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Office of Solid Waste and
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Technology Innovation Office
Washington, DC 20460

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EPA Soil Vapor Extraction (SVE) Enhancement Technology Resource Guide

- **Air Sparging**
- **Bioventing**
- **Fracturing**
- **Thermal Enhancements**

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FOREWORD

Identifying and accessing pertinent information resources that will help site cleanup managers evaluate innovative technologies is key to the broader use of these technologies. This Guide is intended to increase awareness about technical information and specialized support services/resources related to soil vapor extraction enhancement technologies.

Specifically, this document identifies a cross section of information intended to aid users in remedial decision-making, including abstracts of field reports and guidance documents and information to assist in the ordering of publications. In addition, the look-up format of this document allows the user to quickly scan available resources and access more detailed abstracts.

Please let us know about additional information that could make this Guide (and others in the series) more useful to you.

Walter W. Kovalick, Jr., Ph.D.
Director, Technology Innovation Office

NOTICE

This document was prepared by the United States Environmental Protection Agency (EPA) under EPA Contract Number 68-W2-0004, Subcontract Number 92-001-01. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

This document is part of a series of technology resource guides prepared by the Technology Innovation Office. The series includes the following technology guides: the Bioremediation Resource Guide (EPA/542/B-93/004); the Ground-Water Treatment Technology Resource Guide (EPA/542/B-94/009); the Physical/Chemical Treatment Technology Resource Guide (EPA/542/B-94/008); and the Soil Vapor Extraction Resource Guide (EPA/542/B-94/007).

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INTRODUCTION

EPA is committed to identifying the most effective and efficient means of addressing the thousands of hazardous waste sites in the United States. Therefore, the Office of Solid Waste and Emergency Response's (OSWER's) Technology Innovation Office (TIO) is working in conjunction with the EPA Regions and research centers and with industry to identify and encourage the further development and implementation of innovative treatment technologies.

One way to enhance the use of these technologies is to ensure that decision-makers are aware of the most current information on technologies, policies, and other sources of assistance. This Guide was prepared to help identify documents that can directly assist Federal and State site managers, contractors, and others responsible for the evaluation of technologies. Specifically, this Guide is designed to help those responsible for the remediation of RCRA, UST, and CERCLA sites that may employ technologies to enhance Soil Vapor Extraction (SVE). Information on SVE can be found in the **Soil Vapor Extraction (SVE) Treatment Technology Resource Guide.**

This Guide provides abstracts of over 90 SVE enhancement technology guidance documents, overview/program documents, studies and demonstrations, and other resource guides. It also provides a brief summary of the SVE enhancement technologies highlighted in the Guide. These technologies include air sparging, bioventing, hot air injection, steam injection, electrical resistance heating, radio frequency heating, pneumatic fracturing, and hydraulic fracturing. For each type of technology, a matrix is provided to allow easy screening of the abstracted references.

To develop this Guide, a literature search was conducted using a variety of commercial and Federal databases including the National Technical Information Service (NTIS) and Energy Science and Technology Databases. The selected references are not an exhaustive list of all available literature, but rather a representative sample of the available literature. Because of the inherent lag time between document publication and subsequent listing in electronic databases, there may be more recent references available than those included in the Guide. Most of the references in the Guide are of documents published between 1991 and 1994. The documents selected are available from suppliers such as EPA's National Center for Environmental Publications and Information, NTIS, document delivery services, and a variety of libraries. Information in this Guide does not represent an endorsement by EPA.

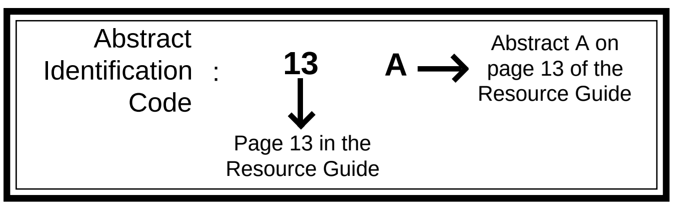
HOW TO USE THIS GUIDE

When using this Guide to identify resource information on SVE enhancement technologies, you may wish to take the following steps:

1. Turn to the **Soil Vapor Extraction Enhancement Technology Resource Matrices** located in the section titled "Technology Summaries" on pages 4 through 12 of this Guide. These matrices list alphabetically by document type over 90 SVE enhancement technology-related documents, identify the type of information provided by each document, and provide a document ordering number.

2. Select the document(s) that appear to fit your needs based on the information in the matrices.

3. Check the abstract identification code. This number refers to an abstract of the document. The number corresponds to a page number in the Guide and the letter corresponds to an abstract on that page.
   For example:



4. Review the abstract that corresponds to the document in which you are interested to confirm that the document will fit your needs.

5. If the document appears to be appropriate, note the document number highlighted under the abstract. For example:

   EPA Document Number: EPA/540/S-92/003

   [Note: Some documents do not have ordering numbers. These documents can be obtained through local, technical, or university libraries.]

6. Turn to the section entitled "How to Order Documents Listed in this Guide" on page 3 of this Guide and order your document using the directions provided.

How To Order Documents Listed In This Guide

Documents listed in this Guide are available through a variety of sources. When ordering documents listed in the Soil Vapor Extraction Enhancement Technology **Abstracts** section of this Guide, use the number listed in the bar below the document title, or refer to the journal or source indicated as part of the title. If using the Soil Vapor Extraction Enhancement Technology Resource **Matrices**, use the number listed below the document title, or refer to the journal or source indicated in the source column. If multiple document ordering numbers are identified, select the appropriate number based on the directions below. EPA/540 and EPA/600 documents may be available through the Center for Environmental Research Information (CERI); EPA/542 documents may be obtained through the National Center for Environmental Publications and Information (NCEPI); and EPA/530 documents may be obtained from the RCRA Information Center (RIC). These document repositories provide in-stock documents free of charge, but document supplies may be limited. Documents obtained through the National Technical Information Service (NTIS) are available for a fee; therefore, prior to purchasing a document through NTIS, you may wish to review a copy at a technical or university library, or a public library that houses government documents.

Document Type	**Document Source**
Publication numbers with the following prefixes: AD DE PB	National Technical Information Service (NTIS) 5285 Port Royal Road Springfield, VA 22161 (703) 487-4650 fax requests to (703) 321-8547 8:30 a.m. - 5 p.m., Eastern Time.

NTIS provides documents for a fee.

Publications with the following numbers: EPA/540 (limited collection) EPA/600	Center for Environmental Research Information (CERI) 26 West Martin Luther King Drive Cincinnati, OH 45268 (513) 569-7562 fax requests to (513) 569-7585 8:00 a.m. - 4:30 p.m., Eastern Time

Out of stock documents may be ordered from NCEPI or may be purchased from NTIS.

Publications with the following numbers: EPA/542 (limited collection)	National Center for Environmental Publications and Information (NCEPI) 11305 Reed Hartman Highway, Suite 219 Cincinnati, OH 45241 (513) 489-8190 fax requests to (513) 489-8695 7 a.m. - 5:30 p.m., Eastern Time.

A document title or number is needed to place an order with NCEPI.
Some out-of-stock documents may be purchased from NTIS.

Publications with the following numbers: EPA/530	RCRA Information Center (RIC) 401 M St., S.W. Mailcode: 5305 Washington, DC 20460 (202) 260-9327 9 a.m. - 4 p.m., Eastern Time.

If you have difficulty finding a document or wish to obtain EPA/510 documents, call:
RCRA/Superfund/OUST Hotline .... (800) 424-9346, (703) 412-9810, TDD: (800) 553-7672, (703) 412-3323

Operates Monday - Friday, 8:30 a.m. - 7:30 p.m., Eastern Time.
Hotline staff can help EPA staff or members of the public locate documents and assist callers with placing document orders.

Air Sparging

Air sparging, also referred to as in situ air stripping, is an in situ remediation technology that involves the injection of air into the subsurface saturated zone and venting through the unsaturated zone to remove subsurface contaminants. During air sparging, air bubbles traverse horizontally and vertically through the saturated and unsaturated zones, creating an underground stripper that removes contaminants by enabling a phase transfer of hydrocarbons from a dissolved or adsorbed state to a vapor phase. When used in combination with soil vapor extraction (SVE), air bubbles carry vapor phase contaminants to a SVE system which removes them. The SVE system controls vapor plume migration by creating a negative pressure in the unsaturated zone through a series of extraction wells. Using air sparging as an SVE enhancement technology increases contaminant movement and enhances oxygenation in the subsurface which increases the rate of contaminant extraction. Air sparging can employ horizontal or vertical wells and is designed to operate at high flow rates. The target contaminant groups for air sparging are volatile organic compounds (VOCs) and fuels. Air sparging is generally more applicable to the lighter gasoline constituents such as benzene, ethylbenzene, toluene, and xylene. It is less applicable to heavier constituents such as diesel fuel and kerosene.

TECHNOLOGY SUMMARY: BIOVENTING

Bioventing Bioventing is an in situ remediation technology that uses microorganisms to biodegrade organic constituents adsorbed on soils in the unsaturated zone. Bioventing enhances the activity of indigenous bacteria and simulates the natural in situ biodegradation of hydrocarbons in soil by inducing air or oxygen flow into the unsaturated zone and, if necessary, by adding nutrients. During bioventing, oxygen may be supplied through direct air injection into residual contamination in soil. Bioventing primarily assists in the degradation of adsorbed fuel residuals, but also assists in the degradation of volatile organic compounds (VOCs) as vapors move slowly through biologically active soil.

Bioventing systems are typically operated at vapor extraction rates lower than those used for soil vapor extraction (SVE) systems in an effort to provide only enough oxygen to sustain microbial activity. Bioventing can be used to treat all aerobically biodegradable constituents; however, it has proven to be particularly effective in remediating releases of petroleum products including gasoline, jet fuels, kerosene, and diesel fuel. Bioventing is most often used at sites with mid-weight petroleum products, such as diesel and jet fuel. Lighter products such as gasoline tend to volatilize readily and can be removed more rapidly using SVE and heavier products such as lubricating oils generally take longer to biodegrade, making bioventing a less effective option.

Pneumatic Fracturing

Pneumatic fracturing is an enhancement technology designed to increase the efficiency of other in situ technologies in difficult soil conditions. Pneumatic fracturing injects pressurized air beneath the surface to develop cracks in low permeability and over-consolidated sediments to create additional subsurface air flow. These new passageways increase the effectiveness of in situ processes, including soil vapor extraction (SVE), and enhance extraction efficiencies by increasing contact between contaminants adsorbed onto soil particles and the extraction system. This technology is used primarily to fracture silts, clays, shale, and bedrock. Pneumatic fracturing is applicable to a complete range of contaminant groups with no particular target group.

Hydraulic Fracturing

Hydraulic fracturing is an enhancement technology designed to increase the efficiency of other in situ technologies in difficult soil conditions. The process involves injecting a fluid which contains sand, polymers, or other compounds to maintain open fractures in the subsurface soils and increase soil permeability. The hydraulic fracturing process is repeated at varying depths (typically 5 to 30 ft) creating a “stack” of sand-filled fractures. This technology is used primarily to fracture silts, clays, shale, and bedrock. Hydraulic fracturing is applicable to a complete range of contaminant groups with no particular target group.

Hot Air Injection

Hot air injection consists of delivering hot air into the subsurface via an injection well to heat the contaminated zone in an effort to strip and recover subsurface contaminants. Hot air injection increases the phase-change and diffusion rates of organic contaminants, liberating them from the porous soil and enabling them to be captured by a SVE system. Hot air injection is often used in conjunction with steam heating to ensure that stripped organics remain in the gas stream. Hot air injection can raise soil temperature; however, because of the low heat capacity of gases, it has limited applications compared to other heating mechanisms. Target contaminant groups for hot air injection include VOCs and semi-volatile organic compounds (SVOCs).

Steam Injection

In situ steam stripping involves: (1) delivering steam to the contaminated zone via injection wells; (2) heating the contaminated zone to vaporize the contaminants and increase their mobility; and (3) creating a pressure gradient to control movement of the contaminants and the steam condensate front to a recovery point. The use of steam stripping results in the flow of contaminant liquids ahead of the steam condensation front. Vaporized components rise to the vadose zone where they can be removed by SVE and treated. The target contaminant groups for steam stripping are VOCs, SVOCs, and fuels.

Electrical Resistance Heating

Electrical resistance heating uses an electric current to heat less permeable soils such as clays and fine-grained sediments so that water and contaminants trapped in these relatively conductive regions are vaporized and ready for vacuum extraction. Electrodes are placed directly into the less permeable soil matrix and activated so that an electrical current passes through the soil, creating a resistance which then heats the soil. The heat dries out the soil causing it to fracture. These fractures make the soil more permeable allowing the use of soil vapor extraction (SVE) to remove the contaminants. The heat created by electrical resistance heating also forces trapped liquids to vaporize and move to the steam zone for removal by SVE. Target contaminant groups for electrical resistance heating include volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and VOC-oil mixtures.

