a surface seal. Down-the-hole heaters have also been used to enhance oil recovery operations. The supplied heat would volatilize the target contaminants and be collected under vacuum by a surface bell arrangement or an actual extraction well. However, limited application of this technique as applied to remediation has been documented.

A thermal blanket system developed by Shell Technology Ventures, Inc. was demonstrated in 1996 at the South Glens Falls Dragstrip in South Glens Falls, New York. The thermal blanket system contained heating elements that heated the ground surface up to 800^{o} to 1000^{o}C, and a vacuum system that drew soil vapors toward and through the blankets. Although the thermal blanket system did not use SVE wells, the system reduced average PCB concentrations of more than 500 mg/kg to less than 2 mg/kg in the treatment zone. Most contaminants were destroyed in the soil near the heat source. Treatment times ranged from more than 24 hours to treat the upper 6 inches of soils to approximately 4 days to treat contaminants 12 to 18 inches deep. For deeper contamination, the technology uses ER heating in vertical or horizontal boreholes in conjunction with the thermal blanket(s) (*Soil & Groundwater Cleanup* 1997).

Conduction heating has several advantages and disadvantages with respect to other thermal enhancement technologies. An advantage of this technology is its ease of implementability and relatively inexpensive cost; however, heat conduction by this method is very slow and inefficient and requires that a large temperature gradient be maintained for acceptable heating rates to be achieved.

7.4 PERFORMANCE AND COST ANALYSIS

This section provides recent performance and cost data for remediation involving thermal enhancement.

7.4.1 Performance

A number of pilot- and full-scale applications of thermal enhancement technologies have been conducted in recent years. The treatment performance of 13 thermal enhancement technology applications are summarized in Table 7-1. This section discusses the treatment and operational performance of steam injection and stripping and ER technologies using three case studies. Cost performance of thermal enhancement technologies is discussed in Section 7.4.2.

7.4.1.1 Rainbow Disposal Site

A representative full-scale demonstration of steam injection and stripping technologies was performed at the Rainbow Disposal site in Huntington Beach, California, by Hughes Environmental Systems, Inc. The Rainbow Disposal site is an active municipal trash transfer facility that was contaminated with diesel fuel, and contained a high-permeability formation and a lower confining layer. In 1984, an underground fuel line was punctured during digging operations, and an estimated 70,000 to 135,000 gallons of No. 2 diesel fuel leaked into the surrounding soil. Free product was present in most monitoring wells in the zone of contamination.

The Rainbow Disposal site geology is characterized by alternating layers of high-permeability sand and low-permeability clay. The fuel flowed downward under gravity through each sand layer and flowed laterally at each sand/clay interface until a break in the clay layer allowed further downward movement. A perched aquifer in a sand layer at 25 to 40 feet bgs prevented further downward movement of contamination. Because of the depth of contamination, excavation and ex situ treatment were not considered practical. In addition, the large amount of free product present at the site and the location of the diesel in a perched aquifer made treatment by SVE impractical. Therefore, the Hughes steam enhanced recovery process (SERP) was selected to treat the contaminated soil at the Rainbow Disposal site.

Treatment using the SERP process began in August 1991 and was evaluated under EPA's SITE program in August and September of 1993. SERP was applied to a lateral treatment area of approximately 2.3 acres at the Rainbow Disposal site. The system was designed with 35 steam injection wells and 38 vapor/liquid extraction wells that were placed in an arrangement with one extraction well surrounded by four injection wells (EPA 1995b). The spacing between the well arrangements depended on the soil permeability and the size and depth of the contamination area. For this implementation, the extraction wells were placed 45 feet from the injection wells, and injection wells were spaced approximately 60 feet apart. The wells were installed to a depth of 40 feet. The extraction system was equipped with a condensation system and a thermal oxidation unit (TOU) to treat vapors removed from the extraction wells.

The treatment objective at the Rainbow Disposal site was to treat TPH to concentrations of less than 1,000 mg/kg. Low levels of BTEX compounds were also present in the soil; however, there were no specific treatment objectives for BTEX compounds at the Rainbow Disposal site. The treatment results indicate that the SERP's removal efficiency was less than expected. Pretreatment samples collected at the site indicated a weighted average concentration of 3,790 mg/kg of TPH, and post-treatment samples had a weighted average concentration of 2,290 mg/kg. This reduction corresponds to a removal efficiency of approximately 40 percent. Forty-five percent of the post-treatment soil sample results were above the cleanup criterion of 1,000 mg/kg. There was a large variability in the posttreatment soil sampling results, probably because of the heterogeneity of the pre-treatment soil contamination. BTEX compounds were not detected in posttreatment soil samples; however, treatment efficiency results for BTEX compounds were inconclusive based on the low concentrations and infrequent detections of BTEX compounds in the untreated soil.

It was estimated that approximately 16,000 gallons of the diesel fuel spill was removed during treatment with the SERP. Since the estimated release was 70,000 to 135,000 gallons and since 4,000 gallons was recovered before the SERP implementation, 12 to 24 percent of the original spill volume has been removed (EPA 1995b). About 5 percent of the recovered diesel was condensed in the SERP's aboveground condensation unit and 95 percent of the diesel was combusted in the TOU.

The reduced efficiencies reported in this demonstration are largely attributable to the soil conditions and uneven temperature distribution. The site geology was not constant over the entire treatment area. The same alternating layers of sand and clay that directed the flow of contamination in the site soil also influenced the treatment process. Removal of contamination trapped in the less-permeable clay layers was difficult because the steam and heat could not penetrate these areas easily, and flow patterns could not be developed to bypass less-permeable areas.

Based on soil temperature profiles from several areas of the site, heating of the soil took much longer than originally anticipated, and high soil temperatures were not maintained in many areas. This may have been because of the hours of operation (16 hours per day, 5 days per week) and excessive operational downtime. The heating rate improved later during the application when the process was operated on a 24-hour-per-day, 6-day-per-week cycle. The unreliable heating of the soil may have led to the failure of the SERP technology to achieve the cleanup criterion for the site.

In summary, steam injection and stripping may be used to remove significant amounts of contamination from the subsurface; however, treatment times may be hard to predict because of the heterogeneity of soil types and uneven heating of soil. In addition, it may be difficult to meet treatment goals with steam injection and stripping systems; however, improved operation of the systems will likely improve treatment efficiency and may reduce contaminant concentration to below treatment goals.

7.4.1.2 Savannah River Site

ER heating methods are potentially effective for removing VOCs from less permeable formations. A representative project is the application of SPSH at the SRS in Aiken, South Carolina. The demonstration site at SRS was located at one of the source areas, the M Area, within the 1-square-mile VOC groundwater plume. The M Area operations resulted in the release of process wastewater to an unlined settling basin. Vadose zone contamination is primarily associated with a leaking process sewer line, solvent storage tank area, settling basin, and the outfall from the settling basin to a branch of the Savannah River. The contaminated target zone was a 10-foot-thick clay layer at a depth of approximately 40 feet bgs in the vadose zone.

SPSH was used to remove VOCs during this technology demonstration. 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. To maintain soil conduction, the electrodes are backfilled with graphite, and small amounts of water containing an electrolyte are added to maintain moisture. The rate of water addition depends on the soil type. At SRS, 1 to 2 gallons/hour of water with 500 mg/L sodium chloride was added at each electrode. A 750 kilovolt-ampere (kVA) trailer-mounted power plant supplied 480 volts of three-phase power to a six-phase power transformer. The six-phase transformer was rated at 950 kVA. Total power applied during the demonstration averaged 200 kilowatts.

The vapor extraction well, which removes the contaminants, air, and steam from the subsurface, is located in the center of the hexagon. At the SRS site, the diameter of the hexagon was 30 feet. Moisture in the extracted air was condensed, and the VOC vapors were treated by electrical catalytic oxidation.

Before treatment using SPSH, the untreated target clay zone contained TCE and PCE at concentrations ranging from nondetected to 181 μg/kg and nondetected to 4,529 μg/kg, respectively. No target cleanup goals were specified for the demonstration. Analytical tests conducted on the treated soil indicate that the median removal of PCE within the electrode array was 99.7 percent. Outside the electrode array, 93 percent of the PCE contamination was removed at a distance of 8 feet from the array. The mass removal rate of PCE increased threefold after the treatment zone was heated and dried.

ER tomography (ERT) was used during the field demonstration to monitor electrical conductivity in the clay treatment zone. The ERT monitoring indicated that the clay layer increased in electrical conductivity (up to twice initial values) during the first 3 weeks of treatment as the soil heated and ER decreased. After that time, conductivity decreased to as low as 40 percent of the pretest value as a result of the drying of the soil and the increased air permeability. Approximately 19,000 gallons of water were removed as steam during the field demonstration, indicating that the soil was dried substantially during the test.

Several operational problems were encountered during the SPSH demonstration. Operational difficulties encountered included drying out of the electrodes and shorting of the thermocouples. Further field experience is expected to facilitate improvement in the design of the system to overcome these difficulties.

In summary, the field demonstration of SPSH at SRS indicates that ER heating has potential to enhance the performance of SVE by heating and drying contaminated soil, thus (1) creating steam to strip contaminants and (2) increasing advection through increased air permeability. Soil drying may lead to increased mass removal rates and faster site remediations, particularly in low-permeability soils where contaminant removal is limited by diffusion.

7.4.1.3 Former Gasoline Station Near St. Paul, Minnesota

During March 1996, KAI Technologies, Inc. (KAI) conducted a three-week pilot-scale demonstration of RFH-enhanced SVE at the site of a former gasoline station near St. Paul, Minnesota. Soil and groundwater at the site were contaminated with petroleum hydrocarbons from a release from an underground dispensing system. From 1991 to 1996, much of the petroleum hydrocarbon contamination was removed from the site by pumping groundwater and using SVE; however, residual petroleum hydrocarbon levels near the underground dispensing system exceeded health risk limits established by the Minnesota Department of Health.

The RFH demonstration equipment, consisting of one RFH well containing a 9-foot antennae applicator, two soil vapor vents, three soil vapor probes, and one groundwater vent, were positioned in the area of the site that contained the highest contaminant concentrations. Analytical data indicated that soil in the three-foot layer encompassing the capillary fringe contained the highest concentrations of petroleum hydrocarbons. The applicator was positioned from 6 feet to 15 feet bgs in the well. The water table was located approximately 10 feet bgs. A 25-kW RF generator supplied RF energy during the demonstration.

During the 3-week demonstration period, soil and groundwater were heated using RFH at a power level of 5 kW and a frequency of 27.12 MHz. Approximately 2,300 kWh of RF energy was delivered to the soil and groundwater at the site. As a result of the application of RFH, soil temperatures were raised from an ambient temperature of approximately 8 ^{o}C to 100 ^{o}C in the immediate vicinity of the RFH applicator and to 40 ^{o}C at a radial distance of 5 feet from the applicator at a depth of 8.5 feet bgs. During the demonstration, the concentration of gasoline-range organics (GRO) in soil were reduced by an approximate factor of two. At the location of the highest predemonstration GRO soil concentration, the GRO concentration was reduced from 2,300 mg/kg to 1,000 mg/kg. However, GRO soil concentrations increased at some sampling locations, which was attributed to redistribution of contaminants during the demonstration and/or heterogeneities in contaminant distribution at the site.

Groundwater concentrations also were reduced during the 3-week demonstration period. At most sampling locations, GRO concentrations were reduced by an order of magnitude. The largest reduction in GRO concentration occurred at a sampling location approximately 13.5 feet from the RFH well. At this location, GRO concentration was reduced from 29 mg/L to 0.1 mg/L in the groundwater.