Radio Frequency Heating

Radio frequency heating is used to increase the mobility of contaminants so they can be removed more easily. The process involves delivering energy to the subsurface via radio-frequency waves which excite molecular motion and induce heating (much in the same way a microwave oven heats food). Heating promotes the volatilization of a wider spectrum of soil contaminants and increases contaminant mobility, thereby increasing extraction rates. After radio frequency heating, sub-surface conditions are excellent for biodegradation of residual contaminants. Radio frequency heating has the potential to increase subsurface temperatures well above the boiling point of water (100°C, 212°F), allowing for more rapid removal of higher boiling point compounds than is possible with other heating mechanisms. Radio frequency heating is used to extract volatile and semi-volatile organic compounds (VOCs and SVOCs) as well as VOC-oil mixtures and other organic compounds that are difficult to remove with ambient temperature vacuum extraction.

ABSTRACTS OF SOIL VAPOR EXTRACTION ENHANCEMENT TECHNOLOGY RESOURCES

The abstracts below describe the contents of pertinent SVE enhancement technology documents. The abstracts are organized alphabetically within each of the five following document types:

To quickly identify documents pertinent to your interest area, see the **Soil Vapor Extraction Enhancement Technology Resource Matrices** in the section titled "Technology Summaries" on page 4-12 of this Guide. The documents in the matrices are organized alphabetically within the document types identified above. The document listings in the matrices can be cross-referenced with the abstracts using the code to the left of the document titles on the matrices. In an effort to limit the number of resources listed here, Records of Decision (RODs) and documents more than five years old are not included. Those seeking RODs may wish to contact the hotlines, dockets, or other sources. These abstracts were obtained from several databases, including NTIS, Energy Science and Technology, Compendex Plus, Enviroline, PTS Newsletter, PTS PROMT, SciSearch, and CA Search.

GUIDANCE DOCUMENTS

13A

A Citizen's Guide to Air Sparging, Fact Sheet.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, March 1992.

EPA Document Number: EPA/542/F-92/010
NTIS Document Number: PB92-235597/XAB

The fact sheet contains a description of air sparging and how it works, the reasons for using this treatment method, an explanation of its performance reliability where air sparging is being used, and a contact for obtaining more information on this treatment.

13B

A Citizen's Guide to Bioventing, Technology Fact Sheet.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, March 1992.

EPA Document Number: EPA/542/F-92/008

This fact sheet provides a general overview of bioventing and bioremediation. It includes a brief discussion of how bioventing works in conjunction with soil vapor extraction and lists some advantages of using bioventing as a remediation technology. This document includes information on site conditions that are most compatible with bioventing and provides examples of sites where bioventing is being applied.

13C

Conceptual Design of Air Sparge/Soil Vent Systems for In Situ Remediation of Petroleum Hydrocarbons, PETRO-SAFE '92 Conference Papers: Volume 7 (Processing and Refining 2), Volume 8 (Transportation and Storage), Volume 9 (Spill Control, Disposal, and Remedial Treatment 1) and Volume 10 (Spill Control, Disposal, and Remedial Treatment 2), Conference Literature.
Clodfelter, C. L., PETRO-SAFE '92: Third Annual Environmental and Safety Conference for the Oil, Gas, and Petrochemical Industries, Houston, TX, January 1992.

A conceptual design for a sparge and vent system is presented. A sparge and vent system consists of air sparging or in situ aeration in combination with soil vapor extraction. With air sparging, a compressed air source provides sparging of the groundwater through aeration points, volatizes dissolved hydrocarbons, and elevates dissolved oxygen (DO) levels in the groundwater. Volatile hydrocarbon vapors migrate more readily than liquid in soil, and are extracted to the atmosphere with the vapor extraction system. Increased oxygen levels in the groundwater and unsaturated soil promotes natural, aerobic biodegradation of the hydrocarbons without nutrient addition. Design considerations for sparge systems include spacing and depth of installation of the sparging points, air injection rates and pressures, and the air source. The design techniques for the soil vapor extraction system have been discussed extensively in the literature, but generally involve spacing of the extraction wells to capture all the hydrocarbons stripped from the groundwater. The soil vapor extraction system can also be modified to enhance oxygen (air) delivery to the unsaturated zone and thus promote natural biodegradation of the petroleum hydrocarbons in the soil. Techniques for monitoring the progress of remediation include: measurement of oxygen and carbon dioxide levels in the soil; DO levels in the groundwater; subsurface air pressures; and petroleum hydrocarbon levels in the discharged air, soil, and groundwater.

14A

How to Evaluate Alternative Cleanup Technologies for Underground Storage Tank Sites, A Guide for Corrective Action Plan Reviewers.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Office of Underground Storage Tanks, October 1994.

EPA Document Number: EPA/510/B-94/003

This manual provides detailed technical guidance for state regulators who oversee cleanups and evaluate corrective actions plans (CAPs) for leaking underground storage tank sites. The technologies addressed in the manual include soil vapor extraction, bioventing, biopiles, landfarming, low-temperature thermal desorption, air sparging, biosparging, and natural attenuation. The text focuses on engineering-related considerations for evaluating each technology; however, this manual does not provide instruction on the design and construction of remedial systems or guidance on regulatory issues. Examples of issues evaluated for each technology include effectiveness, site characteristics, constituent characteristics, pilot scale studies, system components, system design, and operation and monitoring plans. References are provided for each technology.

14B

Remediation by In Situ Aeration: The Power of Volatilization and Bio-Oxidation, Journal Article: Published in *The National Environmental Journal*, v3n4, July-August 1993.
Vance, D. B.

This article provides an overview of soil vapor extraction (SVE), air sparging, bioventing, and biosparging. There is a discussion of SVE and bioventing which includes information on the circumstances under which each technology is optimally effective and a comparison of hydrocarbon removal rates. In addition, the effect of contaminant vapor pressure on SVE remediation rates and the effect of indigenous bacteria on biosparging viability are discussed. The article concludes with a case study on the use of biosparging at a facility where a RCRA hazardous waste drum storage area was being closed. Soil contaminants at the site include ethlybenzene, toluene, total xylenes, and naphthalene; groundwater contaminants include ethylbenzene and total xylenes. Results of the case study, including trends in VOC and CO2 content of recovered soil gas, is provided.

14C

Test Plan and Technical Protocol for a Field Treatability Test for Bioventing, 2nd Revision.
Downey, D. C.; Frand, R.; Hinchee, R. E.; Miller, R. N.; and Ong, S. K., Battelle, U.S. Air Force Center for Environmental Excellence, Environmental Services Office, Engineering-Sciences, Inc., May 1992.

This test plan and technical protocol describes methods for conducting field treatability tests for bioventing technology. The purpose of these field test methods is to measure the soil gas permeability and microbial activity at a contaminated site and to evaluate the potential application of the bioventing technology to remediate the contaminated site. Bioventing is the process of aerating subsurface soils to stimulate in situ biological activity. This report includes an overview of bioventing, various applications of this technology, and discussions of specific sites including Hill Air Force Base (AFB) and Tyndall AFB.

14D

Tiny Bubbles Pop to Deep Clean, Journal Article: Published in *Soils*, October 1992.
Marley, M.; Hazebrouck, D.; and Walsh, M.

This article provides an overview of factors that should be considered when designing, installing, and operating an in situ air sparging system for remediating contaminants found in saturated zone soils. The factors discussed include: bubble geometry and gas channeling; contaminants most amenable to air sparging (i.e., petroleum compounds and chlorinated solvents); gas (air) flow rate; gas (air) injection pressure; site geometry considerations; site geology considerations; injection point interval (i.e., the sparging well screened interval and the depth location of the screened interval with respect to the static water table); radius of injection point influence; and air sparging equipment. A brief discussion of the advantages and disadvantages of air sparging is also included.

OVERVIEW/PROGRAM DOCUMENTS

14E

Air Sparging and Vapor Extraction as a Means of Removing Chlorinated and BTEX Compounds in Complex Groundwater Conditions: Published in the *Superfund XIV Conference and Exhibition Conference Proceedings, Volume 1*, Washington, D.C., November 30 - December 2, 1993.
Barrera, J.A., 1994.

This paper presents full scale air sparging and vapor extraction applications in difficult and atypical conditions. Air sparging, or enhanced groundwater aeration, is an innovative in situ technique used to restore groundwater conditions. Site candidates are usually limited to permeable sediments impacted with highly volatile aromatic and aliphatic compounds. Air sparging involves stripping dissolved volatile organic compounds (VOCs) in shallow or perched aquifers. Typical sparging systems consist of pressurized air injection wells advanced into an aquifer. Controlled air injection encourages aqueous phase VOCs to mobilize upward into the unsaturated soil. Soil vapor extraction (SVE) wells or trenches are employed to recover VOCs transferred into the unsaturated soils. Vapor extraction is typically used in combination with air sparging to recover VOCs and to prevent vapor phase transport off-site.

15A

Air Sparging in Conjunction With Vapor Extraction for Source Removal at VOC Spill Sites, Conference Literature.
Marley, M. C., Fifth National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring, and Geophysical Methods, Las Vegas, NV, May 1991.

Effective source removal is the singularly most important activity in achieving remediation at a contaminated site. Vapor extraction (soil venting) has been demonstrated to be a successful and cost effective remediation technology for removing VOCs from vadose (unsaturated) zone soils. However, in many cases, seasonal groundwater table (GWT) fluctuations, GWT drawdown associated with pump and treat remediation techniques, and spills involving dense, non-aqueous phase liquids (DNAPL) create residually saturated soils below the water table. Vapor extraction alone is not considered to be an optimal remediation technology to address these areas of contamination. Artificial water table drawdown is one approach that may be utilized to expose the contaminated soils, thereby increasing the efficiency of the soil venting process. However, in some cases, this is not a practical, nor cost effective approach. An alternative approach is the use of sparging (injection) wells to inject a hydrocarbon free gaseous medium (standardly air) into the saturated zone below the areas of contamination. The contaminants are dissolved in the groundwater and sorbed on the soil partition into the advective air phase effectively simulating an in situ air stripping system. The stripped contaminants are transported in the air phase to the vadose zone, within the radius of influence of the vapor extraction system. The contaminant vapors are drawn through the vadose zone to a vapor extraction well where they are treated utilizing standard vapor extraction off-gas control system(s).

15B

Air Sparging Technology Evaluation, Proceedings of Research and Development '92, Conference Literature.
Loden, M. E. and Fan, L., Second National Research and Development Conference on the Control of Hazardous Materials, San Francisco, CA, Hazardous Materials Control Resources Institute, February 1992.

Air sparging, which is also referred to as in situ air stripping and in situ volatilization, involves the injection of air into the saturated zone to strip VOCs dissolved in groundwater and absorbed to soils from the saturated zone. The vapor phase contaminants transferred to the unsaturated zone are then captured using soil vapor extraction (SVE). In addition to contaminant removal via mass transfer, the introduction of oxygen by injection of air also enhances subsurface biodegradation of contaminants. The air sparging system design requires consideration of system component compatibility and operation to ensure optimization of blower selection, well configuration design, and air emissions treatment. The technology is applicable to gasoline, solvents, and other volatile contaminants. Air sparging systems are almost always coupled with soil vapor extraction to control the subsurface air flow. Proper hydraulic control is key to preventing migration of contaminants to uncontaminated areas. Air sparging is a relatively new treatment technology. Research efforts to date have not fully elucidated the scientific bases of the system, and the associated engineering aspects are not completely defined. However, a substantial amount of information is available describing the effectiveness and characteristics of air sparging systems. This paper summarizes the available literature and case studies regarding the use of air sparging technology as it has been implemented to date and identifies research needs.

15C

An Overview of In Situ Air Sparging, Journal Article: Published in *Ground Water Monitoring and Remediation*, v13n4, Fall 1993.
Johnson, R. L.; Johnson, P. C.; McWhorter, D. B.; Hinchee, R. E.; and Goodman, I.

In situ air sparging (IAS) is becoming a widely used technology for remediating sites contaminated by volatile organic materials such as petroleum hydrocarbons. Published data indicate that the injection of air into subsurface water saturated areas coupled with soil vapor extraction (SVE) can increase removal rates in comparison to SVE alone for cases where hydrocarbons are distributed within the water saturated zone. However, the technology is still in its infancy and has not been subject to adequate research, nor have adequate monitoring methods been employed or even developed. Consequently, most IAS applications are designed, operated, and monitored based upon the experience of the individual practitioner. The use of in situ air sparging poses risks not generally associated with most practiced remedial technologies; air injection can enhance the undesirable off-site migration of vapors and groundwater contamination plumes. Migration of previously immobile liquid hydrocarbons can also be induced. Thus, there is an added incentive to fully understand this technology prior to application. This overview of the current state of the practice of air sparging is a review of available published literature, a consultation with practitioners, and a range of unpublished data reports, as well as theoretical considerations. Potential strengths and weaknesses of the technology are discussed and recommendations for future investigations are given.

16A

Application of Steam Injection/Vacuum Extraction Treatment Systems to Contaminated Soils: Published in Proceedings of Environmental Protection Agency/Air and Waste Management Association, In Situ Treatment of Contaminated Soil and Water, 1992.
de Percin, P. R., U.S. Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Laboratory.

EPA Document Number: EPA/600/A-93/274

NTIS Document Number: PB94-122579/XAB

Steam Injection/Vacuum Extraction (SIVE) is a method to enable vacuum extraction to treat soils contaminated with semivolatile organic compounds (SVOCs) and to speed the cleanup of soils contaminated with volatile organic compounds (VOCs). The steam injection raises the soil temperature causing more VOCs and SVOCs to vaporize into the soil air spaces. The vacuum extraction wells create a pressure drop in the soil causing gas flow to the well and thus removing the vaporized organics. This pressure drop maintains the concentration gradient forcing the organics contaminants into the vapor phase and allowing for further removal of the organics. After a considerable amount of laboratory research, SIVE is now being applied to field situations. One full-scale remediation has been performed and several pilot-scale systems have been installed and are now being studied. This paper discusses each of these systems, the data that will be obtained, and the information that still needs to be developed.

16B

Bioventing Remediates Hydrocarbon Contamination, Journal Article: Published in *The National Environmental Journal*, v3n6, November-December 1993.
Morrow, S.

This article discusses the uses of bioventing to remediate soils contaminated with organic contaminants, in particular fuel hydrocarbons, and heavy organic contaminants such as No. 2 oil and diesel fuel. A brief discussion of ways to analyze the effectiveness of boiventing is included, and advantages and disadvantages of boiventing are presented. The article concludes with the results of a boiventing treatability study. The study was conducted to determine the best treatment for remediating a landfill contaminated with volatile chloroform and semivolatile organic waste, including trichloroethylene, phthalates, and highly organic sludge.

16C

Cleaning Up Underground Contaminants, Journal Article: Published in *Energy and Technology Review,* May 1994.

At hundreds of industrial and government sites across the United States, environmental consulting firms are designing permanent containment systems for underground contaminants such as hydrocarbon fuels, cleaning solvents, and industrial chemicals. In quantities of thousands of liters or more, these chemicals threaten to contaminate drinking water supplies for hundreds of years. Typical containment systems (e.g., deep wells of cement or clay, or hydraulic pumping to control groundwater movement) can keep the chemicals from further contaminating groundwater if they are properly maintained for many years, but they do not remove the contaminants. Clearly, removing the contaminants from the soil is a much preferable solution than containing them and attempting to prevent their spread. A dynamic underground stripping process that combines steam and electrical heating of underground soils with vacuum extraction of vapors and fluids and guiding these processes by real-time monitoring methods is described.

16D

Comparison of the Effectiveness of Emerging In Situ Technologies and Traditional Ex Situ Treatment of Solvent-Contaminated Soils, Conference Literature.
Just, S. R. and Stockwell, K. J., ACS Symposium 518: Emerging Technologies in Hazardous Waste Management III, Atlanta, GA, October 1991.

Since the implementation of RCRA's Land Disposal Restrictions (LDRs) in November 1990, solvent contaminated soils must meet higher cleanup standards. This document looks at various treatment technologies, both standard and innovative, in light of the LDRs. The innovative soil vapor extraction (SVE) enhancement technologies reviewed include radio frequency heating, stream stripping, and in-situ bioremediation. The document describes each technology and discusses the applicability and feasibility of each technology. In addition, it analyzes test results from studies conducted to evaluate the technologies. The test results include data on the cleanup levels achieved at the study sites. Each technology review lists the advantages and disadvantages of the technology and includes a diagram of the technology. The conclusion of this document presents a comparison of the removal efficiencies of all the technologies discussed, including the non-innovative technologies.

17A

Dual Process Strips Contaminants in Soil, Journal Article: Published in *Environmental Protection*, v4n11, November 1993.
Dieter, D. K.

This article provides an overview of the steam injection and vacuum extraction (SIVE) process, which uses injection wells to introduce steam into the subsurface in conjunction with extraction wells to remove both groundwater and vapors from subsurface soils. The steam, as it flows from injection well to extraction well, strips contaminants from subsurface soils. The heat transferred to the subsurface increases the phase-change and diffusion rates of volatile and semi volatile organic compounds (VOCs and SVOCs) thereby reducing the time required for contaminant extraction. Included in the discussion are advantages of using SIVE over other injection techniques, benefits of using SIVE to remove chlorinated solvents, as well as equipment needs for implementing this technology.

17B

Engineering Forum Issue: Considerations in Deciding to Treat Contaminated Unsaturated Soils In Situ.
Smith, L. A., Battelle, Columbus, OH, U.S. Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Laboratory, December 1993.

EPA Document Number: EPA/540/S-94/500

NTIS Document Number: PB94-177771/XAB

The purpose of the document is to provide assistance in deciding in situ treatment of contaminated soils as a potentially feasible remedial alternative. Technical considerations that affect the decision to treat soils in situ are discussed. General factors which influence the selection of in situ treatment are hydrogeologic flow regime, regulatory standards, time available for remediation, removal logistics, and waste conditions. The document also provides information relevant to reviewing and screening in situ technologies. Factors important to the following in situ technologies are discussed: solidification/stabilization, soil vapor extraction, bioremediation, bioventing, vitrification, radio frequency heating, soil flushing, and steam injection and extraction. Systems for delivery and recovery of liquids, vapors, and energy to and from the subsurface are included.

17C

Enhance Performance of Soil Vapor Extraction, Journal Article: Published in *Chemical Engineering Progress*, v89n6, June 1993.
Noonan, D. C.; Glynn, W. K.; and Miller, M. E.

Hydrocarbon recovery as a means of soil and groundwater remediation has received considerable attention in the last few years as the shortcomings of groundwater pump-and-treat technologies have become more evident. A previous article covered a wide range of in situ cleanup technologies and provided guidance on how to choose among them. This article examines soil vapor extraction (SVE) in more detail and explains how to improve the performance of SVE by combining it with air sparging or steam injection. Air sparging injects air below the groundwater surface to promote the volatilization of volatile organic compounds (VOC) from the groundwater into the vadose zone so that the VOCs can be removed via the SVE system. Steam injection injects steam into the vadose zone to increase the subsurface temperatures, thereby volatilizing organic compounds with high boiling points.

17D

Enhancing Vacuum Extraction of Volatile Organics Using Electrical Heating, Conference Literature.
Buettner, H. M.; Daily, W.; and Ramirez, A., Lawrence Livermore National Laboratory, CA, U.S. Department of Energy, Washington, DC, September 1991.

NTIS Document Number: DE93-015978/XAB

Vacuum extraction is an effective tool for the in situ removal of liquid, residual, and vapor phase volatile hydrocarbons from subsurface soils (Trowbridge, 1990). The vacuum extraction process creates air flow through soils by decreasing the gas phase pressure in the soil matrix. As the air flows through the pore spaces, volatile organic compounds (VOCs) are volatilized and moved from the soil towards an extraction well. The effectiveness of the process varies with the permeability of the soil. For a given vacuum pressure applied to a well, higher air flow rates will be observed in coarser-grained sediments which have higher gas permeabilities, than fine-grained sediments. Soils with lower gas permeabilities such as silts and clays, require a stronger vacuum to induce air flow through the soil. The capacity to induce air flow through fine-grained materials reaches an upper limit when the required vacuum capacity cannot be achieved. Remediation of fine-grained soils using vacuum extraction may be ineffective because a closer spacing between extraction wells will be required, or in fact may become impossible for soils with very low permeabilities.

17E

Experimental Examination of Integrated Soil Vapor Extraction Techniques, Journal Article: Published in Proceedings of the Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration, Houston, TX, November 4-6, 1992.
Johnson, R. L.; Bagby, W.; Perrott, M.; and Chen, C. T., Oregon Graduate Institute of Science and Technology,

Beaverton Department of Environmental Science and Engineering, U.S. Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Laboratory.

EPA Document Number: EPA/600/J-92/280

NTIS Document Number: PB93-131738/XAB

Soil vapor extraction (SVE) has been shown to be effective at removing hydrocarbons from the unsaturated zone. However, at many spill sites significant fractions of the mass are at or below the water table, in which case SVE is far less effective. To improve its efficiency in cases where gasoline is trapped below the water table, SVE can be used in conjunction with other techniques to reach the trapped mass. In the last few years the direct injection of air into the formation below the water table (i.e., in situ sparging) has become a popular technique. Another approach is to lower the water table to improve air flow in the vicinity of the trapped product. This can be accomplished either in the localized area of a groundwater drawdown cone or as the result of larger scale dewatering. In experiments conducted at the Oregon Graduate Institute (OGI), hydrocarbon spills into a large three-dimensional physical model filled with sand are being used to study the efficiencies of SVE combined with other techniques. Experiments to date have examined SVE operating as a stand-alone technique, as well as in conjunction with air sparging below the water table, dewatering of the 'smear zone' (i.e., where product is trapped as residual below the water table), and air injection into the dewatered smear zone.

18A

Fundamentals of Bioventing Applied to Fuel Contaminated Sites, Journal Article: Published in *Environmental Progress*, v12n1, February 1993.
Dupont, R. R.

Bioventing entails the use of soil vapor extraction (SVE) systems for the transport of oxygen to the subsurface, where indigenous organisms are stimulated to aerobically metabolize fuel components. Bioventing systems are designed and configured to optimize oxygen transfer and oxygen utilization efficiency, and are operated at much lower rates and with configurations much different than those of conventional SVE systems. Bioventing system applications and design are contrasted to those of conventional SVE systems, and the two key elements of bioventing system design evaluation, i.e., in situ microbial activity and air permeability determinations, are highlighted in this paper. The application of bioventing to vadose zone bioremediation was reviewed with particular emphasis on its advantages over aqueous based bioremediation systems in terms of its superior oxygen transfer efficiency. Finally, the application of bioventing and bioventing design concepts are illustrated through a case study of JP-4 jet fuel contaminated soil remediation at Hill AFB, Utah.

18B

Give Soils a Breath of Fresh Air, Journal Article: Published in *Soils*, November-December 1991.
Heuckeroth, R. W.

This article provides a brief overview of in situ remediation technologies including pump and treat, soil washing, vapor abatement, SVE, and SVE enhancement technologies. The SVE enhancement technologies discussed include air sparging, as it is used to remediate contaminated soil and ground water, and bioventing, as it is used to remediate contaminated soil. Each discussion includes a brief description of how the technology works as well as advantages and disadvantages of the technology. The article concludes with a general discussion of ex situ remediation technologies.

18C

Horizontal Wells Can Lower Costs of Remediating Soil, Groundwater, Journal Article: Published in *Oil and Gas Journal*, v91n48, November 1993.

Conventional approaches to soil and groundwater remediation make extensive use of vertical wells that penetrate the various contamination phases—liquid, absorbed, dissolved, and vapor. But advances in horizontal drilling have added a new dimension to the remediation of hazardous soils and groundwater. Whereas conventionally drilled wells are perpendicular to the central axis of hazardous waste, horizontal wells can travel parallel to the axis. Dual wells can flank entire plumes for aggressive treatment, and sparge points can become sparge barriers—boundaries against migration of the contaminants. Under the right conditions, a single horizontal well can treat areas that previously required as many as 10 vertical wells. This not only reduces drilling costs, but also eliminates redundant hardware for groundwater pumping or soil vapor extraction. The paper briefly describes five applications and discusses limitations to the use of the technology.

18D

Horizontal Wells in Subsurface Remediation, Proceedings of HMC-South '92 Exhibitor Conference and Exhibition, Conference Literature.
Losonsky, G. and Beljin, M. S., HMC-South '92: Hazardous Materials Control Research Institute Meeting, New Orleans, LA, February 1992.

This paper reports on horizontal wells which offer an effective alternative to vertical wells in various environmental remediation technologies. Hydrogeological advantages of horizontal wells over vertical wells include a larger zone of influence, greater screen length, higher specific capacity, and lower groundwater screen entrance velocity. Because of these advantages, horizontal wells can reduce treatment time and costs of groundwater recovery (pump-and-treat), in situ groundwater aeration (sparging), and soil gas extraction (vacuum extraction). Horizontal wells are also more effective than vertical wells in landfill leachate collection (under-drains), bioremediation, and horizontal grout injection.

19A

Hydraulic Fracturing to Improve Remediation of Contaminated Soil, Conference Literature.
Slack, W.W., OH; Kemper, M.; and Murdoch, L.C., University of Cincinnati, May 1994.