7.4.2 Cost Analysis

This section presents costs developed from past applications of thermal enhancement technologies. These costs were derived from cost analyses conducted for the field demonstrations of the steam injection/stripping and ER case studies discussed in Section 7.4.1. Where possible, cost comparisons are presented to show the difference in costs between using conventional SVE treatment and using SVE with a thermal enhancement. Costs for the use of steam injection/stripping at the Rainbow Disposal site and for the use of ER at the SRS site are presented below.

7.4.2.1 Steam Injection/Stripping Costs

Because of the nature of contamination at the Rainbow Disposal site, operation of a conventional SVE system would not have been practical to remediate the site. Contaminants were present as free product at the site in saturated soil. Therefore, no cost comparison can be made between remediation of the site with conventional SVE and with steam injection/stripping.

Treatment costs were developed for 12 cost categories as part of the SITE demonstration at the Rainbow Disposal site (EPA 1995b). Cost were developed for the actual costs developed during two years of operation at the Rainbow Disposal site; however, because the SERP system had significant (50 percent) downtime during this period, costs were also developed for an "ideal" (0 percent downtime) case and for a "typical" (25 percent downtime) case. For each of the three cost analyses, it was assumed that 95,000 yd^3 of soil would be treated. The results of the economic analysis for the actual, ideal, and typical cases are presented in Table 7-2. Figure 7-5 presents the costs per yd^3 for each of the 12 cost categories for the typical case.

As shown in Table 7-2, the soil treatment cost ranges from about $\$29/yd^3$ to $\$43/yd^3$ for the ideal and actual cases, respectively. Labor is the largest cost for use of SERP, accounting for about one third of the total cost. Since labor costs are directly proportional to the duration of remediation, factors that would increase or decrease the remediation time would impact the total cost most significantly. Startup costs and utilities are also significant costs for use of SERP, together accounting for about one-third of the total cost. The cost per yd^3 is significantly less than the cost of excavating and treating the soil; however, as discussed in Section 7.4.1.1, SERP did not meet the treatment goal, and additional treatment may be necessary. Continued treatment would have increased the total cost and the cost per yd^3 for the site.

7.4.2.2 Electrical Resistance Costs

The targeted zone of contamination treated during the field demonstration of the SPSH technology at the SRS site is in the vadose zone and is amenable to conventional SVE treatment; therefore, a cost comparison can be made between remediation with conventional SVE and with SVE used with SPSH. An independent cost analysis prepared for the DOE by the Los Alamos National Laboratory (DOE 1995) presents costs for

SPSH and compares costs for treatment using SVE alone and treatment using SVE enhanced with SPSH. The results of the cost analysis are presented below.

Costs were developed for a hypothetical site that contained a 100-foot diameter area that was contaminated with VOCs and SVOCs from 20 to 120 feet bgs. It was assumed that off-gases from the SVE extraction well would be destroyed in a catalytic oxidation system. It was also assumed that capital costs would be amortized over a 10-year period.

The estimated costs for SPSH are presented in Table 7-3. The total capital costs were estimated to be $1,278,000, and the total annual operation and maintenance costs were estimated to be $204,000. The power source for the SPSH system and the vacuum extraction system are the largest capital costs, accounting for about two-thirds of the capital costs. For the 29,000 yd^3 of soil at the hypothetical site described previously, capital costs account for about $44/yd^3.

The DOE (1995) cost analysis indicates that the total cost of SPSH would be $86/yd^3 of treated soil and that the total cost of SVE would be $576/yd^3 of treated soil. The cost analysis assumed that the site would be remediated in 5 years using SPSH and in 50 years using conventional SVE; however, the basis of this assumption is not given. The time required to remediate the site is critical for any cost comparison and may be estimated from modeling contaminant removal rates and field testing. The field study indicated that mass removal rates measured in the extraction vent tripled after soil temperatures reached about 100 ^oC. Results of a recent report that compared costs of thermal enhancement technologies and conventional treatment technologies are also presented.

7.4.3 Additional Cost Studies

A recent report also compares the costs for thermal enhancement technologies with conventional treatment technologies (Bremser and Booth 1996). The report studied costs for thermal enhancement and conventional treatment technologies for five different types of contamination as presented below:

Type of Contamination	Thermal Enhancement Technology	Conventional Treatment Technology
Shallow vadose zone contamination	Thermally enhanced vapor extraction system (TEVES)	Excavation and Treatment
Deep vadose zone VOC contamination	3-Phase soil heating	SVE
	6-Phase soil heating	SVE
Deep vadose zone SVOC contamination	RF heating	SVE
Deep vadose zone with groundwater contamination	Dynamic underground stripping (DUS)	PT/SVE
Restricted access contamination	RF heating using dipole antennae (RFD)	SVE

The report is based on results of demonstrations of thermal enhancement technologies at DOE sites. The report concluded that in every treatment case described above, the thermal enhancement technologies were significantly less expensive than the conventional technologies. The report suggests that the thermal technologies save money by remediating the contaminants in an estimated 6 months due to the increased mass removal rate, as compared to conventional SVE treatment that is estimated to take 5 years to complete. Figure 7-6 presents the cost comparisons, on a cost per yd^3 treated basis, for the five treatment scenarios described above.

7.5 VENDORS

A number of vendors or companies provide thermal enhancement technologies or services. Some technologies, such as steam injection and hot air injection, use standard equipment such as injection wells and boilers that can be designed and constructed to meet site-specific needs. These technologies can be implemented by a relatively large number of companies. Other technologies, such as six-phase heating and RFH, require more specialized equipment that are provided by a more limited number of vendors. Table 7-4 presents a list of vendors of thermal enhancement technologies. Table 7-5 presents potential contaminants and media that can be treated by the thermal enhancement technologies.

7.6 STRENGTHS AND LIMITATIONS

The various types of thermal enhancement technologies have different strengths and limitations. The strength and limitations of each type of thermal treatment technology are provided below.

7.6.1 Steam Injection/Stripping

The primary strengths of steam injection technologies include:

- They provide both heat and pressure to a formation to remove contaminants in the vapor, aqueous, and NAPL phases. When used in combination with vacuum vapor extraction wells, the steam injection system can provide a large differential pressure to move contaminants toward the extraction wells.
- Steam injection is more mature than other thermal enhancement technologies to remove NAPLs.

The primary limitations of steam injection technologies include:

- Site geology may limit the performance of steam injection/stripping technologies. The soil should have moderate to high permeability to allow the steam front to move through the soil. Impermeable soil formations such as clay materials may not be suitable for steam injection treatment.
- The subsurface geology must provide a confining layer below the depth of contamination to prevent contamination from migrating vertically downwards. A confining layer is especially important for applications when steam stripping is used to remove DNAPL. In addition, a low-permeability surface layer may be needed to prevent steam breakthrough for shallow soil applications.
- Data from the application of steam technologies suggest that soil will remain at elevated temperatures for an extended period of time. High soil temperatures can delay use of the site or inhibit natural biodegradation of the residual contamination.

7.6.2 Hot Air Injection

The primary strength of hot air injection technologies include:

- Hot air injection is comparatively inexpensive. Hot air can be much easier to provide than high-quality steam. For example, heated air from a TOU can be reinjected into the subsurface.

The primary limitations of hot air injection technologies include:

- Hot air injection is not a very efficient means for delivering heat to the subsurface because of the relatively low heat capacity of air and the high energy losses in the piping systems.

7.6.3 Radio-Frequency Heating

The primary strengths of RFH technologies include:

- With RFH, much faster heating rates and uniform heating can potentially be obtained than with competing technologies.
- The technology does not involve any type of fluid injection and is operated under vacuum containment conditions, so chances of contaminant spreading is minimized.

The primary limitations of RFH technologies include:

- The high temperatures associated with RFH inhibit biological activity and may induce some fracturing of the soil structure as the soil dries.

7.6.4 Electrical Resistance

The primary strengths of ER heating technologies include:

- The process uses common AC electricity, lowering capital costs and making the technology cost competitive with RFH.
- The technology can be used to enhance bioremediation by increasing biodegradation rates through heating the soil. The electrodes used in this process are typically thin, and it therefore requires little soil disturbance to install them.

The primary limitations of ER heating technologies include:

- The ER heating system is limited to the temperature that can be applied to the contaminated region. This process is capable of achieving maximum temperatures of 100 °C.
- The effectiveness of the technology depends on soil moisture. Once the soil has been dried by the electrodes, heating becomes uneven, and efficiencies decrease.

7.7 RECOMMENDATIONS

Thermal enhancement technologies can enhance treatment efficiency and removal rates if certain site or contaminant characteristics constrain SVE treatment efficiency. Thermal enhancement technologies can also be used to increase removal rates, thereby decreasing required treatment time. Steam injection/stripping should be considered for sites that contain nonaqueous phase liquids or high concentrations of SVOCs and TPH because contaminants are pushed ahead of the condensing water vapor toward the typical extraction wells. Additionally, some of the contaminants are vaporized or solubilized by the injection of steam and are moved toward the extraction wells by an applied vacuum. However, application of steam injection and stripping systems is limited to medium- to high-permeability soils. ER heating is more appropriate for heating and drying low-permeability soil in the vadose zone. RFH and ER heating can be used to heat soil if site conditions restrict the use of injection wells.

7.8 REFERENCES

This section includes a list of references cited in Chapter 7 (Subsection 7.8.1) and a table presenting professional contacts in the field of thermal enhancement technologies (Subsection 7.8.2).

7.8.1 Cited References

American Academy of Environmental Engineers. 1994. Innovative Site Remediation Technology: Vacuum Vapor Extraction. WASTECH. Volume 1 of 8.

Bremser, John and Booth, Steven R. 1996. Cost Studies of Thermally Enhanced In Situ Soil Remediation Technologies. Prepared for Los Alamos National Laboratory Environmental Technology Costs-Savings Analysis Project. LA-UR-96-1683. May.

Dablow, Jay. 1996. Memorandum Regarding Vendor Information and Performance Data. To Mike Johnson, Tetra Tech EM Inc. September 6.

EPA. 1994. Vendor Information System for Innovative Treatment Technologies (VISITT), Version 4.0. Database Prepared by Office of Solid Waste and Emergency Response, Technology Innovation Office. Cincinnati, Ohio.

EPA. 1995a. Radio Frequency Heating, KAI Technologies, Inc.: Innovative Technology Evaluation Report. Office of Research and Development. Washington, DC. EPA/540/R-94/528. April.

EPA. 1995b. In Situ Steam Enhanced Recovery Process Hughes Environmental Systems, Inc.: Innovative Technology Evaluation Report. Office of Research and Development. Washington, DC. EPA/540/R-94/510. July.

EPA. 1995c. IITRI Radio Frequency Heating Technology: Innovative Technology Evaluation Report. Office of Research and Development. Washington, DC. EPA/540/R-94/527. June.

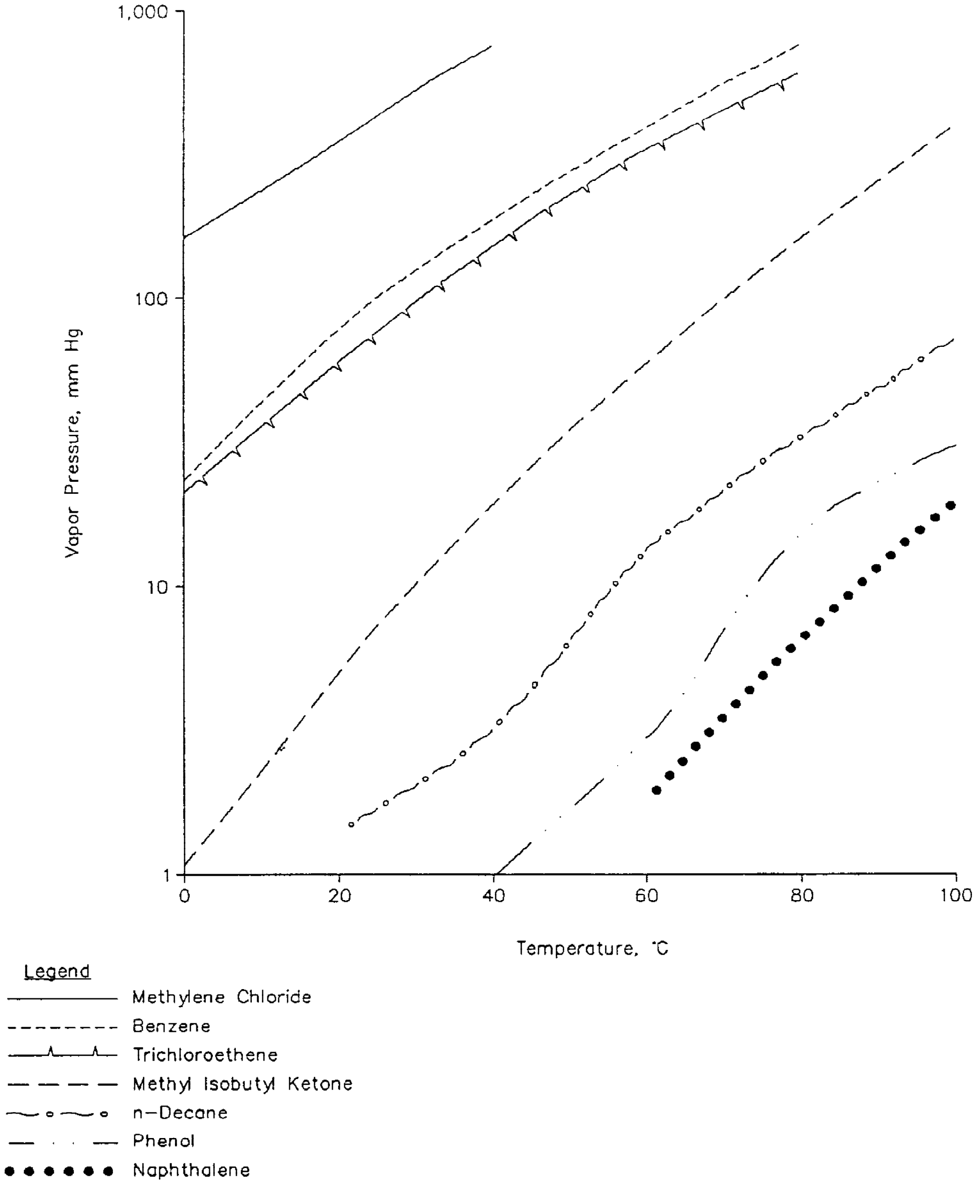
Soil & Groundwater Cleanup. 1997. May.

7.8.2 Professional Contacts

A list of thermal enhancement technology experts is provided in the table below.

Name	Affiliation
Dr. Roger Aines (510) 423-7184	Lawrence Livermore National Laboratory
John F. Dablow III (310) 371-1394	Fluor Daniels GTI, Inc.
Paul de Percin (513) 569-7797	EPA National Risk Management Research Laboratory
Harsh Dev (312) 567-4257	IIT Research Institute
Raymond Kasevich (603) 431-2266	KAI Technologies, Inc.
Laurel Staley (513) 569-4257	EPA National Risk Management Research Laboratory
Michelle Simon (513) 569-7469	EPA National Risk Management Research Laboratory
Theresa Bergman (509) 376-3638	Battelle Pacific Northwest Laboratory