EPA Document Number: EPA/540/R-94/503

This paper provides an overview of the applications of hydraulic fracturing to enhance the performance of in situ remediation technologies, such as bioremediation and SVE. The paper also includes a discussion of the benefits of hydraulic fracturing. For example, hydraulic fractures can increase the area of influence around an extraction well by a factor of ten, which greatly enhances the ability of the extraction system to remove contaminants. The paper indicates that low permeability silts, clays, or rock are most favorable to hydraulic fracturing. Descriptions of hydraulic fracturing technology demonstrations at field sites are included.

19B

In Situ Radio Frequency Heating to Enhance Vapor Extraction of Contaminants from Soil, Journal Article: Published in *Industrial Health and Hazards Update*, v94n1, January 1995.

This report provides an overview of a radio frequency heating field demonstration program. The demonstration site is contaminated with residual solvents, namely trichloroethylene and perchoroethylene, which are held in vadose zone clay deposits. The field demonstration is using radio frequency heating to enhance the effectiveness of SVE in site remediation, by increasing the contaminant vapor pressure, diffusivity, and the permeability of the clay.

19C

Introducing USACE's Soil Vapor Extraction and Bioventing Engineer Manual: Published in *Proceedings of HMCRI Federal Environment Restoration IV and Defense Cleanup Southeast Conference,* Atlanta, Georgia, March 14-15.
Baker, R.S., ENSR Consulting and Engineering, Acton, MA; Becker, D.J., U.S. Army Corps of Engineers-Missouri River Division, Omaha, NE, 1995.

This document provides a preview of the information that is contained in an engineering manual (EM) prepared for the U.S. Army Corps of Engineers (USACE) on the engineering and design of SVE and bioventing systems. The EM assembles and consolidates design considerations and guidance information for practitioners of SVE and bioventing. This document discusses the purpose and intended audience of the EM and provides a general overview of the topics addressed in the manual. The topics include tools and resources; SVE and bioventing application strategy; fundamental principles; site characterization and technology screening; bench- and pilot-scale testing for SVE and bioventing; design and full-scale SVE and bioventing systems; design documents; start-up requirements; operations and maintenance; system shutdown and confirmation of cleanup; cost estimating and other considerations; and appendices.

19D

Livermore Dynamic Stripping Method Cleans Gasoline Leaking Underground, Journal Article: Published in *Ground Water Monitor*, v9n25, December 1993.

This article discusses using "dynamic" underground stripping, a combination of steam and electric heating, with soil vapor extraction (SVE) to remove gasoline from the soil. Results from the first full-scale test conducted at the Lawrence Livermore National Laboratory are evaluated. This article also discusses the possibility of using "dynamic" underground stripping to remove chlorinated solvents such as trichloroethylene and perchloroethane.

19E

LNAPL Remediation by Soil Vapor Extraction and Air Sparging, Journal Article: Published in *Ground Water*, v32n5, September/October 1994.
Holt, W., Marion Environmental Inc., Chattanooga, TN, September/October 1994.

The use of soil vapor extraction (SVE) in combination with in situ air sparging (IAS) has the potential to be effective at quickly removing volatile organic contamination from soils and ground water in a cost effective manner. IAS is a process for treating volatile organic contaminants in ground water and soil in the saturated zone by the injection of air. The air displaces water in the soil matrix, creating a transient porosity, and increases dissolved oxygen levels in the ground water. The injected air removes contaminants through volatilization and biodegradation. Innovative enhancement technologies such as IAS are rapidly replacing more conventional excavation and pump-and-treat remediation methods.

20A

Radio Frequency Heating Technology Enhances Soil Vapor Extraction, Journal Article: Published in *Hazardous Waste Consultant* v12n4, July/August 1994.

This article discusses the benefits of using radio frequency heating as an SVE enhancement technology, including its ability to increase subsurface permeability, temperature, and contaminant vapor pressure. The article includes a discussion of two field tests which showed reduced levels of No. 2 fuel oil and organchlorine pesticides when radio frequency heating was applied.

20B

Recent Results from the SITE Program, Journal Article: Published in *Hazardous Waste Consultant*, v12n1, January-February 1994.

This paper presents results from the Superfund Innovative Technology Evaluation (SITE) program testing of 12 innovative technologies. Two SVE enhancement technologies included in the paper are pneumatic fracturing and hydraulic fracturing. Both pneumatic and hydraulic fracturing are used to fracture rock and compacted soil which creates conductive channels, thereby increasing contaminant extraction rates. The discussion of each includes a process description, SITE demonstration results, and average costs. For the pneumatic fracturing test, the primary contaminant of concern was trichloroethylene. For the hydraulic fracturing test, the contaminants of concern include ethylbenzene, benzene, toluene, xylene, a number of chlorinated solvents, and petroleum hydrocarbons. Contact names are provided.

20C

Refinements Upgrade Vapor Extraction: New Developments Enhance Use and Performance, Journal Article: Published in *Soils*, March 1994.

This article provides a brief overview of three SVE refinements. The first refinement is a turnkey SVE package that can be customized to meet specific site needs. The second is a two-phase SVE system which is a single treatment method applicable to all states of volatile hydrocarbon contamination. The key to the two-phase system is that the well screening extends below the natural water table and upwards into the vadose zone which allows soil gases drawn into the well to entrain the liquid phase so that both the gas and liquid phases are transported to the surface. The third enhancement technology is a hot air injection vapor extraction system which features a network of hot air injection ducts placed within a soil matrix. The hot air is able to volatilize and absorb the contaminants as it passes through the soil to reach the vapor extraction ducts.

20D

REMEDIATION: Air Sparging Gains Acceptance for Remediation of Underground Storage Tank Leaks, Journal Article: Published in *Waste Treatment Technology News*, v8n4, February 1993.

EPA Region 5 has acknowledged BP Company for its role in demonstrating the effectiveness of using air sparging technology, in combination with soil vapor extraction (SVE), to remediate leaks from underground storage tanks. This method is reported to reduce cleanup time at an average site by more than one year over using SVE alone. This article provides an overview of air sparging, as well as contact names and phone numbers.

20E

Remediation of Contaminated Subsurface Soils by Bioventing, Conference Literature.
Litherland, S. T.; Anderson, D. W.; Allen, P. G.; and Dykes, R. S., Hazardous Materials Control/Superfund 92: 13th Annual Conference and Exhibition, Hazardous Materials Control Resources Institute, December 1992.

Soil venting or soil vapor extraction is a technology which has in recent years been fairly widely accepted for the remediation of soils contaminated with volatile organic compounds (VOC). To affect VOC removal, a vacuum is applied to the vadose or unsaturated zone to volatilize the residual organics and pull the vapors to the surface for treatment. A relatively new adaptation of soil vapor extraction is bioventing. Although the systems used for soil venting and bioventing are very similar, the approaches are slightly different. Soil vapor extraction (SVE) primarily relies on the stripping of VOCs which then often require treatment. SVE also is limited to volatile compounds. A bioventing system promotes degradation of the organic chemicals in the subsurface soil so that the required above ground treatment of extracted vapors is minimized. Although most of the work in bioventing completed to date has been with jet fuels, the technology shows significant promise in the cost-effective remediation of sites affected not only with fuels, but also with some of the less volatile hydrocarbons.

20F

Remediation Technologies Screening Matrix and Reference Guide, Second Edition.
U.S. Department of Defense, Environmental Technology Transfer Committee, Federal Remediation Technologies Roundtable, October 1994.

EPA Document Number: EPA/542/B-94/013

NTIS Document Number: PB95-104782

This guide can be used to screen and evaluate candidate cleanup technologies for contaminated installations and waste sites. The guide incorporates cost and performance data to the maximum extent possible and focuses primarily on demonstrated technologies. The guide addresses contaminant properties and behavior, and identifies potential treatment technologies based on their applicability to specific contaminants and media. It also provides an overview of each treatment process and how it will impact technology implementation. The SVE enhancement technologies discussed in the guide include bioventing, pneumatic fracturing, thermally enhanced SVE, high temperature thermal desorption, low temperature thermal desorption, oxygen enhancement with air sparging, air sparging, hot water or steam flushing/stripping, hydrofracturing, and air stripping. Each technology profile, contained in this guide, includes a description, applicability, limitations, data needs, performance data, cost, site information, points of contact, and references. The five contaminant groups highlighted are VOCs, SVOCs, fuels, inorganics, and explosives.

21A

Scaling Up Vertical Soil Vapor Extraction Pilot Tests to Horizontal Systems: Published in the *Superfund XIV Conference and Exhibition Conference Proceedings, Volume 2,* Washington, D.C., November 30 - December 2, 1993.
Bass, D.H., Groundwater Technology, Inc., Norwood, MA, 1994.

A design tool has been developed which estimates the vacuum/ flow performance of both horizontal and vertical SVE wells of varying diameters, screened over various intervals, based on pilot tests data from a single well. Equations describing the relationship between these parameters are generated by modifying and adapting the standard transport equations for a buried vertical sheet to represent vertical well, horizontal well, and vented trench SVE systems respectively. This approach yields reliable results so long as the screened intervals do not intercept strata of significantly differing permeability. Two examples of scaling up a vertical well SVE pilot test to a horizontal SVE system are presented and discussed.

21B

Simulations of In Situ Air Stripping Demonstration at Savannah River.
Robinson, B. A.; Rosenberg, N. D.; Zyvoloski, G.A.; and Viswanathan, H., Los Alamos National Laboratory, NM, U.S. Department of Energy, Washington, DC, June 1994.

NTIS Document Number: DE94-013855/XAB

This report assesses the performance of the in situ air stripping technology demonstrated at the Savannah River Integrated Demonstration (SRID) site. This technology is a combination of air injection below the water table and vacuum extraction in the vadose zone, using a pair of horizontal wells. Our approach is based on the construction of a site-specific numerical model using the FEHM flow and transport code. We use the model as a tool to investigate improvements to performance, to improve the prediction of the performance of this technology over longer periods of time and at different sites, and to compare performance with other remediation technologies.

21C

SVE, Air-Stripping Needed at Hastings Site, Journal Article: Published in *Superfund Week,* v8n41, October 1994.

This article briefly discusses the proposed use of SVE and air sparging to remediate contaminated groundwater at the Hastings site in Hastings, Nebraska. An overview and cost estimate of the work being conducted at various operable units is included. Costs slated for the groundwater remediation effort are between 6 and 7 million dollars. The contaminants of concern at the site are primarily chlorinated solvents and include trichloroethene, 1,1,1-trichloroethane, tetrachloroethene, and 1,1-dichloroethene. The project is still in the design phase and construction is scheduled to begin in February 1995. Contacts names are provided.

21D

Technology Assessment of Soil Vapor Extraction and Air Sparging.
Loden, M. E., Camp, Dresser and McKee, Inc., Cambridge, MA, U.S. Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Laboratory, September 1992.

EPA Document Number: EPA/600/R-92/173

NTIS Document Number: PB93-100154/XAB

Air sparging, also called ‘in situ air stripping’ and ‘in situ volatilization’ injects air into the saturated zone to strip away volatile organic compounds (VOCs) dissolved in groundwater and absorbed into soil. These volatile contaminants transfer in a vapor phase to the unsaturated zone where soil vapor extraction (SVE) can then capture and remove them. In addition to removing VOCs via mass transfer, the oxygen in the injected air enhances subsurface biodegradation of contaminants. Air sparging is a relatively new treatment technology. Research efforts have not yet fully elucidated the scientific basis (or limitations) of the system, nor completely defined the associated engineering aspects. However, a substantial body of available information describes the effectiveness and characteristics of air sparging systems. This document summarizes the available literature and addresses case studies of practical air sparging applications. It also identifies needs for further research.

22A

Technology Evaluation Report: SITE Program Demonstration Test, Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase 1, Volume 1.
Science Applications International Corp., Hackensack, NJ,
U.S. Environmental Protection Agency, Cincinnati, OH,
Risk Reduction Engineering Laboratory, July 1993.

EPA Document Number: EPA/540/R-93/509

NTIS Document Number: PB93-216596/XAB

The Pneumatic Fracturing Extraction (PFE) process developed by Accutech Remedial Systems, Inc., makes it possible to use vapor extraction to remove volatile organics at increased rates from a broader range of vadose zones. The low permeability of silts, clays, shales, etc., would otherwise make such formations unsuitable for cost-effective vapor extraction and require more costly approaches. Pneumatic fracturing provides an innovative means of increasing the permeability of a formation, thus extending the radius of influence so contaminants can be effectively extracted. In the PFE process, fracture wells are drilled in the contaminated vadose zone and left open bore (uncased) for most of their depth. A packer system is used to isolate small (2 ft) intervals so that short bursts (- 20 sec) of compressed air (less than 500 psig) can be injected into the interval to fracture the formation. The process is repeated for each interval. The fracturing extends and enlarges existing fissures and/or introduces new fractures, primarily in the horizontal direction. When fracturing is complete, the formations are then subjected to vapor extraction.

22B

The Application of In Situ Air Sparging as an Innovative Soils and Groundwater Remediation Technology, Journal Article: Published in *Ground Water Monitoring Review*, v12n2, Spring 1992.
Marley, M. C.; Hazebrouck, D. J.; and Walsh, M. T.

Vapor extraction (soil venting) has been demonstrated to be a successful and cost-effective remediation technology for removing VOCs from the vadose (unsaturated) zone. However, in many cases, seasonal water table fluctuations, drawdown associated with pump-and-treat remediation techniques, and spills involving dense, non-aqueous phase liquids (DNAPL) create contaminated soil below the water table. Vapor extraction alone is not considered to be an optimal remediation technology to address this type of contamination. An innovative approach to saturated zone remediation is the use of sparging (injection) wells to inject a hydrocarbon-free gaseous medium (typically air) into the saturated zone below the areas of contamination. The contaminants dissolved in the groundwater and sorbed onto soil particles partition into the advective air phase, effectively simulating an in situ air-stripping system. The stripped contaminants are transported in the gas phase to the treatment system. In situ air sparging is a complex multifluid phase process, which has been applied successfully in Europe since the mid-1980s. To date, site-specific pilot tests have been used to design air-sparging systems. Research is currently underway to develop better engineering design methodologies for the process. Major design parameters to be considered include contaminant type, gas injection pressures and flow rates, site geology, bubble size, injection interval (areal and vertical) and the equipment specifications. Correct design and operation of this technology has been demonstrated to achieve groundwater cleanup of VOC contamination to low part-per-billion levels.

22C

The Application of Pneumatic Fracturing Extraction for Removal of VOC Contamination in Low Permeable Formations, Conference Literature.
Cicalese, M. E. and Mack, J. P., McLaren/Hart; Accutech Remedial Systems; New Jersey Institute of Technology;
I&EC Special Symposium, American Chemical Society, Atlanta, Georgia, September 27-29, 1993.

This document provides a description of pneumatic fracturing at a site impacted by dense non-aqueous phase liquids (DNAPLs) in clay and bedrock formations. Equipment specifications and construction requirements are also highlighted with the use of graphics. This paper also highlights plans for the Hillsborough Superfund Innovative Technology Evaluation (SITE) demonstration comprised of the McLaren/Hart Environmental Engineering Corp., Accutech Remedial Systems Inc., the Hazardous Substance Management Research Center (HSMRC), and the New Jersey Institute of Technology team.

22D

Using Pneumatic Fracturing for In-Situ Remediation of Contaminated Sites, Journal Article: Published in *Remediation*, Spring 1995.
Schuring, J.R.; Chan, P.C.; and Boland, T.M., 1995.

This articles provides a general description of the concept of pneumatic fracturing and a discussion of pneumatic fracturing apparatus. Key technological considerations are also discussed, including fracture initiation, fracture orientation, fracture flow, and treatable contaminants and soils. The article contains three case studies which describe different pneumatic fracturing applications. The case studies include enhancement of vapor extraction in clay; enhancement of vapor extraction in bedrock; and enhancement of product recovery in stratified deposits. The article concludes with a discussion of cost benefits associated with pneumatic fracturing.

23A

VOCs in Non-Arid Soils Integrated Demonstration: Technology Summary.
U.S. Department of Energy, Washington, DC, Office of Technology Development, February 1994.

NTIS Document Number: DE94-008863/XAB

The Volatile Organic Compounds (VOCs) in Non-Arid Soils Integrated Demonstration (ID) was initiated in 1989. The objectives for ID included testing the integrated demonstration concept, demonstrating and evaluating innovative technologies/systems for the remediation of VOC contamination in soils and groundwater, and transferring technologies and systems to internal and external customers for use in full-scale remediation programs. The demonstration brought together technologies from DOE laboratories, other government agencies, and industry for demonstration at a single test bed. The Savannah River Site was chosen as the location for this ID as the result of VOC contamination of soil and groundwater. The primary contaminants, trichlorethylene and tetrachloroethylene, originated from an underground process sewer line servicing a metal fabrication facility at the M-Area. Some of the major technical accomplishments for ID included the successful demonstration of the following: in situ air stripping coupled with horizontal wells to remediate sites through air injection and vacuum extraction; crosshole geophysical tomography to map moisture content and lithologic properties of the contaminated media; in situ radio frequency and ohmic heating to increase mobility of the contaminants, thereby speeding recovery and the remedial process; high-energy corona destruction of VOCs in the off-gas of vapor recovery wells; application of a Brayton cycle heat pump to regenerate carbon adsorption media used to trap VOCs from the off-gas of recovery wells; in situ permeable flow sensors and the colloidal borescope to determine groundwater flow; chemical sensors to rapidly quantify chlorinated solvent contamination in the subsurface; and in situ bioremediation through methane/nutrient injection to enhance degradation of contaminants by methanotrophic bacteria.

STUDIES AND DEMONSTRATIONS TEST DESIGN

23B

Air Sparging and Groundwater Flow: Optimizing the Remediation Potential of Air Sparging Through a Horizontal Well, Journal Article: Published in *Journal of Environmental Health*, v56n3, October 1993.
Wade, A.; Holland, B.; and Wallace, G., Association of Groundwater Scientists and Engineers (AGWSE) Educational Seminar on Chlorinated Volatile Organic Compounds In Groundwater.

Soil Vapor Extraction (SVE) systems are effective in volatilizing and extracting TCE from the soil in the vadose zone. When used in combination with air sparging systems, SVE systems can also be effective in volatilizing TCE from soil and groundwater in the saturated zone. At a site in the Midwest, several plumes of TCE-contaminated groundwater, with concentrations ranging from several hundred to several thousand [mu]g/1, have been identified in an unconfined sand and gravel aquifer in which the groundwater flows at approximately 0.5 feet/day. TCE concentrations of several thousand [mu]g/1 have been detected in the vadose zone. A pilot study will be conducted of a new design of air sparging at the site. A horizontal sparging well and associated SVE system will be located perpendicular to a plume down gradient from its source, but within the associated area of vadose zone contamination. In addition, a vertical air sparging well and SVE system will be located at the source to accelerate volatilization of VOCs from the soil and groundwater in the area of greatest contamination.

23C

Application of Microbial Biomass and Activity Measures to Assess In Situ Bioremediation of Chlorinated Solvents, International Symposium.
Phelps, T. J.; Herbes, S. E.; Palumbo, A. V.; Pfiffner, S. M.; and Mackowski, R., Oak Ridge National Laboratory, TN, U.S. Department of Energy, Washington, DC, 1993.

NTIS Document Number: DE94-002489/XAB

Evaluating the effectiveness of chlorinated solvent remediation in the subsurface can be a significant problem given uncertainties in estimating the total mass of contaminants present. If the remediation technique is a biological activity, information on the progress and success of the remediation may be gained by monitoring changes in the mass and activities of microbial populations. The in situ bioremediation demonstration at the U.S. Department of Energy (DOE) Savannah River Site (SRS) is designed to test the effectiveness of methane injection for the stimulation of sediments. Past studies have shown the potential for degradation by native microbial populations. The design and implementation of the SRS Integrated Demonstration is described in this volume. A control phase without treatment was followed by a phase withdrawing air. The next phase included vacuum extraction plus air injection into the lower horizontal well located below the water table. The next period included the injection of 1 percent methane in air followed by injection of 4 percent methane in air. Literature hypothesizes that the injection of methane would stimulate methanotrophic populations and thus accelerate biological degradation of TCE. Measuring the success of bioremediation is a complex effort that includes monitoring changes in microbial populations associated with TCE degradation. These monitoring efforts are described in this paper and in related papers in this volume.

24A

Electrovoice Site Demo Underway, Journal Article: Published in *Superfund Week*, v7n45, November 19, 1993.

This brief article discusses a Superfund Innovative Technology Evaluation (SITE) demonstration which is investigating the effectiveness of air sparging and soil vapor extraction in remediating soil and groundwater that are contaminated with VOCs. The year-long demonstration project is taking place at the Electrovoice Superfund site in Buchanan, Michigan. This article includes contact names and phone numbers.

24B

EPA Selects Linemaster Cleanup, Journal Article: Published in *Superfund Week*, v7n29, July 1993.

Soil vapor extraction (SVE), in conjunction with air stripping and carbon adsorption, was selected as the remedy for removing volatile organic compounds, including TCE, at the Linemaster Switch Corporation Superfund site. This brief article describes the site conditions and provides contact names and phone numbers.

24C

Navy Hires Corps to Extract Hastings VOCs, Journal Article: Published in *Defense Cleanup*, v5n15, April 15, 1994.

A pilot study using soil vapor extraction and air sparging to remediate soil and groundwater at five sites in the Hastings East Industrial Park is going to be conducted by the Kansas City (Missouri) District of the Army Corps of Engineers. Contaminants at the five sites include trichloroethene, 1,1,1-trichloroethane, and other volatiles found in the vadose zone. This brief article includes contact names and phone numbers.

24D

Picillo SVE, UV/Oxidation Systems Eyed, Journal Article: Published in *Superfund Week*, v7n26, July 1993.

Soil vapor extraction (SVE) using hot air injection as an enhancement technology is a selected remedy for the Picillo Pig Farm Superfund site in Rhode Island. Ground water, surface water, soil, and sediments are contaminated with volatile and semi-volatile organic compounds. The injected hot air would volatilize the contaminants, while catalytic oxidation would break down the volatile organics. In addition, ground water would be pumped and treated using carbon adsorption and UV/oxidation. Depending upon costs, ground water may be treated by means of air stripping with carbon adsorption instead of hot air injection. Contact names and phone numbers are provided.

24E

Pilot-Scale Evaluation of Groundwater Air Sparging: Site-Specific Advantages and Limitations, Proceedings of Research and Development ‘92, Conference Literature.
Martin, L. M.; Sarnelli, R. J.; and Walsh, M. T., Second National Research and Development Conference on the Control of Hazardous Materials, San Francisco, CA, Hazardous Materials Control Resources Institute, February 1992.

Vapor extraction (soil venting) has been demonstrated to be a successful and cost-effective remediation technology for removing VOCs from vadose (unsaturated) zone soils. However, in many cases, spills involving heavier than water solvents create residually contaminated soils below the water table. The use of air sparging wells to inject air into the saturated zone below the areas of contamination in combination with vapor extraction in the unsaturated zone is a possible approach to remediating these saturated zone soils. The contaminants dissolved in the groundwater and absorbed on the soil are partitioned into the vapor phase by the introduction of pressured air, which effectively simulates an in situ air stripping system. Ideally, the stripped contaminants are transported in the vapor phase to the vadose zone, within the radius of influence of the vapor extraction system. A pilot-scale air sparging/vapor extraction (AS/VE) system was installed at the site of a closed manufacturing facility located in Connecticut to evaluate the effectiveness of remediating saturated zone soils contaminated with VOCs (mainly trichloroethene, TCE) which are impacting groundwater quality. The system was operated continuously for 4 weeks with air sparging at varying depths, flow rates, and pressures, as well as continuous monitoring of total VOCs removed in the vapor phase. Water levels, dissolved oxygen, VOC levels and vapors were also monitored in 10 shallow wells within the vicinity of the pilot study area before, during, and after system operation.

24F

Sandia National Laboratories Mixed Waste Landfill Integrated Demonstration, Conference Literature.
Tyler, L. D.; Phelan, J. M.; Prindle, N. K.; Purvis, S. T.; and Stormont, J. C., Sandia National Laboratories, Albuquerque, NM, U.S. Department of Energy, Washington, DC, 1992.

NTIS Document Number: DE92-015005/XAB

The Mixed-Waste Landfill Integrated Demonstration (MWLID) has been assigned to Sandia National Laboratories (SNL) by the U.S. Department of Energy (DOE) Office of Technology Development. The mission of the MWLID is to assess, implement, and transfer technologies and systems that lead to quicker, safer, and more efficient remediation of buried chemical and mixed-waste sites. The MWLID focus is on two landfills at SNL in Albuquerque, New Mexico: the Chemical Waste

Landfill (CWL) and the Mixed-Waste Landfill (MWL). These landfills received chemical, radioactive, and mixed wastes from various SNL nuclear research programs. A characterization system has been designed for the definition of the extent and concentration of contamination. This system includes historical records, directional drilling, and emplacement membrane, sensors, geophysics, sampling strategy, and on site sample analysis. In the remediation task, in situ remediation systems are being designed to remove volatile organic compounds (VOCs) and heavy metals from soils. The VOC remediation includes vacuum extraction with electrical and radio-frequency heating. For heavy metal contamination, electrokinetic processes are being considered. The MWLID utilizes a phased, parallel approach. Initial testing is performed at an uncontaminated site adjacent to the CWL. Once characterization is underway at the CWL, lessons learned can be directly transferred to the more challenging problem of radioactive waste in the MWL. The MWL characterization can proceed in parallel with the remediation work at CWL. The technologies and systems demonstrated in the MWLID are to be evaluated based on their performance and cost in the real remediation environment of the landfills.