FIGURE 7-1
RELATIONSHIP BETWEEN INCREASING TEMPERATURE AND VAPOR PRESSURE FOR SEVERAL CHEMICALS

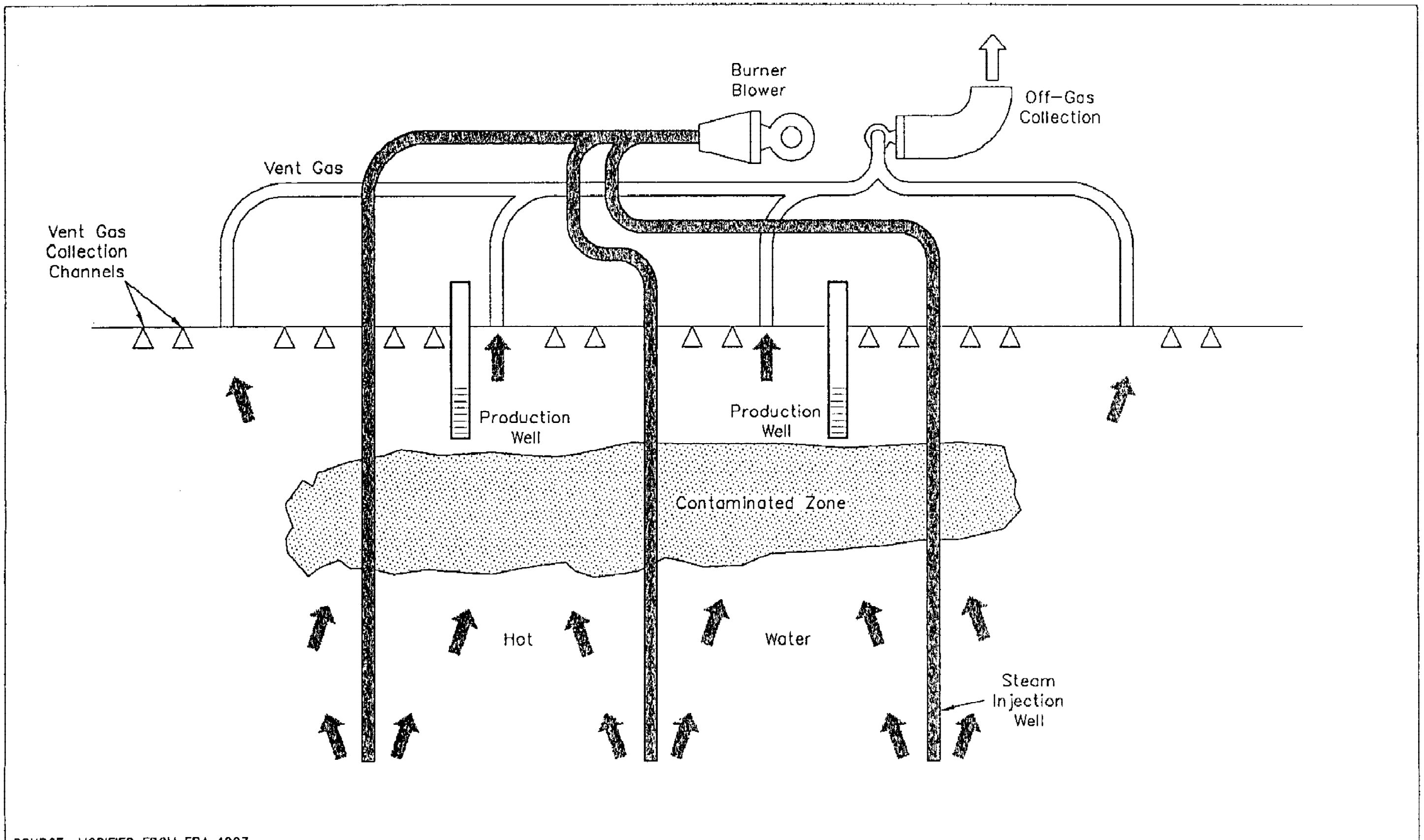


SOURCE: MODIFIED FROM PERRY 1983

RELATIONSHIP BETWEEN INCREASING TEMPERATURE AND VAPOR PRESSURE FOR SEVERAL CHEMICALS

FIGURE 7-1

FIGURE 7-2
TYPICAL SOIL VAPOR EXTRACTION ENHANCEMENT WITH STEAM INJECTION SYSTEM

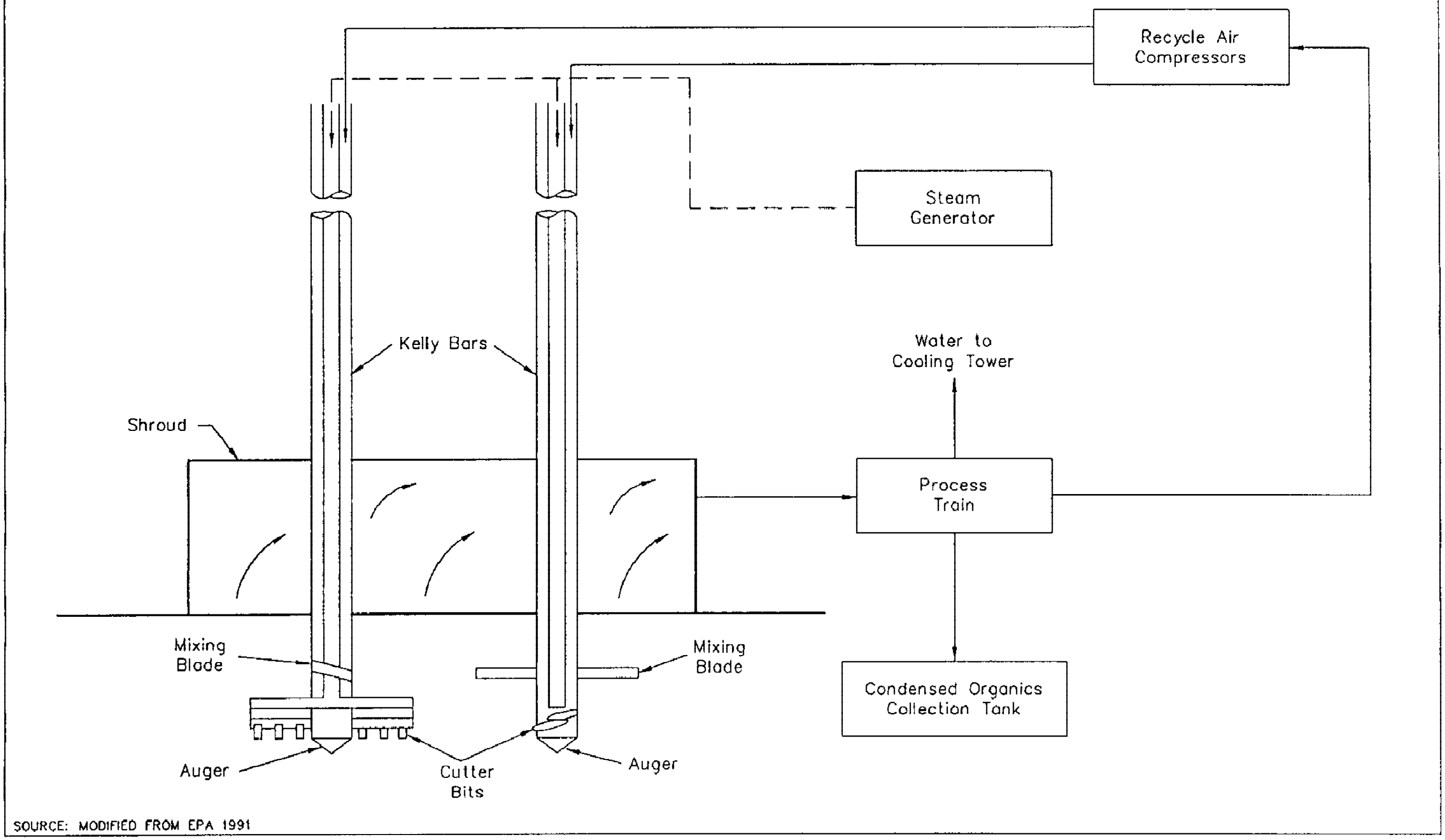


SOURCE: MODIFIED FROM EPA 1993

TYPICAL SOIL VAPOR EXTRACTION ENHANCEMENT
WITH STEAM INJECTION SYSTEM

FIGURE
7-2

FIGURE 7-3
HOT AIR INJECTION THROUGH DRILL AUGER

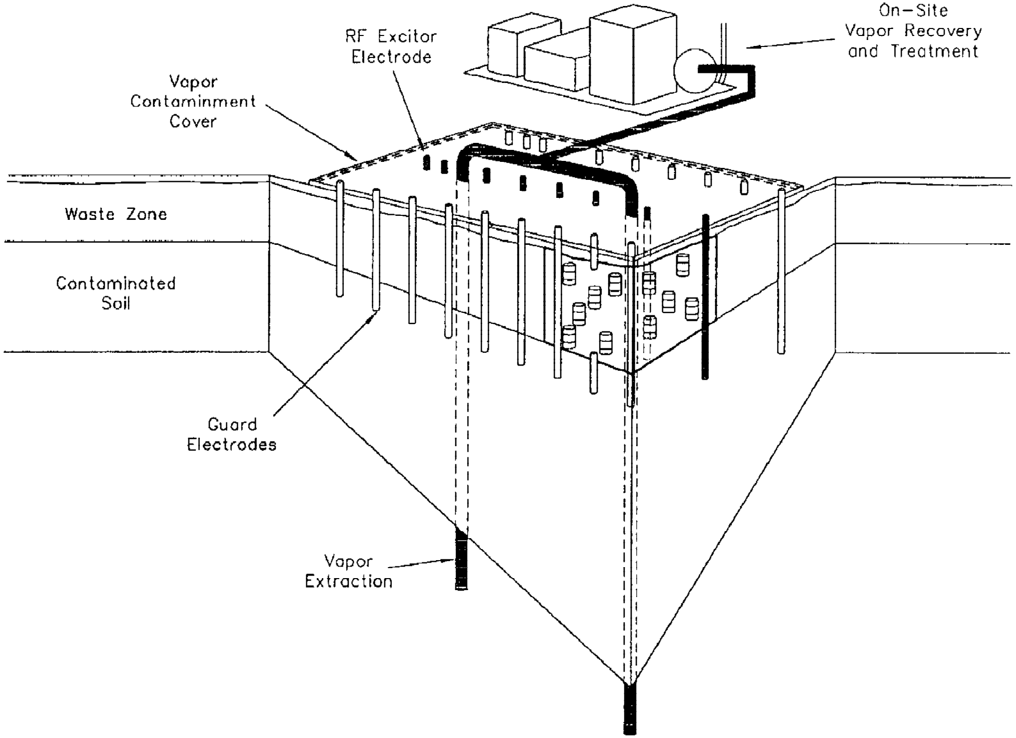


SOURCE: MODIFIED FROM EPA 1991

HOT AIR INJECTION THROUGH DRILL AUGER

FIGURE 7-3

FIGURE 7-4
SOIL VAPOR EXTRACTION ENHANCEMENT WITH RADIO-FREQUENCY HEATING AT SANDIA NATIONAL LABORATORY

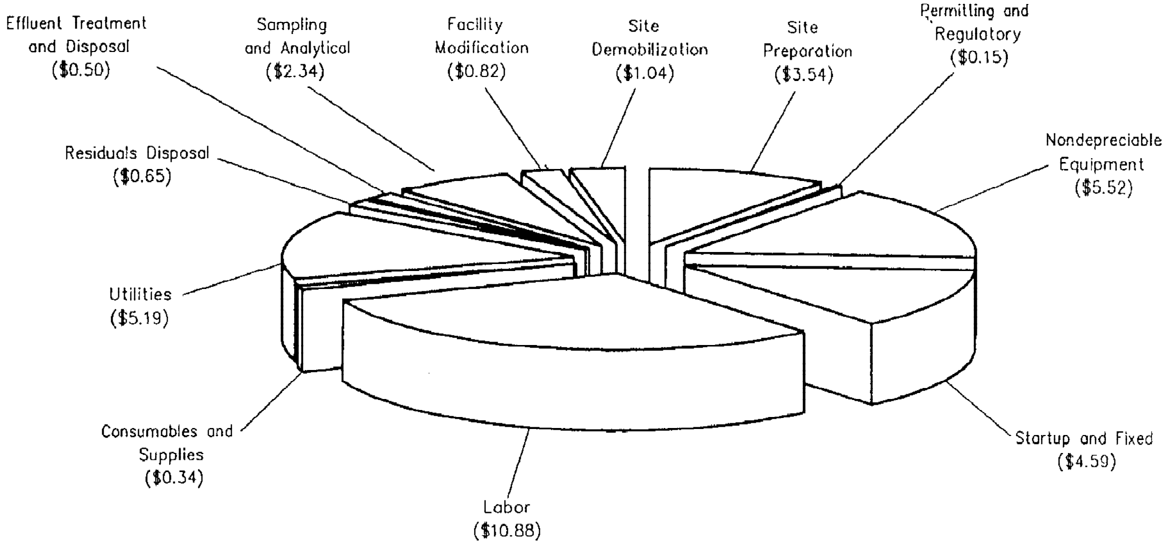


SOURCE: MODIFIED FROM EPA 1995b

SOIL VAPOR EXTRACTION ENHANCEMENT
WITH RADIO FREQUENCY HEATING
AT SANDIA NATIONAL LABORATORY

FIGURE
7-4

FIGURE 7-5
COST ANALYSIS OF THE STEAM-ENHANCED RECOVERY PROCESS



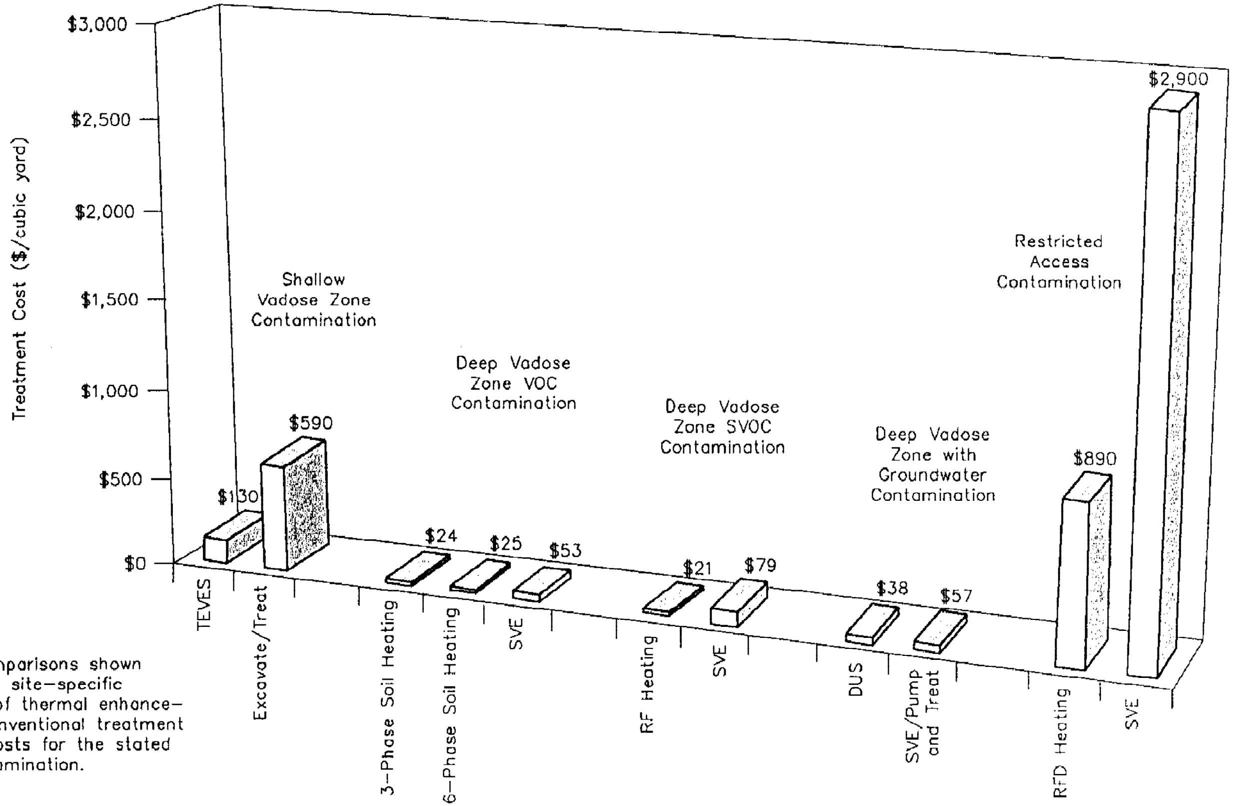
Note: Costs shown are cost per cubic yard.

SOURCE: MODIFIED FROM EPA 1995c

COST ANALYSIS OF THE STEAM-ENHANCED RECOVERY PROCESS

FIGURE 7-5

FIGURE 7-6
COST COMPARISON OF THERMAL ENHANCEMENT AND CONVENTIONAL TREATMENT TECHNOLOGIES



Note:
The cost comparisons shown are based on site-specific assessment of thermal enhancement and conventional treatment technology costs for the stated type of contamination.