25A

Scientists Test Mixed Waste Remedies at Sandia Landfills, Journal Article: Published in *Ground Water Monitor*, v8n20, October 1992.

Electrical and radio-frequency heating are being used with soil vapor extraction (SVE) to remove VOCs from ground water at two landfills at Sandia National Laboratories. In addition, electrokinetic processes are being employed to remove heavy metals. This brief article describes site conditions and provides contact information.

25B

Textron Eyes SVE at its Cone Drive Plant, Journal Article: Published in *Superfund Week*, v9n1, January 1995.

This article discusses Textron Inc.'s proposal to use SVE in combination with air sparging to remediate the Cone Drive Textron gear plant site in Travese City, MI. The soil at the site is contaminated with perchloroethylene (PCE). The PCE has impacted the groundwater plume which migrates off-site and beneath an adjacent property. The site and contaminant migration path is described in detail. In addition to the PCE, oily, nonaqueous phase liquids (NAPLs) may be floating on the water table, and xylene and naphthalene can be found in the ground. The proposed SVE/air sparging system would be installed to remediate the source area of the plume at the plant site. Contact names are provided.

STUDIES AND DEMONSTRATIONS STUDY RESULTS

25C

Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase 1. Applications Analysis Report.
Skovronek, H. S., Science Applications International Corp., Hackensack, NJ, U.S. Environmental Protection Agency, Washington, DC, Office of Emergency and Remedial Response, March 1993.

EPA Document Number: EPA/540/AR-93/509

NTIS Document Number: PB94-117439/XAB

The report summarizes and analyzes the SITE demonstration of Accutech's Pneumatic Fracturing Extraction (PFE) process at an industrial park in New Jersey. Based on the results of 4-hour tests before and after fracturing, extracted air flow rate increased an average 600 percent and trichloroethene (TCE) mass removal rate increased about 675 percent, primarily due to the increased air flow. The radius for effective vapor extraction also was enlarged by fracturing; extracted air flow rates increased 700 percent to 1,400 percent in wells at a 10 ft radius and 200 percent to 1,100 percent in wells 20 ft from the fracture well. With passive air inlets, the extracted air flow rate increased about 19,500 percent, and TCE mass removal rate increased 2,300 percent. The estimated cost for full-scale remediation of the site with PFE is \$307/kg (\$140/lb) of TCE removed based on the SITE demonstration experience and information provided by the developer. Major contributing factors include: labor (29 percent); capital equipment (22 percent); and emissions collection/disposal (19 percent). Numerous assumptions are used in arriving at this cost. The results of the two Hot Gas Injection (HGI) tests are inconclusive.

25D

A Full-Scale Bioventing Test to Remediate Fuel Hydrocarbons in Clay Soils at a Federal Installation, Conference Literature.
Makdisi, R. S.; Stanin, F. T.; Phelps, M. B.; and Downey, D. C., Second Annual Federal Environmental Restoration Conference and Exhibition, Washington, DC, May 1993.

A long-term leak from a No. 2 diesel fuel tank resulted in the contamination of approximately 10,000 cubic yards of soil beneath, and adjacent to, an office building on a U.S. Air Force installation. Soils had been contaminated to a depth of over 40 feet, with fuel residuals ranging from approximately 500 to 2,000 mg total petroleum hydrocarbon (TPH)/kg. The primary regulatory concern at this site is the potential for groundwater contamination from alkylbenzenes and polyaromatic hydrocarbons. An in situ bioventing technique that removes fuel residuals through the introduction of oxygen (via air) to the subsurface to promote microbial fuel degradation was selected for full-scale testing on the site. A primary vapor extraction well (VEW-1) was constructed near the center of the spill site in the backfill material and connected to a 50 scfm vacuum system. A secondary vapor extraction well (VEW-2) was installed in the undisturbed soils to estimate soil gas permeability. Nine multi-depth vapor monitoring points (VMPs) were used to analyze soil gas permeability, radius and influence, oxygen enhancement, and the biological respiration of fuel hydrocarbons. Three primary tests were conducted. The first test measured the vacuum influence at varying depths and distances from the central extraction well. The results clearly demonstrated the ability of this low-rate vacuum to stimulate soil vapor flow at the 35 to 40 foot depth and up to 100 feet laterally from the central extraction well.

26A

An Integrated Approach to the Remediation of a UST Leak: Pilot-Scale Studies at Cameron Station, Research Article: Published in *Federal Facilities Environmental Journal*, v5n1, Spring 1994.
Shepard, L. T.; Martino, L. E.; Reed, L. L.; Dziewulski, D. M.; Joss, C. J.; and Sydelko, T. G.

This articles discusses the process Argonne National Laboratory (ANL) used in a pilot-scale remediation study to determine the effectiveness of an innovative SVE technology at remediating an underground gasoline spill at the Cameron Station Military Reservation in Alexandria, Virginia. The innovative SVE technology consists of an internal-combustion engine which is used to volatilize the contaminants in-situ, extract them, and burn any hazardous vapors. As part of this study, ANL investigated the applicability of indigenous bacteria for in-situ bioremediation and the usefulness of bioventing for remediating residual, heavier gasoline fractions left after SVE remediation of the lighter gasoline fractions. The study determined that as a result of the geohydrologic conditions at the site and the associated problems with using horizontal wells for SVE, it was inappropriate to design a system using horizontal wells at the site. Instead, the option of using a dual vacuum extraction system with vertical wells to extract and treat soil gas and groundwater was suggested. Such a system would also enhance the in-situ biodegradation of the gasoline present in the subsurface by bioventing.

26B

Bioventing—An Emerging Remediation Technology, Conference Literature.
Ross, D. and Sudano, P., Proceedings of the 25th Mid-Atlantic Industrial Waste Conference, Bucknell University; University of Cincinnati; University of Delaware; Drexel University; Howard University; et al, Hazardous and Industrial Wastes, 1993.

This paper provides a description of bioventing and discusses how the effects of bioventing can be measured by monitoring soil oxygen concentrations, soil carbon dioxide concentrations, and microbial activity in soil. This paper includes two bioventing case studies. The first case study evaluates the potential use of bioventing to remediate unsaturated waste and soil layers contaminated with VOCs and SVOCs (including PAHs). Parameters evaluated in this study include microbial activity, oxygen concentration, carbon dioxide concentration, VOCs and SVOCs. Results of the first case study indicate that bioventing is a viable remediation alternative for the site. The second case study discusses the use of bioventing in combination with soil vapor extraction (SVE) to remediate VOC contaminated soil and groundwater at an active industrial manufacturing facility. This case study includes a brief description of the SVE/bioventing system used at the manufacturing facility and a discussion of the results of the study. Parameters such as oxygen and carbon dioxide soil concentrations indicate that the SVE/bioventing system has been effective at the site.

26C

Bioventing—A New Twist on Soil Vapor Remediation of the Vadose Zone and Shallow Groundwater, Conference Literature.
Yancheski, T. B. and McFarland, M. A., Sixth National Outdoor Action Conference on Aquifer Restoration, Groundwater Monitoring and Geophysical Methods, Las Vegas, NV, May 1992.

Bioventing, which is a combination of soil vapor remediation and bioremediation techniques, may be an innovative, cost-effective, and efficient remedial technology for addressing petroleum contamination in the vadose zone and shallow groundwater. The objective of bioventing is to mobilize petroleum compounds from the soil and groundwater into soil vapor using soil vapor extraction and injection technology, and to promote the migration of the soil vapor upward to the turf root zone for degradation by active near-surface microbiological activity. Promoting and maintaining optimum microbiological activity in the turf root rhizosphere is a key component to the bioventing technique. Preliminary ongoing U.S. Environmental Protection Agency bioventing pilot studies (Kampbell, 1991) have indicated that this technique is a promising remediation technology, although feasibility studies are not yet complete. However, based on the preliminary data, it appears that proper bioventing design and implementation will result in substantial reductions of petroleum compounds in the capillary zone and shallow groundwater, complete degradation of petroleum compounds in the turf root zone, and no surface emissions. A bioventing system was installed at a site in southern Delaware with multiple leaking underground storage tanks in early 1992 to remediate vadose zone and shallow groundwater contaminated by petroleum compounds. The system consists of a series of soil vapor extraction and soil vapor/atmospheric air injection points placed in various contamination areas and a central core remediation area (a large grassy plot). This system was chosen for this site because it was least costly to implement and operate as compared to other remedial alternatives (soil vapor extraction with carbon or catalytic oxidation of off-gas treatment, in situ bioremediation, etc.), and results in the generation of no additional wastes.

27A

Bioventing: A Successful Soil Vapor Remediation Technique for the Vadose Zone and Shallow Groundwater, Conference Literature.
Yancheski, T. B. and McFarland, M. A., Hazardous Materials Control/Superfund 92: 13th Annual Conference and Exhibition, Hazardous Materials Control Resources Institute, December 1992.

Bioventing, a combination of soil vapor remediation and bioremediation techniques, is an innovative, cost-effective, and efficient remedial technology for addressing petroleum contamination in the vadose zone and shallow groundwater. The objective of bioventing is to transfer petroleum compounds from the soil and groundwater into soil vapor using soil vapor extraction and injection technology and to promote the migration of the soil vapor upward to the turf root zone for degradation by active near-surface microbiological activity. Promoting and maintaining optimum microbiological activity in the turf root rhizosphere is a key component of the bioventing technique. A bioventing system was installed at a site in southern Delaware with multiple leaking underground tanks during the Summer of 1992 to remediate the vadose zone and shallow groundwater contaminated by petroleum compounds. The system, a combination of soil vapor extraction and injection points, has very successfully reduced concentrations of petroleum compounds in the soil and has reduced the amount of free product and petroleum concentrations in the shallow groundwater to the extent that nearby residential wells are no longer threatened. Soil and groundwater cleanup goals for the site are expected to be reached within 1 to 2 years of operation. Total remediation costs to date have been less than $35,000. The bioventing system is a promising low cost and effective alternative for the cleanup of petroleum related soil and groundwater contamination and has application at hundreds of similar sites where there is little money available for remediation.

27B

Bioventing Feasibility Study of Low Permeability Soils for Remediation of Petroleum Contamination, Conference Literature.
Brackney, K.M., Idaho State Government, Boise, ID, March 1994.

NTIS Document Number: DE94-014144/XAB

A site characterization of leaking underground gasoline and diesel storage tanks at the University of Idaho, West Farm Operations Center, identified approximately 800 cubic yards of petroleum-contaminated soil exceeding regulatory action limits of 100 ppm TPH. Bioventing, a combination of in situ soil vapor extraction and microbial degradation, was selected as a remedial alternative on the basis of the presumably unsaturated paleo-soil with a 45-foot depth to groundwater, and a microbial study which concluded that indigenous petroleum-degrading microorganisms existed throughout the contamination. Soil vapor extraction tests were conducted by applying a 60-inch water column vacuum to a soil vapor extraction well and monitoring pneumatic pressure drawdown in 12 adjacent pneumatic piezometers and vertically distributed piezometer clusters. Pressure drawdown versus time data plots indicated that air permeability was inadequate everywhere at the site except at 20 feet below ground surface. Low soil permeability created conditions for a perched water table that was documented during the investigation, resulting in unsatisfactory conditions for in situ bioventing.

27C

Bioventing Petroleum Contaminated Soils, Proceedings of Emerging Technologies for Hazardous Waste Management, Conference Literature.
Vogel, C. M. and Tedder, D. W., American Chemical Society (ACS) Special Symposium on Emerging Technologies in Hazardous Waste Management, Atlanta, GA, September 1992.

Soil vapor extraction (SVE) is a cost effective method for removing volatile hydrocarbons from unsaturated soils. This process also provides oxygen to the subsurface which enhances the biodegradation of the volatile and nonvolatile hydrocarbon contaminants. Bioventing technology combines the oxygen delivery capabilities of SVE with nutrient and moisture management to maximize the amount of hydrocarbon removal by biodegradation and minimize the amount of removal attributed to volatilization. There is a growing list of bioventing field demonstrations designed to remove a wide range of petroleum hydrocarbons from the vadose zone. In this paper bioventing field data is presented from a pilot-scale study at Tyndal AFB FL, a full-scale cleanup effort at Hill AFB UT, and a feasibility study in cold weather environment.

27D

Bioventing with Soil Warming in Alaska, Conference Literature.
Sayles, G. D.; Brenner, R. C.; Hinchee, R. E.; and Vogel, C. M., 86th Annual Meeting and Exhibition of the Air and Waste Management Association (AWMA), Denver, CO, Air and Waste Management Association, June 1993.