SOURCE: MODIFIED FROM BREMSER AND BOOTH 1996

COST COMPARISON OF THERMAL
ENHANCEMENT AND CONVENTIONAL
TREATMENT TECHNOLOGIES

FIGURE
7-6

TABLE 7-1

THERMAL ENHANCEMENT PERFORMANCE DATA
(Page 1 of 3)

Vendor	Thermal Enhancement	Scale	Date of Demo	Location	Target Contaminant	Concentration Before Treatment	Concentration After Treatment	Volume Treated	Soil Type	Treatment Time	Source
Battelle Pacific Northwest Laboratories	Six Phase Soil Heating	Field Demo	NA	Aiken, South Carolina	PCE TCE	ND to 500 mg/kg ND to 200 mg/kg	ND to 0.5 mg/kg ND to 0.5 mg/kg	1,100 yd^3	clayey soil	18 days	EPA 1994
Geo-Con, Inc.	Hot air injection	Full	NA	Piketon, Ohio	TCE	1 to 100 mg/kg	10 mg/kg	20,000 yd^3	clayey soil	NA	EPA 1994
Flour-Daniels GTI (FD GTI)	Steam Sparging	Full	1995	Bremerton, Washington	No. 6 Fuel Oil Diesel Fuel	88,000 mg/kg TPH	Ongoing	25,000 yd^3	sandy till	Ongoing	Tetra Tech 1996
FD GTI	Hot Air Sparging	Full	1993	Union, Massachusetts	Chlorinated Solvents	100 mg/kg soil 10 mg/L groundwater (gw)	Ongoing	30,000 yd^3	glacial till	Ongoing	Tetra Tech 1996
FD GTI	Electrokinetic Heating	Full	1994	Netherlands	BTEX Diesel Fuel	BTEX (gw): 13,400 μg/L Diesel (gw): 7,300 μg/L TPH (soil): 9,000 mg/L	BTEX (gw): ND Diesel (GW): <50 μg/L TPH (soil): 9 to 220 mg/L	10,500 yd^3	sandy clay	24 weeks	Tetra Tech 1996
Hrubetz Environmental Services, Inc. (Hrubetz)	Hot air injection	Full	1990	Ottawa, Ontario Canada	Jet Fuel	21,000 mg/L	ND to 215 mg/L	300 yd^3	NA	90 days	EPA 1994
Hrubetz	Hot air injection	EPA demo	NA	Kelly Air Force Base, Texas	Jet Fuel (JP-4)	NA	12,799 lb removed	890 yd^3	NA	18 days	EPA 1994

TABLE 7-1

THERMAL ENHANCEMENT PERFORMANCE DATA
(Page 2 of 3)

Vendor	Thermal Enhancement	Scale	Date of Demo	Location	Target Contaminant	Concentration Before Treatment	Concentration After Treatment	Volume Treated	Soil Type	Treatment Time	Source
Hughes Environmental Systems, Inc.	Steam recovery	Full	1991	Huntington Beach, California	TPH (diesel fuel)	3,790 mg/kg	2,290 mg/kg	150,000 yd^3	layered sand/clay	730 days	EPA 1995b
IIT Research Institute (IITRI)	RF Heating	EPA Demo	1994	Kelly Air Force Base, Texas	Aromatics Nonaromatics	40 mg/kg 200 mg/kg	2.84 mg/kg 7.2 mg/kg	44 yd^3	silt, clay, and cobbles	60 days	EPA 1995c, EPA 1994
IITRI	RF heating	Pilot	1992	Rocky Mountain Arsenal, Colorado	Aldrin Dieldrin Endrin Isodrin	1,100 mg/kg 490 mg/kg 630 mg/kg 2,000 mg/kg	11 mg/kg 3.2 mg/kg 2.8 mg/kg 2.8 mg/kg	30 yd^3	sandy clays and clayey sands	35 days	EPA 1995c, EPA 1994
IITRI	RF heating	Pilot	1989	Volk Air National Guard Base, Wisconsin	Aromatic VOCs Aliphatic VOCs Aromatic SVOCs Aliphatic SVOCs Hexadecane	212 mg/kg 4,189 mg/kg 252 mg/kg 1,663 mg/kg 31.5 mg/kg	0.88 mg/kg 28 mg/kg 2.3 mg/kg 95 mg/kg 5.4 mg/kg	19 yd^3	sandy soil	13 days	EPA 1995c, EPA 1994
KAI Technologies, Inc. (KAI)	RF heating	Pilot	1996	St. Paul, Minnesota	TPH (gasoline)	2,300 mg/kg	1,000 mg/kg	Not available	Not available	20 days	Price, et. al. 1997
KAI	RF heating	EPA Demo	1994	Kelly Air Force Base, Texas	TRPH	1,238 mg/kg	636.9 mg/kg	56 yd^3	sandy soil	45 days	EPA 1995a
Lawrence Livermore National Laboratory (LLNL)	Steam stripping and electrical heating	Full	1993	LLNL	BTEX TPH (gasoline)	4,800 mg/kg 8,600 gallons	140 mg/kg 1000 gallons	100,000 yd^3	alluvial soil w/silt clay and gravel	145 days	EPA 1995b

TABLE 7-1

THERMAL ENHANCEMENT PERFORMANCE DATA
(Page 3 of 3)

Vendor	Thermal Enhancement	Scale	Date of Demo	Location	Target Contaminant	Concentration Before Treatment	Concentration After Treatment	Volume Treated	Soil Type	Treatment Time	Source
Novaterra, Inc.	Steam stripping	Full	1988	San Pedro, California	DCA DCE Bis(2-ethylhexyl) phthalate Aromatics Butyl carbitol	10 to 200 mg/kg 20 to 100 mg/kg 100 to 80,000 mg/kg 1,200 mg/kg 6,000 mg/kg	0.47 to 0.82 mg/kg 0.23 to 2.41 mg/kg 52.67 mg/kg 10.77 mg/kg 4.20 mg/kg	30,000 yd^3	NA	late 1989 to early 1990	EPA 1994
Praxis Environmental Technologies, Inc.	Steam extraction	Pilot	1988	McClellan Air Force Base, California	TCE	ND to 40 mg/L	ND to 0.05 mg/L	5,000 yd^3	NA	NA	EPA 1994
R.E. Wright Environmental, Inc.	Steam stripping	Pilot	NA	Bradford, Pennsylvania	TPH	50,000 to 100,000 mg/kg	4,500 mg/kg	330 yd^3	NA	45 days	EPA 1994
SIVE Services	Steam injection	Full	1989	San Jose, California	VOCs	NA	70,000 lb removed	30,000 yd^3	NA	400 days	EPA 1994

Notes:

Demo	Demonstration	TPH	Total petroleum hydrocarbon	mg/L	Milligram per liter
NA	Not applicable	DCE	Dichloroethene	mg/kg	Milligram per kilogram
PCE	Tetrachloroethene	DCA	Dichloroethane	VOC	Volatile organic compound
TCE	Trichloroethene	lb	Pound	SVOC	Semivolatile organic compound
ND	Nondetect	yd^3	Cubic yard		
BTEX	Benzene, toluene, ethylbenzene, and total xylenes				

TABLE 7-2

HUGHES STEAM-ENHANCED RECOVERY PROCESS COST SUMMARY

Cost Category	Approximate Actual Costs for the Rainbow Disposal Site		Estimated Ideal Cost for the Rainbow Disposal Site		Estimated Cost for a Typical Site of the Same Size	
	Total $	$/yd^3	Total $	$/yd^3	Total $	$/yd^3
Site Preparation	338,000	3.56	326,000	3.43	336,000	3.54
Permitting and Regulatory	16,000	0.17	11,000	0.12	14,000	0.15
Non-Depreciable Equipment	523,000	5.51	522,000	5.50	524,000	5.52
Startup and Fixed	759,000	7.99	414,000	4.35	436,000	4.59
Labor	1,362,000	14.34	776,000	8.16	1,034,000	10.88
Consumables and Supplies	43,000	0.46	24,000	0.26	32,000	0.34
Utilities	631,000	6.65	280,000	2.95	493,000	5.19
Effluent Treatment and Disposal	71,000	0.75	36,000	0.37	47,000	0.50
Residuals and Waste Handling and Disposal	67,000	0.71	49,000	0.52	61,000	0.65
Sampling and Analytical	300,000	3.16	196,000	2.06	222,000	2.34
Facility Modification, Repair, and Replacement	151,000	1.59	58,000	0.61	78,000	0.82
Site Demobilization	139,000	1.47	99,000	1.04	99,000	1.04
Total	4,400,000	46.36	2,791,000	29.37	3,376,000	35.56

Source: Modified from U.S. Environmental Protection Agency 1995b.

Notes:

yd^3 Cubic yard

TABLE 7-3

SIX PHASE SOIL HEATING COST SUMMARY

Cost Description	Total Cost ($)
Capital Costs	
Mobilization	9,000
Power Source	286,000
Water Source	24,000
Alternating Current (AC) Applications Well	54,000
Site Characterization and Well Installation	53,000
Soil Vapor Extraction Pilot Testing	13,000
Permitting	16,000
Vacuum System	175,000
Treatment System	51,000
Dismantlement and Demobilization	23,000
Startup	21,000
Subtotal	725,000
Construction Management	73,000
Engineering, Design, and Inspection	181,000
Project Management	44,000
Contingency	255,000
Total Capital Cost	1,278,000
Annual Operation and Maintenance (O&M) Costs	
Field Monitoring	76,000
Monitoring and Reporting	58,000
System Operation and Maintenance	70,000
Total Annual O&M Costs	204,000

TABLE 7-4

THERMAL ENHANCEMENT TECHNOLOGY VENDORS[a]
(Page 1 of 2)

Name of Vendor	Address, Phone, Fax	Point of Contact
Battelle Pacific Northwest Laboratories	Battelle Boulevard, P.O. Box 999, Mailstop B1-40 Richland, Washington 99352 (509) 376-3638	Theresa Bergsman
Flour Daniels GTI	20000/200 Mariner Ave. Torrance, California 90503 (310) 371-1394	Jay Dablow
Geo-Con, Inc.	4075 Monroeville Boulevard Corporate One, Building II, Suite 400 Monroeville, Pennsylvania 15146 (412) 856-7700	Linda M. Ward
Hrubetz Environmental Services, Inc.	5949 Sherry Lane, Suite 525 Dallas, Texas 75225 (214) 363-7833	Barbara Hrubetz
IIT Research Institute	10 West 35th Street Chicago, Illinois 60616 (312) 567-4257	Harsh Dev
KAI Technologies, Inc.	170 West Road #7 Portsmouth, New Hampshire 03801 (603) 431-2266	Raymond S. Kasevich
Millgard Environmental Corporation	12900 Stark Road Livonia, Michigan 48150 (313) 261-9760	Jim Brannigan
Praxis Environmental Technologies, Inc.	1440 Rollins Road Burlingame, California 94010 (415) 548-9288	Dr. Lloyd Stewart
R.E. Wright Environmental, Inc. (REWEI)	3240 Schoolhouse Road Middletown, Pennsylvania 17057 (717) 944-5501	Richard C. Cronee, Ph.D.

TABLE 7-4

THERMAL ENHANCEMENT TECHNOLOGY VENDORS[a]
(Page 2 of 2)

Name of Vendor	Address, Phone, Fax	Point of Contact
SIVE Services	555 Rossi Drive Dixon, California 95620 (916) 678-8358	Douglas K. Dieter
Terra Vac, Inc.	1555 Williams Drive, Suit 102 Marrieta, Georgia 30066-6282 (770) 421-8008	Charles Prince

Note: a This list is not inclusive of all vendors capable of providing thermal enhancement technologies. This list reflects those vendors that had been contacted in preparation of this report.