Bioventing supplies oxygen in situ to oxygen deprived soil microbes by forcing air through unsaturated contaminated soil at low flowrates. Unlike soil venting or soil vacuum extraction technologies, bioventing attempts to stimulate biodegradative activity while minimizing stripping of volatile organics, thereby destroying the toxic compounds in the ground. The U.S. EPA Risk Reduction Engineering Laboratory began a 3-year field study of in situ bioventing in the Summer of 1991 in collaboration with the U.S. Air Force at Eielson Air Force Base (AFB) near Fairbanks, Alaska. The site has JP-4 jet fuel contaminated unsaturated soil where a spill has occurred in association with a fuel distribution network. The contractor operating the project is Battelle Laboratories, Columbus, OH. At Eielson AFB, bioventing is being studied in shallow soils in a cold climate in conjunction with soil warming methods to enhance the average biodegradation rate during the year. Roughly 1 acre of soil is contaminated with JP-4 from a depth of roughly 2 feet to the water table at 6 to 7 feet. The test area was established by laying down a relatively uniform distribution of air injection/withdrawal wells and constructing four 50 foot square test plots within the test area. Thus, the test plots should receive relatively uniform aeration. One plot is a control, i.e., bioventing only with no heating. Three plots are being used to evaluate the following three strategies of combining bioventing with warming of the soil above ambient temperature to increase the rate of biodegradation year-round: (i) passive solar warming; (ii) application of warm water; and (iii) buried heat tape. The presentation will summarize the results for the first one and one half years of operation including in situ biodegradation rates due to bioventing as a function of season and soil warming method, and an evaluation of the success of the various soil warming methods at maintaining elevated soil temperatures.

28A

Dynamic Underground Stripping Demonstrated at Lawrence Livermore National Laboratory Gasoline Spill Site, Livermore, California: Published in *Remediation Case Studies: Groundwater Treatment.*
Member Agencies of the Federal Remediation Technologies Roundtable, March 1995.

EPA Document Number: EPA/542/R-95/003

This document provides comprehensive information on the use of Dynamic Underground Stripping (DUS) to remediate the Lawrence Livermore National Laboratory (LLNL) site in Livermore, California. DUS is a combination of three technologies: steam injection, electric heating, and underground imaging. Between 1952 and 1979, up to 17,000 gallons of leaded gasoline were released from underground storage tanks beneath a gasoline filling station at the 800-acre site. Soil and groundwater were found to be contaminated with BTEX (benzene, toluene, ethylbenzene, and xylene) and fuel hydrocarbons. A commercial-scale field demonstration of DUS, completed between 1992 and 1993, removed 7,600 gallons of gasoline from the site. This document includes a DUS technology description and performance report as well as discussions of technology applicability and alternatives, cost, regulatory/policy requirements and issues, and lessons learned. Appendices providing detailed information on demonstration site characteristics, technologies, performance, commercialization/intellectual property, and cost are also included.

28B

Electrical Soil Cleaning Process, Journal Article: Published in *Water Environment & Technology*, v5n1, January 1993.

A new technology that uses electricity to clean gasoline and other solvents from soil and groundwater has been tested successfully at Lawrence Livermore National Laboratory's Site, an experimental test facility near Tracy, California. Cleanup of soil and groundwater contaminants is enhanced by heating the soil electrically. In this process, electric currents flow through the soil, heating it up in much the same way as the heating element in a common household electric heater. When combined with a system for extracting vapors from the soil, the method shows promise for speeding up the cleanup process. The small-scale test conducted recently at the site is the first demonstration of the technology at a contaminated site. The test showed that the vacuum-induced extraction removal rate of the common solvent trichloroethylene from soil was more than doubled by the addition of electrical heating. A large-scale test was planned for late 1992 when electrical heating and vapor extraction were to be combined with steam injection for cleaning a gasoline spill from the soil and groundwater at the laboratory's main site in Livermore, California.

28C

Feasibility of Hydraulic Fracturing of Soil to Improve Remedial Actions.
Murdoch, L. C.; Losonsky, G.; Cluxton, P.; Patterson, B.; and Klich, I., Cincinnati University, OH, U.S. Environmental Protection Agency, Cincinnati, OH, Risk Reduction Engineering Laboratory, April 1991.

EPA Document Number: EPA/600/2-91/012

NTIS Document Number: PB91-181818/XAB

Hydraulic fracturing, a method of increasing fluid flow within the subsurface, should improve the effectiveness of several remedial techniques, including pump and treat, vapor extraction, bio-remediation, and soil-flushing. The technique is widely used to increase the yields of oil wells, but is untested under conditions typical of contaminated sites. The project consisted of laboratory experiments, where hydraulic fractures were created in a triaxial pressure cell, and two field tests, where fractures were created at shallow depths in soil. The laboratory tests show that hydraulic fractures are readily created in clayey silt, even when it is saturated and loosely-consolidated. Many of the laboratory observations can be explained using parameters and analyses based on linear elastic fracture mechanics. Following the field tests, the vicinity of the boreholes was excavated to reveal details of the hydraulic fractures. Maximum lengths of the fractures, as measured from the borehold to the leading edge, averaged 4.0 m, with the average area being 19 sq m. Maximum thickness of sand ranged from 2 to 20 mm, averaging 11 mm. As many as four fractures were created from a single borehold, stacked one over the other at vertical spacing of 15 to 30 cm.

29A

Final Report: In Situ Radio Frequency Heating Demonstration, Progress Report.
Jarosch, T. R.; Beleski, R. J.; and Faust, D., Westinghouse Savannah River Co., Aiken, SC, U.S. Department of Energy, Washington, DC, January 1994.

NTIS Document Number: DE94-008274/XAB

A field demonstration of in situ radio frequency heating was performed at the Savannah River Site (SRS) as part of the U.S. Department of Energy-Office of Technology Development's Integrated Demonstration. The objective of the demonstration was to investigate the effectiveness of in situ radio frequency (RF) heating as an enhancement to vacuum extraction of residual solvents (primarily trichloroethylene and perchloroethylene) held in vadose zone clay deposits. Conventional soil vacuum extraction techniques are mass transfer limited because of the low permeabilities of the clays. By selectively heating the clays to temperatures at or above 100 degrees Celsius, the release or transport of the solvent vapors is enhanced as a result of several factors including an increase in the contaminant vapor pressure and diffusivity and an increase in the effective permeability of the formation with the release of water vapor.

29B

Fluid Injection Helps Vacuum Extract Contaminants, Journal Article: Published in *Soils*, March 1994.
Cox, R. E.

This paper discusses the use of fluid injection as an SVE enhancement technology at the Sand Creek Superfund site in Denver, Colorado. The conditions of the Sand Creek site are described and the performance of the fluid injection and vacuum extraction (FIVE) process are discussed. Contaminants of concern at the site were found in both the soil and ground water and included petroleum hydrocarbons and chlorinated compounds such as tetrochloroethylene, trichloroethylene, chloroform, and methylene chloride. Of the targeted contaminants, only tetrochloroethylene was detected in significant quantities. The FIVE system removed 1,270 kilograms of targeted contaminants and more than 49,000 kilograms of VOCs during two months of operation.

29C

Hydraulic Fracturing Technology: Applications Analysis and Technology Evaluation Report.
U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinnati, OH, September 1993.

EPA Document Number: EPA/540/R-93/505

This paper discusses the hydraulic fracturing process and illustrates its technical capabilities and specific contaminants (e.g., ethylbenzene and organic compounds) remedied as it is applied in conjunction with soil vapor extraction and bioremediation. It also presents test findings (e.g., vapor yields and contaminant recovery) from two sites, including performance enhancements, costs, and time durations.

29D

Hydraulic Fracturing to Improve In Situ Remediation of Contaminated Soil, Concerence Literature.
Murdoch, L.C.; Kemper, M.; and Wolf, A., 1992 Annual Meeting of the Geological Society of America (GSA), Cincinnati, OH.

Hydraulic fracturing, a method that is widely used to increase the production of oil wells at great depth in rock, is currently being evaluated to increase the yield of environmental wells at shallow depths in soil. In some tight formations, the method promises to improve the effectiveness of in situ remediation, whereas elsewhere it should allow in situ techniques, such as vapor extraction or bioremediation, to be used where they otherwise would be economically infeasible. The authors have tested the method of creating hydraulic fractures in soil at six sites underlain by over consolidated, silty-clay glacial drifeet. In most cases, the fractures are gently dipping features that grow away from the borehole and climb toward the ground surface. Fractures 20 to 35 feet in maximum dimension are readily created at depths of 5 to 15 feet. They are filled with between 5 feet [sup 3] and 12 feet [sup 3] of well-sorted, coarse-grained sand, which provides an average thickness of 0.2 to 0.4 inches. Hydraulic fractures can be created one on top of another, stacked with depth at vertical spacing of 0.5 to 1 foot. Preliminary field tests lasting 40 days in uncontaminated ground at the Center Hill Research Facility in Cincinnati, Ohio show that hydraulic fractures increase the yield and the area affected by a well during vapor extraction. Flow rates to a well intersecting two hydraulic fractures were roughly 10 times greater than an identical well that lacked hydraulic fractures. A pressure head of [minus] 1 inch of water was measured 25 feet from the fractured well, whereas similar pressure head was measured only 2.5 to 3.0 feet from the conventional well. Field demonstrations funded by the U.S. Environmental Protection Agency are currently underway at two vapor extraction sites in Chicago, Illinois and a bioremediation site in Dayton, Ohio. Other field demonstrations at contaminated sites are planned for the near future.

30A

In Situ Air Stripping of Contaminated Groundwater at U.S. Department of Energy, Savannah River Site - Aiken, South Carolina: Published in *Remediation Case Studies: Groundwater Treatment.*
Member Agencies of the Federal Remediation Technologies Roundtable, March 1995.

EPA Document Number: EPA/542/R-95/003

The document provides comprehensive information on the use of in situ air stripping to remediate contaminated groundwater at the U.S. Department of Energy (DOE) Savannah River site in Aiken, South Carolina. An estimated 3.5 million pounds of solvents were discharged from aluminum forming and metal finishing operations performed at the site between 1958 and 1985, with over 2 million pounds sent to an unlined settling basin. A pump and treat program has been ongoing since 1985 for removal of VOCs from the groundwater and a field demonstration using in situ air stripping was conducted from 1990 to 1993. The demonstration was part of a program at Savannah River to investigate the use of several technologies to enhance the pump and treat system. The in situ air stripping process increased VOC removal over conventional vacuum extraction from 109 pounds per day to 129 pounds per day. This document includes a technology description and performance report, as well as discussions of technology applicability and alternatives, cost, regulatory/policy requirements and issues, lessons learned, and references. Appendices providing more detailed information on demonstration site characteristics, technology descriptions, performance, and commercialization/intellectual property are also included.

30B

In Situ Remediation Technology Status Report: Hydraulic and Pneumatic Fracturing.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, April 1995.

EPA Document Number: EPA/542/K-94/005

This document describes the research and development of hydraulic and pneumatic fracturing technologies to remove contaminants from the soil and groundwater at waste disposal and spill sites. Included are summaries of ten hydraulic and pneumatic fracturing technology demonstrations. Each technology demonstration summary contains a description of the demonstration, the wastes treated, the current status, demonstration results, contacts, and references.

30C

In Situ Remediation Technology Status Report: Thermal Enhancements.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, April 1995.

EPA Document Number: EPA/542/K-94/009

This document describes the development and application of in situ thermal enhancement as a technology to remove contaminants from soils and ground water at waste disposal and spill sites. Included are summaries of ongoing or future demonstrations and commercial applications, completed demonstrations, and current research. Each summary includes a description of the demonstration, the wastes treated, the demonstration results or site status, contacts, and references.

30D

New Pollutant Extraction Technique Results Termed Excellent, Journal Article: Published in *Report on Defense Plant Wastes*, v4n19, September 11, 1992.

The results of a demonstration which used pneumatic fracturing in combination with soil vapor extraction (SVE) to extract contaminants from low-permeability geologic formations are discussed. The results are promising and indicate that air flow was increased 80 times when pneumatic fracturing was used with SVE as opposed to when SVE was used alone. The primary contaminant at the study site was trichloroethylene (TCE); however, the article discusses the potential application of pneumatic fracturing for remediating sites with contaminants such as perchloroethylene and polynuclear aromatic hydrocarbons (PAHs).

30E

New Soil Cleanup Technology, Journal Article: Published in *New Jersey Industry Environmental Alert*, v3n12, September 1992.

Pneumatic fracturing, catalytic oxidation, and hot air injection technologies were used, in conjunction with soil vapor extraction (SVE), to remove VOCs from soil and bedrock at the Somerville site. This article enumerates the advantages of using these enhancement technologies with SVE. Contact names are provided.

31A

Passive Remediation of Chlorinated Volatile Organic Compounds Using Barometric Pumping.
Rossabi, J.; Looney, B. B.; Dilek, C. A. E.; Riha, B.; and Rohay, V. J., Westinghouse Savannah River Co., Aiken, SC, U.S. Department of Energy, Washington, DC, 1993.