TABLE 7-5

WASTE APPLICATIONS

Vendor	Contaminants and Contaminant Groups Treated											
	Halogenated VOCs	Halogenated SVOCs	VOCs	SVOCs	Pesticide	Dioxins/ Furans	PCBs	Solvents	BTEX	Acetonitrile	Organic Acids	Reference Sources
BATTELLE PACIFIC NORTHWEST LABORATORIES	A	P	P	P	P	P	NA	A	P	NA	NA	EPA 1994
FLOUR DANIEL GTI	A	A	A	A	P	NA	P	A	A	NA	P	Dablow 1996
GEO-CON, INC.	A	A	P	P	A	NA	NA	A	NA	A	A	EPA 1994
HRUBETZ ENVIRONMENTAL SERVICES, INC.	P	P	A	A	P	P	P	A	A	P	P	EPA 1994
IIT RESEARCH INSTITUTE	A	A	A	A	A	NA	P	A	A	NA	NA	EPA 1994
KAI TECHNOLOGIES, INC.	A	A	A	P	NA	NA	P	A	P	P	P	EPA 1994
PRAXIS ENVIRONMENTAL TECHNOLOGIES, INC.	A	A	A	A	NA	NA	P	A	A	NA	NA	EPA 1994
R.E. WRIGHT ENVIRONMENTAL, INC.	P	P	A	A	P	P	P	P	A	NA	P	EPA 1994
SIVE SERVICES	A	P	A	P	P	P	P	A	A	P	P	EPA 1994

Vendor	Media Types Treated								
	Soil (in situ)	Soil (ex situ)	Sludge	Solid	Natural Sediment (in situ)	Natural Sediment (ex situ)	Groundwater (in situ)	DNAPL	LNAPL	Reference Sources
BATTELLE PACIFIC NORTHWEST LABORATORIES	A	NA	P	NA	A	NA	P	P	P	EPA 1994
FLOUR DANIEL GTI	A	A	P	A	P	P	A	A	A	Dablow 1996
GEO-CON, INC.	A	NA	NA	P	A	NA	NA	NA	NA	EPA 1994
HRUBETZ ENVIRONMENTAL SERVICES, INC.	A	NA	NA	NA	P	NA	P	NA	P	EPA 1994
IIT RESEARCH INSTITUTE	A	NA	P	NA	P	NA	NA	P	P	EPA 1994
KAI TECHNOLOGIES, INC.	A	P	P	P	P	P	NA	P	P	EPA 1994
PRAXIS ENVIRONMENTAL TECHNOLOGIES, INC.	A	NA	P	NA	A	NA	P	P	A	EPA 1994
R.E. WRIGHT ENVIRONMENTAL, INC.	A	P	NA	NA	P	P	A	P	A	EPA 1994
SIVE SERVICES	A	NA	NA	NA	P	NA	P	A	A	EPA 1994

Notes:

A - Actually treated
P - Potentially treatable
NA - Not Applicable

Appendix A

(This appendix contains Jpeg images to be posted at a later date.)

Appendix B

1.0 BIBLIOGRAPHY

The following subsections list all bibliographic references consulted while preparing this document, including those specifically cited earlier in the text. The references are listed by chapter.

1.1 CHAPTER 1

EPA. 1996. VISITT 5.0 Bulletin. Vendor Information System for Innovative Treatment Technologies - An Electronic Yellow Pages of Innovative Treatment Technologies and Vendors. EPA-542-N-96-006. Office of Solid Waste and Emergency Response. Technology Innovation Office. Washington, DC.

1.2 CHAPTER 3

Ahlfeld, D.P., A. Dahmani, and W. Ji. 1994. A Conceptual Model of Field Behavior of Air Sparging and Its Implications for Application. Groundwater Monitoring and Remediation. Fall 1994. Pages 132-139.

Baker, Ralph S., R. Pemmireddy, and D. McKay. 1996. Evaluation of Air-Entry Pressure during In Situ Air Sparging: A Potentially Rapid Method of Feasibility Assessment. Proceeding of the First International Symposium on In-Situ Air Sparging, Las Vegas, Nevada, October 24-25, 1996.

Barrera, J.A. 1994. Air Sparging and Vapor Extraction as a Means of Removing Chlorinated and BTEX Compounds in Complex Groundwater Conditions. Superfund XIV Conference and Exhibition Conference Proceedings. Volume 1.

Billings and Associates, Inc. 1996. Project Description for Firehouse Site. Available on World Wide Web. at http://www.aristotle.com/sparging/sites. July.

Billings and Associates, Inc. 1996. Project Description for BF1 Site. Available on World Wide Web. at http://www.aristotle.com/sparging/sites. July.

Billings and Associates, Inc. 1996. Project Description for Bloomfield Site. Available on World Wide Web. at http://www.aristotle.com/sparging/sites. July.

Terra Vac, Inc. 1995a. Project Description for Underground Storage Tanks - Irvine, California. July.

Terra Vac, Inc. 1995b. Project Description for Fabricated Metal Products - New Paris, Indiana. May.

Brown, R.A. and R. Fraxedas. 1991. Air Sparging - Extending Volatilization to Contaminated Aquifers. Prepublication draft presented at the Symposium on Soil Venting. Robert S. Kerr, Environmental Research Laboratory. Houston, Texas. April 29 - May 1.

Dahmani, M.A., D.P. Ahlfeld, W. Ji, and M. Farrel. 1994. Air Sparging Laboratory Study. Air Sparging for Site Remediation, ed. Robert E. Hinchee. Lewis Publishers. Ann Arbor, MI. Pages 108-111.

Hinchee, R E. 1994. Air Sparging for Site Remediation. Lewis Publishers. Ann Arbor, MI.

Holt, W. 1994. LNAPL Remediation by Soil Vapor Extraction and Air Sparging. Ground Water. Volume 32, No. 5. September/October.

Ji, W., A. Dahmani, D.P. Ahlfeld, J.D. Lin, and E.H. Hill. 1993. Laboratory Study of Air Sparging: Air Flow Visualization. Groundwater Monitoring and Remediation. Fall. Pages 115-126.

Johnson, R.L., P.C. Johnson, R.E. McWhorter, R.E. Hinchee, and I. Goodman. 1993. An Overview of In Situ Air Sparging. Groundwater Monitoring and Remediation. Fall. Pages 127-135.

Lundegard, Paul D., D. La Brecque. 1996. Integrated Geophysical and Hydrologic Monitoring of Air Sparging Flow Behavior. Proceedings of the First International Symposium on In-Situ Air Sparging, Las Vegas, NV, October 24-25, 1996.

Marley, M.C. 1992. Air Sparging in Conjunction with Vapor Extraction for Source Removal at VOC Spill Sites. Hazardous Contaminated Soils. Chapter 34, Pages 579-589.

Marley, M.C., P.J. Hazenbrouck, and M.T. Walsh. 1992. The Application of In Situ Air Sparging as an Innovative Soils and Groundwater Remediation Technology. Groundwater Monitoring Review. Volume 12 (2). Spring.

Marley, M.C., and F. Li. 1994. Air Sparging: An Efficient Groundwater and Soils Remediation Technology. Air Sparging for Site Remediation, ed. Robert E. Hinchee. Pages 23-37. Lewis Publishers. Ann Arbor, MI.

Marley, Michael C., and C.J. Bruel. 1995. In Situ Air Sparging: Evaluation of Petroleum Industry Sites and Consideration for Applicability, Design, and Operation. American Petroleum Institute. API Publication 4609.

Pijls, C.B.G.M., L.G.C.M.Urlings, H.B.R.J. van Vree, and F. Spuij. 1994. Applications of In Situ Soil Vapor Extraction and Air Injection. Air Sparging for Site Remediation, (ed.) Robert E. Hinchee. Pages 128-136. Lewis Publishers. Ann Arbor, MI.

Tetra Tech EM Inc. 1997. Personal Communication between Dawn Cosgrove of Tetra Tech EM Inc. and Dave Becker of the U.S. Army Corps of Engineers. May.

U.S. Environmental Protection Agency (EPA). 1995. Soil Vapor Extraction (SVE) Enhancement Technology Resource Guide. EPA/542-B-95-003. Office of Solid Waste and Emergency Response. Technology Innovation Office. Washington, DC.

EPA. 1992. A Technology Assessment of Soil Vapor Extraction and Air Sparging. EPA/600/R-92/173. Office of Research and Development. Washington, DC.

EPA. 1993. An Overview of Underground Storage Tank Remediation Options. EPA 510-F-93-029. Office of Underground Storage Tanks. Washington, DC. October.

Wade, A., B. Holland, and G. Wallace. 1993. Air Sparging and Groundwater Flow: Optimizing Remedial Potential of Air Sparging through a Horizontal Well. Journal of Environmental Health. Volume 56 (3). October.

Wehrle, K., and J. Brauns. 1994. Groundwater Circulation Due to Air Injection: General Aspects and Experimental Results for Layered Subsoil. Air Sparging for Site Remediation, ed. Robert E. Hinchee. Lewis Publishers. Pages 20-127. Ann Arbor, MI.

1.3 CHAPTER 4

Baker, R.S., and J. Bierschenk. 1995. Vacuum-Enhanced Recovery of Water and NAPL: Concept and Field Test. Journal of Soil Contamination. Volume 4(1). Pages 57-76.

Brown, R.A., R.J. Falotico, and D.M. Peterson. 1994. Dual Phase Vacuum Extraction Systems for Groundwater Treatment: Design and Utilization. Superfund XV Conference and Exhibition Proceedings.

Dodson, M.E., B.E. Trowbridge, and D. Ott. 1994. Use of In-Situ Dual Vacuum Extraction for Remediation of Soil and Ground Water. Thirty-Third Hanford Symposium on Health and the Environment--In-Situ Remediation: Scientific Basis for Current and future Technologies. November.

Ghalib, S., and K.H. Kastman. 1995. DNAPL Remediation Using Dual-Phase Extraction. Superfund 16 Conference and Exhibition Proceedings.

Groundwater Service, Inc. (GSI). 1997. Summary of Representative Project Experience. May.

Hackenberg, T.N., J.J. Mastroianni, C.E. Blanchard, J.G. Morse. 1993. Analysis Methods and Design of Vacuum Enhanced Pumping Systems to Optimize Accelerated Site Cleanup.

Koerner, C.E., and J.D. Long. 1994. Two-Phase Groundwater and Soil Vapor Extraction. In Hazmacon Conference, San Jose, CA.

Kruseman, G.P., and N.A. de Ridder. 1991. Analysis and Evaluation of Pumping Test Data. ILRI, Wageningen, The Netherlands. 1991. Second Edition.

Lindhult, E.C., J.M. Tarsavage, and K.A. Foukaris. 1995. Remediation in Clay using Two-Phase Vacuum Extraction. National Conference on Innovative Technologies for site Remediation and Hazardous Waste Management Proceedings.

Mastroianni, J., C. Blanchard, T. Hackenberg, and J. Morse. 1994. Equipment Design Considerations and Case Histories for Accelerated Clean-up Using Vacuum Enhanced Pumping.

McCoy and Associates, Inc. 1992. Special Feature: Innovative In Situ Cleanup Processes. The Hazardous Waste Consultant. September/October.

Miller, A.W., and D. R. Gan. 1995. Soil and Groundwater Remediation Using Dual-Phase Extraction Technology. Superfund 16 Conference and Exhibition Proceedings.

Roth, R., P. Bianco, M. Rizzo, N. Pressly, and B. Frumer. 1995. Phase I Remediation of Jet Fuel Contaminated Soil and Groundwater at JFK International Airport Using Dual-Phase Extraction and Bioventing. Superfund 16 Conference and Exhibition Proceedings.

Roy, K.A. 1991. Dual Vacuum Extraction Sinks Below the Surface in Groundwater Cleanup. Hazmat World. November.

Safrin, T. 1996. Dual-Phase Treatment Reduces Cleanup Time and Cost. Environmental Technology. May/June.

Stenning, A.H., and C.B. Martin. 1968. An Analytical and Experimental Study of Air-Lift Pump Performance. Transactions of the ASME Journal of Engineering for Power. Pages 106-110. April.

Tornatore, P.M. 1994. Remediating Low Permeability sites with 2-Phase Extraction - Case Studies. Superfund XV Conference and Exhibition Proceedings.

Trowbridge, B.E., and D.E. Ott. 1991. The Use of In-Situ Dual Extraction for Remediation of Soil and Groundwater. National Groundwater Association and National Water Well Association.

EPA. 1991. Soil Vapor Extraction Technology Reference Handbook. EPA/540/2-91/003. Office of Solid Waste and Emergency Response. Technology Innovation Office. Washington, DC.

EPA. 1996. Vendor Information System for Innovative Treatment Technologies (VISITT), Version 5.0. Database. Office of Solid Waste and Emergency Response. Technology Innovation Office. Washington, DC.

Wellensiek, M.R., K.T. McCreanor. 1993. Accelerated Implementation of a Dual-Phase Soil Vapor Extraction System. Superfund XIV Conference and Exhibition Proceedings.

Wisconsin Department of Natural Resources. 1993. Guidance for Design, Installation, and Operation of Soil Venting Systems. PUBL-SW185-93. July.

1.4 CHAPTER 5

Armstrong, J.E., C.A. Mendoza, B.J.Moore, and P.E. Hardisty. 1994. A Comparison of Horizontal Versus Vertical Wells for Soil Vapour Extraction. Calgary, Alberta. September 21-28.

Baker, J.N., et. al. 1993. Use of a Horizontal Air-Dispersion System to Enhance Biodegradation of Diesel Fuel Contaminated Soils. In: Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration. The Westin Galleria, Houston, Texas (Ground Water Management Book 17). Pages 383-395. November 10-12.

Bardsley, D.S. 1995. Horizontal Well Materials. World Wide Web Home Page (http//:www.horizontalwell.com). By Environmental Consultants LLC.

Barrow, J.C. 1994. The Resonant Sonic Drilling Method: An Innovative Technology for Environmental Restoration Programs. Ground Water Monitoring Review. Volume 14(2). Pages 153-161.

Conger, R.M. and K. Trichel. 1993. A Ground-Water Pumping Application for Remediation of a Chlorinated Hydrocarbon Plume with Horizontal Well Technology. In: Proceedings of the Seventh National Outdoor Action Conference and Exposition, Las Vegas, Nevada. Dublin, Ohio. National Ground Water Association. Pages 47-61.

Dickinson, W.W., R.W. Dickinson, P.A. Mote, and J.S. Nelson. 1987. Horizontal Radials for Geophysics and Hazardous Waste Remediation. Presented at Superfund ‘87. Silver Spring, Maryland. Hazardous Waste Control Research Institute. Pages 371-375.

Downs, C.E. 1996. Multimedia Remediation Applications of Horizontal Wells. In: Proceedings of the Tenth National Outdoor Action Conference and Exposition, Las Vegas, Nevada. National Ground Water Association. Pages 237-243. May 13-15.

Gaillot, G. 1996. Operation of Horizontal Wells for In Situ Leachate Collection. In: Proceedings of the Tenth National Outdoor Action Conference and Exposition, Las Vegas, Nevada. National Ground Water Association. Pages 207-220. May 13-15.

Ghandehari, M.H., and others. 1994. In Situ Remediation of Groundwater Using Horizontal Well Air Injection. In: Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration. The Westin Galleria, Houston, Texas. Pages 221-235. November 2-4.

Horizontal News. 1995. Published by Colorado Center for Environmental Management for the Department of Energy Office of Technology Development. Volume 1, Number 1, Winter.

Horizontal News. 1995. Published by Colorado Center for Environmental Management for the Department of Energy Office of Technology Development. Volume 1, Number 2, Fall.

Horizontal Wells are Cost-Effective for In Situ Air Stripping (no author). 1992. Ground Water Monitoring Review. Volume 12. Number 3. Page 55.

Johnson, R.L., and others. 1993. An Overview of In Situ Air Sparging. Ground Water Monitoring and Remediation. Volume 13. Number 4. Pages 127-135.

Joshi, S.A. 1991. Horizontal Well Technology. Tulsa, Oklahoma. Pennwell Books.

Kaback, D.D., B.B. Looney, C.A. Eddy, and T.C. Hazen. Innovative Ground Water and Soil Remediation: In Situ Air Stripping Using Horizontal Wells, Westinghouse Savannah River Company, Savannah River Site, Aiken South Carolina.

Kaback, D., and D. Oakley. 1996. Horizontal Environmental Wells in the United States: A Catalogue. Colorado Center for Environmental Management. April.

Karlsson, H. and Bitto, R. 1990. New Horizontal Well Bore System for Monitor and Remedial Wells. Presented at Superfund ‘90, Washington D.C., November 26-28.

Karlsson, H. 1993. Horizontal Systems Technology for Shallow Site Remediation. Journal of Petroleum Technology. February.

Knaebel, K.S. 1981. Simplified Sparger Design. Chemical Engineering. Pages 116-117. March 9.

Looney, B.B., T. Hazen, D. Kaback, and C. Eddy. 1991. Full-Scale Field Test of the In Situ Air Stripping Process at the Savannah River Integrated Demonstration Test Site. WSRC-RD-91-22. Aiken, South Carolina. Westinghouse Savannah River Company. July.

Losonsky, G., and others. 1996. Comparing Horizontal Groundwater Extraction Well Efficiencies at hazardous Waste Sites - Implications for Well Planning and Development. In: Proceedings of the Tenth National Outdoor Action Conference and Exposition, Las Vegas, Nevada. National Ground Water Association. Pages 183-188. May 13-15.

Lowe, G.A., II, and W.S. Watkins. 1994. Viability of Horizontal Directional Drilling Utilization for Soil and Groundwater Remediation. In: Proceedings of the Energy-Sources Technology Conference, New Orleans, Louisiana. American Society of Mechanical Engineers. New York, NY. PD-Volume 56. Pages 215-219.

Lundegard, P.D. and G. Anderson. 1996. Multi-Phase Numerical Simulation of Air Sparging Performance: Groundwater. Volume 34(3). Pages 451-460.

Lundegard, P.D., Chaffee, B and D. LaBrecque, 1996. Effective Design of a Horizontal Air Sparging Well. Presented at the St. International Conference on Air Sparging, International Network of Environmental Training, Inc. October.

Maccagno, M.D., S.D. Ross, and P.E. Hardisty. 1996. Containment of a Dissolved-Phase Plume Using a Horizontal Well. In: Proceedings of the Tenth National Outdoor Action Conference and Exposition, Las Vegas, Nevada. National Ground Water Association. Pages 221-236. May 13-15.

Mast, V.A. and K.E. Koerner. 1996. Environmental Horizontal Directional Drilling Technology. No-Dig Engineering, Volume 3 (2). Pages 17-21. March/April.

May, D.W. 1994. The Use of Horizontal Wells for Subsurface Soil and Aquifer Restoration, Drilling Technology. In: J.P. Vozniak, ed,. American Society of Mechanical Engineers, New York, NY. PD-Volume 56. Pages 227-239.

Mendoza, C.A. 1992. VapourT Users Guide. Department of Geology, University of Alberta, Edmonton.

Morgan, J.H. 1992. Horizontal Drilling Applications of Petroleum Technologies for Environmental Purposes. Ground Water Monitoring Review. Volume 12 (3). Pages 98-102.

Oakley, D., et. al. 1992. The Use of Horizontal Wells in Remediating and Containing a Jet Fuel Plume: Preliminary Findings. In: Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration. The Westin Galleria, Houston, Texas. Ground Water Management Book 14. 13 Pages. November 4-6.

Perry, R.H. and C.H. Chilton, ed. 1975. Chemical Engineers Handbook. Fifth Edition. McGraw Hill. New York.

Roth, R.J., P.V. Bianco, and C. Palmer. 1995. Pilot Study Report International Arrivals Building JFK International Airport, Jamaica, NY. Prepared by TerraVac. November 17.

Roth, R.J., and N.C. Pressly 1996. Remediation of Jet-Fuel-Contaminated Soil and Groundwater at JFK International Airport Using Horizontal Air Sparging and Soil Vapor Extraction. Presented at the First International Conference on Air Sparging. International Network of Environmental Training, Inc. October 24.

Sale, T.C. and D. Applegate. 1994. Oil Recovery at a Former Wood Treating Facility. Proceedings of the Innovative Solutions for Contaminated Site Management, Water Environment Federation, Miami, FL.

Schroeder, J.D., et al. 1992. In Situ Air Stripping: Cost Effectiveness of a Remediation Technology Field Tested at the Savannah River Integrated Demonstration Site. LA-UR-92-1927. Los Alamos National Laboratory, New Mexico.

Staller, G.E., R.P. Wenyde, and R.R. Layner. 1994. Casing Pull Tests for Directionally Drilled Environmental Wells. Sandia Report SAND94-2387 UC-2000. Albuquerque, NM. Sandia National Laboratories. November.

Swanson, G.J. 1996. New Product Enters Environmental Drilling Market. Water Well Journal. Volume L (5). Pages 62-64.

Ta Inglis, T.A. 1987. Directional Drilling, Petroleum Engineering, and Development Studies. Volume 2. Graham and Trotman. Boston, MA.

Tarshish, M. 1992. Combined Mathematical Model of Flow in an Aquifer-Horizontal Well System. Ground Water. Volume 30(6). Pages 931-935.

Treadway, C. 1996. Horizontal Direction Drilling: Environmental Applications. Water Well Journal. Volume L (5). Pages 57-61.

U.S. Army Corps of Engineers. 1995. Soil Vapor Extraction and Bioventing, Engineer Manual. EM 1110-1-4001. November.

U.S. Department of Energy 1995. In Situ Bioremediation Using Horizontal Wells, Innovative Technology Summary Report. prepared by Colorado Center for Environmental Management. Denver, CO.

EPA. 1994. Alternative Methods for Fluid Delivery and Recovery. EPA/625/R-94/003. Office of Research and Development. Washington, DC.

EPA. 1996. Vendor Information System for Innovative Treatment Technologies (VISITT), Version 4.0. Database Prepared by Office of Solid Waste and Emergency Response. Technology Innovation Office. Washington, D.C.

Vinsome, P.D.W., and G.M. Shook. 1993. Multi-Purpose Simulation. Journal of Petroleum Science and Engineering. Volume 9. Pages 29-38.

Wade, A., and others. 1996. Performance Comparison Between a Horizontal and a Vertical Air Sparging Well: A Full-Scale One-Year Pilot Study. In: Proceedings of the Tenth National Outdoor Action Conference and Exposition, Las Vegas, Nevada. National Ground Water Association. Pages 189-206. May 13-15.

Wemple, R.P., and others. 1994. Final Report for SOL/NM Environmental Drilling Project. Sandia Report SAND94-2388 UC-2000. Albuquerque, NM and Livermore, CA. Sandia National Laboratories. November.

Westinghouse Savannah River Company (WSRC). 1989. Well Completion Report on Installation of Horizontal Wells for In Situ Remediation Tests. WSRC-RP-89-784. Aiken, SC. Westinghouse Savannah River Company. August.

WSRC. 1992. Demonstration of Utility Industry Horizontal Drilling System: Horizontal Well AMH-5 Installation Report. WSRC-TR-93-008. Aiken, SC. Westinghouse Savannah River Company. December.

WSRC. 1992. Demonstration of Eastman Christensen Horizontal Drilling System, Integrated Demonstration Site, Savannah River Site. WSRC-TR-92-577. Aiken, SC. Westinghouse Savannah River Company. December.

WSRC. 1993. Demonstration of River Crossing Technology for Installation of Environmental Horizontal Wells: AMH-6 and AMH-7 Installation Report. WSRC-TR-93-387. Aiken, SC. Westinghouse Savannah River Company. May.

WSRC. 1993. Summary Report of the Drilling Technologies Tested at the Integrated Demonstration Site. WSRC-TR-93-565. Aiken, SC. Westinghouse Savannah River Company. October.

Westmoreland, J. 1994. Evaluation of an Air Drilling Cutting Containment System. Sandia Report SAND94-0214 UC-721. Albuquerque, NM. Sandia National Laboratories. April.

Wilson, D.D. 1994. Horizontal Wells. Water Well Journal. Volume 48 (9). Pages 45-47.

Wilson, D. D. 1995a. Introduction to 1995 NGWA Environmental Horizontal Well Seminar. World Wide Web Home Page (http//:www.horizontalwell.com). October.

Wilson, D.D. 1995b. Environmental Horizontal Well Drilling and Installation Methods. World Wide Web Home Page (http//:www.horizontalwell.com), by Environmental Consultants, LLC.

Wilson, D.D., and D.S. Kaback. 1993. Industry Survey for Horizontal Wells. Final Report. WSRC-TR-93-511. Aiken, SC. Westinghouse Savannah River Company. July.

Wilson, D.D., and D.S. Kaback. 1993. Results of a Survey of Horizontal Environmental Well Installations. In: Vozniak, J.P. ed., Drilling Technology 1994. American Society of Mechanical Engineers. New York, NY. PD-Volume 56. Pages 193-199.

Wilson, D.D., and D.S. Kaback. 1993. Horizontal Wells Improve Access for VOC Remediation: Stretching the Limit for the Utility Industry. In: Abstract from the 1993 National Ground Water Association National Convention. Ground Water. Volume 31 (5). Pages 853-854.

Wu, J., and H. Juvkan-Wold. 1994. The Effect of Wellbore Curvature on Tubular Buckling and Lockup, Drilling Technology. In: Vozniak, J.P., ed., American Society of Mechanical Engineers. New York, NY. PD-Volume 56. Pages 17-25.

1.5 CHAPTER 6

Accutech Remedial Systems, Inc. 1996. Pneumatic Fracturing Project Summaries and Photographs Submitted by Mike Galbraith. Keyport, NJ. August.

Anderson, D.B., B.M. Peyton, J.J. Liskowitz, C. Fitzgerald, and J.R. Schuring. 1995. Enhancing In Situ Bioremediation with Pneumatic Fracturing. Report prepared by Battelle Memorial Institute under DOE contract DE-AC06-76RLO 1830. Pages 1-12.

Baker, J.E. and B. Leach. 1995. Soil Fracturing Cracks Soil Remediation Barriers. Environmental Solutions. Volume 8 (3). Pages 26-27.

Baker, J.E. and S.L. Wells. 1995. Use of Hydraulic Fracturing to Enhance Soil Vapor Extraction - a Case Study. In: Emerging Technologies in Hazardous Waste Management Vii. Tedder, D.W., ed. American Chemical Society Special Symposium. Pages 559.

Begor, K.F., M.A. Miller, and R.W. Sutch. 1989. Creation of an Artificially Produced Fractured Zone to Percent Contaminated Ground Water Migration, Ground Water Volume 27 (1). Pages 57-65.

Clark, L.J. 1988. The Field Guide to Water Wells and Boreholes. John Wiley and Sons, Inc., New York. 155 p.

Davis-Hoover, W.J., S.J. Vesper, and L.C. Murdoch. 1992. Delivery Techniques and Enhancement of Bioremediation for in Situ Restoration of Contaminated Subsurface Soils. Subsurface Restoration Conference, Dallas. Pages 1-3. June.

Davis-Hoover, W.J., L.C. Murdoch, S.J. Vesper, H.R. Pahren, O.L. Sprokel, C.L. Chang, A. Hussain, and W.A. Ritschel. 1993. Hydraulic Fracturing to Improve Nutrient and Oxygen Delivery for In Situ Bioreclamation. In: In Situ Bioreclamation. Hinchee, R.E. and R.F. Olfenbuttel, (eds.) Butterworth-Heinemann Publisher. Pages 67-82.

Dorrler, R.C. and S.R. Green. 1993. Innovative System Combines Technologies: Pneumatic Fracturing and Air Injection Blow Old-fashion Pump-and-Treat Method out of the Water. Soils. Pages 26-29. October.

Du, Y., A. Aydin, and L.C. Murdoch. 1993. Incremental Growth of a Shallow Hydraulic Fracture at a Waste Remediation Site, Oakbrook, Illinois from Inversion of Elevation Changes. Int. J. Rock Mech. Min. Sci. Volume 30 (7). Pages 1273-1279.

Echo-Scan Corporation. 1996. Fracture Monitoring and Mapping Project Summaries Submitted by M. Deryl Wood. Cary, NC. August.

Frac Rite Environmental Ltd. 1996. Hydraulic Fracturing Project Summaries Submitted by Gordon H. Bures. Calgary, Canada. July.

Frank, U. 1994. U.S. Environmental Protection Agency's Superfund Innovative Technology Evaluation of Pneumatic Fracturing Extraction. J. Air and Waste Management Assoc. Volume 44. Pages 1219-1223.

Frank, U. and N. Barkley. 1995. Remediation of Low-permeability Subsurface Formations by Fracturing Enhancement of Soil Vapor Extraction. Journal of Hazardous Materials, Volume 40. Pages 191-201.

FRX Inc. 1996. Hydraulic Fracturing Project Summaries and Photographs Submitted by William W. Slack and Larry C. Murdoch. Cincinnati, OH. July.

Fuss and O'Neill, Inc. 1996. Hydraulic Fracturing Project Summary Submitted by David L. Bramley. Manchester, CT. July.

Green, S.R. and R.C. Dorrler. 1996. Four Bullets Shoot down Costs: Combined Technology Approach Cleans up Faster and Cheaper than Pump-and-Treat. Soil and Groundwater Cleanup. March.

Keffer, E.B., J.J. Liskowitz, and C.D. Fitzgerald. 1996. The Effect of Pneumatic Fracturing When Applied to Groundwater Aquifers. In: Proceedings of the Sixth West Coast Conference on Contaminated Soils and Groundwater. Pages 1-21.

Liskowitz, J., J. Schuring, and J.P. Mack. 1993. Application of Pneumatic Fracturing Extraction for the Effective Removal of VOCs in Low Permeable Formations. Ground Water Management. Volume 16. Pages 249-265.

Lundy, D.A., C.J. Carleo, and M.M. Westerheim. 1994. Hydrofracturing Bedrock to Enhance DNAPL Recovery. Proceedings of the Eighth National Outdoor Action Conference and Exposition. Minneapolis, MN. Pages 129-143.

Mack, J.P. and H.N. Apsan. 1993. Using Pneumatic Fracturing Extraction to Achieve Regulatory Compliance and Enhance VOC Removal from Low-permeability Formations. Remediation. Summer. Pages 309-326.

Miller, R.R 1996. Blast-Enhanced Fracturing. Technology Summary Report. TS-96-01. Ground-Water Remediation Technologies Analysis Center. Pittsburgh, PA.

Murdoch, L.C. 1993. Hydraulic Fracturing of Soil During Laboratory Experiments, Parts I, II, and III. Geotechnique. Volume 43 (2). Pages 255-287.

Murdoch, L.C., G. Losonsky, I. Klich, and P. Cluxton. 1990. Hydraulic Fracturing to Increase Fluid Flow. In: F. Arendt and Others, (eds.) Contaminated Soil. Kluwer Academic Publishers, Netherlands. Pages 1087-1094.

Murdoch, L.C., G. Losonsky, P. Cluxton, B. Patterson, I. Klich, and B. Braswell. 1991. Feasibility of Hydraulic Fracturing of Soil to Improve Remedial Actions. Project Summary. EPA/600/S2-91/012. Office of Research and Development. Cincinnati, OH.

Pisciotta, T., D. Pry, J.R. Schuring, P.C. Chan, and J. Chang. 1994. Enhancement of Volatile Organic Extraction in Soil at an Industrial Site. In: Proceedings of FOCUS Conference on Eastern Regional Ground Water Issues. Pages 1-13.

Tetra Tech EM Inc. 1996. Hydraulic Fracturing Photographs Submitted by Roger Argus and Ingrid Klich. Vienna, VA. July.

Schuring, J.R., P.C. Chan, and T.M. Boland. 1995. Using Pneumatic Fracturing for In-Situ Remediation of Contaminated Sites. Remediation. Spring. Pages 77-89.

Smith, L.P. and R.E. Heeks. 1992. Innovative Remedial Technologies Applied to Chlorinated Solvents in Fractured Rock. Proceedings 5th Annual Hazardous Materials and Environmental Management Conference. Chicago, IL.

U.S. Environmental Protection Agency (EPA). 1991. Stabilization Technologies for RCRA Corrective Actions. EPA/625/6-91/026.

EPA. 1993a. Accutech Pneumatic Fracturing and Hot Gas Injection, Phase 1. Application Analysis Report. EPA/540/AR-93/509. Office of Research and Development. Washington, DC.

EPA. 1993b. Technology Evaluation Report: Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase 1. Volume 1. EPA/540/R-93/509. Office of Research and Development. Cincinnati, OH.

EPA. 1993c. Applications Analysis and Technology Evaluation Report. Hydraulic Fracturing Technology. EPA/540/R-93/505. Office of Research and Development. Washington, DC.

EPA. 1993d. Technology Demonstration Summary: Hydraulic Fracturing Technology. EPA/540/SR-93/505. Center for Environmental Research Information. Cincinnati, OH.

EPA. 1994. Alternative Methods for Fluid Delivery and Recovery. Manual. EPA/625/R-94/003. Office of Research and Development. Washington, DC.

EPA. 1995. In Situ Remediation Technology Status Report: Hydraulic and Pneumatic Fracturing. EPA542-K-94-005. Office of Solid Waste and Emergency Response. Technology Innovation Office. Washington, DC.

EPA. 1996. Vendor Information System for Innovative Treatment Technologies (VISITT) Version 5.0. Database. Office of Solid Waste and Emergency Response. Technology Innovation Office. Washington, DC.

Wolf, A. and L.C. Murdoch. 1993. A Field Test of the Effect of Sand-filled Hydraulic Fractures on Air Flow in Silty Clay. Ground Water Management. Volume 15. Pages 161-175.

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American Academy of Environmental Engineers. 1994. Innovative Site Remediation Technology: Vacuum Vapor Extraction. Volume 1 of 8. WASTECH.

Bremser, J. and S.R. Booth. 1996. Cost Studies of Thermally Enhanced In Situ Soil Remediation Technologies. Prepared for Los Alamos National Laboratory Environmental Technology Costs-Savings Analysis Project. LA-UR-96-1683. May.

Dablow, Jay. 1996. Memorandum Regarding Vendor Information and Performance Data. To Mike Johnson, Tetra Tech EM Inc. September.

Perry, R.H., ed. 1963. Perry's Chemical Engineers' Handbook, 4th Edition. McGraw-Hill, Inc. New York. Pages 3-47 through 3-60.

EPA. 1991. Toxic Treatments, In Situ Steam/Hot-Air Stripping Technology: Applications Analysis Report. EPA/540/A5-90/008. Office of Research and Development. Washington, DC.

EPA. 1993. Superfund Innovation Technology Evaluation Program Technology Profiles. Sixth Edition. EPA/540/R-93/526. Office of Research and Development. Washington, DC.

EPA. 1995a. Radio Frequency Heating, KAI Technologies, Inc.: Innovative Technology Evaluation Report. EPA/540/R-94/528. Office of Research and Development. Washington, DC.

EPA. 1995b. IITRI Radio Frequency Heating Technology: Innovative Technology Evaluation Report. EPA/540/R-94/527. Office of Research and Development. Washington, DC.

EPA. 1995c. In Situ Steam Enhanced Recovery Process Hughes Environmental Systems, Inc.: Innovative Technology Evaluation Report. EPA/540/R-94/510. Office of Research and Development. Washington, DC.