NTIS Document Number: DE94-006387/XAB

The purpose of the Savannah River Integrated Demonstration Program, sponsored by the U.S. Department of Energy, is to demonstrate new subsurface characterization, monitoring, and remediation technologies. The interbedded clay and sand layers at the Integrated Demonstration Site (IDS) are contaminated with chlorinated volatile organic compounds (CVOCs). Characterization studies show that the bulk of the contamination is located in the approximately 40 m thick vadose zone. The most successful strategy for removing contaminants of this type from this environment is vapor extraction alone or in combination with other methods such as air sparging or enhanced bioremediation. Preliminary work at IDS has indicated that natural pressure differences between surface and subsurface air caused by surface barometric fluctuations can produce enough gas flow to make barometric pumping a viable method for subsurface remediation. Air flow and pressure were measured in wells across three stratigraphic intervals in the vadose zone. The subsurface pressures are correlated to surface pressure fluctuations, but are damped and lagging in phase corresponding to depth and stratum permeability. Piezometer wells that are screened at lower elevations exhibit a greater phase lag and damping than wells screened at higher elevations where the pressure wave from barometric fluctuations passes through a smaller number of low permeable layers. The phase lag between surface and subsurface pressures results in significant fluxes through these wells. The resultant air flows through the subsurface and impacts CVOC fate and transport. With the appropriate controls (e.g., solenoid valves) a naturally driven vapor extraction system can be implemented requiring negligible operating costs, yet capable of a large CVOC removal rate (as much as 1-2 kg/day in each well at the IDS).

31B

Performance of Horizontal Versus Vertical Vapor Extraction Wells.
Birdsell, K. H.; Roseberg, N. D.; and Edlund, K. M., Los Alamos National Laboratory, NM, U.S. Department of Energy, Washington, DC, June 1994.

NTIS Document Number: DE94-013643/XAB

Typically, vertical vapor extraction wells are used for site remediation of volatile organic chemicals in the vadose zone. Over the past few years, there has been an increased interest in horizontal wells for environmental remediation. Despite the interest and potential benefits of horizontal wells, there has been little study of the relative performance of horizontal and vertical vapor extraction wells. This study uses numerical simulations to investigate the relative performance of horizontal versus vertical vapor extraction wells under a variety of conditions. The most significant conclusion drawn from this study is that in a homogeneous medium, a single, horizontal vapor extraction well outperforms a single, vertical vapor extraction well (with surface capping) only for long, linear plumes. Guidelines are presented regarding the use of horizontal wells.

31C

PFE Process Increases VOC Extraction Rate, Journal Article: Published in *E&P Environment*, v5n5, March 1994.

This brief article discusses the benefits of using pneumatic fracturing in combination with soil vapor extraction (SVE) to remove contaminants from low-permeability soils. Study results for the extraction of trichloroethane are discussed and the possibility of extracting other volatile contaminants such as benzene, toluene, ethylbenzene, and xylene (BTEX) is mentioned. Study results show that air flow rates increased by six times, and trichloroethane mass removal rates increased by almost seven times over SVE alone. Contact names and phone numbers are provided.

31D

Pilot-Scale Studies of Soil Vapor Extraction and Bioventing for Remediation of a Gasoline Spill at Cameron Station, Alexandria, Virginia.
Harrison, W.; Joss, C. J.; and Martino, L. E., Argonne National Laboratory, IL, U.S. Department of Defense, Washington, DC, July 1994.

NTIS Document Number: DE94-01776/XAB

Approximately 10,000 gallons of spilled gasoline and unknown amounts of trichloroethylene and benzene were discovered at the U.S. Army's Cameron Station facility. Because the Base will be closed and turned over to the city of Alexandria in 1995, the Army sought the most rapid and cost-effective means of spill remediation. At the request of the Baltimore District of the U.S. Army Corps of Engineers, Argonne conducted a pilot-scale study to determine the feasibility of vapor extraction and bioventing for resolving remediation problems and to critique a private firm's vapor-extraction design. Argonne staff, working with academic and private-sector participants, designed and implemented a new systems approach to sampling, analysis and risk assessment. The U.S. Geological Survey's AIRFLOW model was adapted for the study to simulate the performance of possible remediation designs. A commercial vapor-extraction machine was used to remove nearly 500 gallons of gasoline from Argonne-installed horizontal wells. By incorporating numerous design comments from the Argonne project team, field personnel improved the system's performance. Argonne staff also determined that bioventing stimulated indigenous bacteria to bioremediate the gasoline spill. The Corps of Engineers will use Argonne's pilot-study approach to evaluate remediation systems at field operation sites in several states.

32A

Rapid Removal of Underground Hydrocarbon Spills: Published in *Energy and Technology Review,* July 1992.
Aines, R; and Newmark, R.

This document provides a general overview of dynamic underground stripping (DUS). DUS combines in situ steam injection, electrical resistance heating, and fluid extraction to rapidly remove and recover subsurface contaminants such as solvents or fuels. The document discusses overall system engineering tests of the technology that were conducted at a "clean site." Specifically, the results of testing steam injection and electrical heating capabilities are examined. The article concludes with a brief discussion of plans to clean up a 17,000 gallon gasoline spill at the site in Lawrence Livermore National Laboratory in Livermore, California.

32B

Remediation of Low Permeability Subsurface Formations by Fracturing Enhancement of Soil Vapor Extraction, Journal Article: Published in *Journal of Hazardous Materials,* v40n2, February 1995.
Frank, U. and Barkley, N., U.S. Environmental Protection Agency Risk Reduction Engineering Lab, Cincinnati, OH, Environmental Protection Agency, February 1995.

This article provides an overview of the Superfund Innovative Technology Evaluation (SITE) of hydraulic and pneumatic fracturing. Hydraulic and pneumatic fracturing are used to enhance the ability of technologies such as SVE to remove volatile contaminants from the soil. The article includes results from several demonstrations which show orders of magnitude increases in subsurface vapor flow and contaminated vapor extraction rates when hydraulic or pneumatic fracturing is applied. The article also indicates that fracturing is most beneficial when used on tightly packed soil having low permeability.

32C

Researchers Aim to Make Pump and Treat Technology Obsolete, Journal Article: Published in *Environment Week*, v6n49, December 1993.

This article discusses the results of a pilot test which used steam and electric heating in combination with soil vapor extraction (SVE) to clean up an underground gasoline spill in Livermore, California. The pilot test was sponsored by the Lawrence Livermore National Laboratory and the University of California at Berkeley. The project involved removing 7,800 gallons of gasoline from approximately 80,000 cubic yards of soil. The combination of steam and electric heating, referred to as "dynamic" underground stripping, is discussed as an innovative alternative to conventional "pump and treat" technologies. The article also discusses future plans for additional tests of "dynamic" underground stripping which include using the technology for the removal of trichloroethylene. Imaging technology used in conjunction with the stripping system is also discussed.

32D

SITE Technology Demonstration Summary: Accutech Pneumatic Fracturing Extraction and Hot Gas Injection, Phase I, Federal Government Report.
Skovronek, H. S., U.S. Environmental Protection Agency, Risk Reduction Engineering Laboratory, Cincinatti, OH, August 1993.

EPA Document Number: EPA/540/SR-93/509

EPA's Superfund Innovative Technology Evaluation (SITE) program promotes the development of innovative technologies that will reduce pollution at hazardous waste sites. To improve vapor extraction from the vadose zone, Pneumatic Fracturing Extraction (PFE) has been developed by Accutech Remedial Systems. PFE involves the creation of new fractures and enlargement of older fractures by injecting bursts of compressed air into narrow wellbores. Results are presented from PFE tests to extract trichloroethene (TCE) from a contaminated industrial site in New Jersey. Compression-heated air was injected into a central well and was extracted from one or more monitoring wells. Temperature, air-flow rates, and TCE mass removal rates were monitored. Results indicated that only very low concentrations of TCE were found in the extracted air, both before and during hot-air injection. When tests were conducted at another area of the contaminated site, where higher TCE concentrations were anticipated, the TCE mass removal rate increased by about 50 percent. Cost data on the new technology, which appears attractive for VOC-contaminated formations with low permeability, are considered.

32E

Six-Phase Soil Heating Accelerates VOC Extraction From Clay Soil, Conference Literature.
Gauglitz, P. A.; Roberts, J. S.; Bergsman, T. M.; Caley, S. M.; Heath, W. O., Battelle Pacific Northwest Labs., Richland, WA, International Nuclear and Hazardous Waste Management Conference, Atlanta, GA, August 14-18, August 1994.

Six-Phase Soil Heating (SPSH) was demonstrated as a viable technology for heating low permeability soils containing volatile organic contaminants. Testing was performed as part of the Volatile Organic Compounds in Non-Arid Soils Integrated Demonstration (VOC Non-Arid ID) at the Savannah River Site. The soil at the integrated demonstration site is contaminated with perchloroethylene (PCE) and trichloroethylene (TCE); the highest soil contamination occurs in clay-rich zones that are ineffectively treated by conventional soil vapor extraction due to the very low permeability of the clay. The SPSH demonstration sought to heat the clay zone and enhance the performance of conventional soil vapor extraction. Soil samples were collected before and after heating to quantify the efficacy of heat-enhanced vapor extraction of PCE and TCE from the clay soil. Results show that contaminant removal from the clay zone was 99.7% (median) within the electrode array. Outside the array where the soil was heated, but to only 50(degrees)C, the removal efficiency was 93%, showing that heating accelerated the removal of VOCs from the clay soil.

33A

Soil and Groundwater Restoration by Steam Enhanced Extraction, Journal Article: Published in *Ground Water*, v31n5, September-October 1993.
Udell, K. S., Association of Groundwater Scientists and Engineers (AGWSE) Educational Seminar on Chlorinated Volatile Organic Compounds in Groundwater.

The acceleration of recovery rates of second phase liquid contaminants from the subsurface during gas or water pumping operations is realized by increasing the soil and groundwater temperature. Several methods of delivery of thermal energy to soils and groundwater are possible. Of these methods, steam injection combined with groundwater pumping and vacuum extraction appears to be the most economical and versatile technique to recover volatile, semivolatile, and nonvolatile contaminants from the subsurface. One-dimensional experiments have shown effective removal of both volatile and semivolatile second liquid phase chemicals, and nonvolatile aqueous phase contaminants from sand packs. Two-dimensional experiments with homogeneous and layered sand packs have shown rapid recovery of semivolatile hydrocarbon liquids and dense chlorinated solvents. The enhancement of mass transfer from lower permeability regions during the depressurization mode of operation has been observed. As a result of these experiments, several mechanisms have been identified which account for the observed removal of the contaminants. These are vaporization of components with low boiling points, enhanced evaporation rates of semivolatile components, physical displacement of low viscosity liquids, dilution and displacement of aqueous contaminants, and removal of residual contaminants by vacuum drying. Field-scale studies of steam injection and vacuum extraction confirm the effectiveness of this technique and its applicability to contaminants found above and below the water table.

33B

Soil Vapor Extraction From Hydraulic Fractures in Glacial Till: Initial Field Testing in Chicago, Illinois, Conference Literature.
Schroeder, S. D.; McKenzie, D. B.; and Murdoch, L. C., 85th Annual Meeting of the Air Waste Management Association (AWMA), Air and Waste Management Association, June 1992.

Hydraulic fracturing, used for several decades to increase the yield from oil and water wells, may increase the effectiveness of in situ remedial technologies in glacial till. Three fractures at each of two locations were created at a Chicago study site at depths of 6 to 12 feet by the University of Cincinnati-Center Hill to evaluate the impact of hydraulic fracturing on the SVE process. SVE wells were installed to access each of the fractures, and two SVE wells were installed in native till to serve as a control. Soil pore-pressure probes were installed to measure air pressure as a function of depth and radial distance. At depths of 3 feet or less, the radius of influence of the fractured wells was approximately 20 feet, whereas the radius of influence of the nonfractured wells was only 13 feet of influence of the fractured well was at least 5 feet at depths of 7 feet, whereas the radius was 3 feet. Well yields from fractured and nonfractured wells were approximately 1 to 1.5 cfm with an applied vacuum of 9 to 11 inches Hg. Well yields decreased as soil pore water accumulated within the extraction wells.

33C

Steam Injection/Vacuum Extraction, Phase 2, Treatability Investigation, Site Characterization, and Design, Final Report.
Heglie, J.; Koster, R.; Pexton, R.; and Stewart, L., CH2M/Hill, Sacramento, CA, December 1991.

NTIS Document Number: AD-A243745/7/XAB

The U.S. Air Force is planning to conduct a pilot test of steam injection and vapor extraction remediation technology at McClellan AFB. This innovative technology, under development by Kent Udell at the University of California at Berkeley, combines in situ steam injection into soil in both the vadose (unsaturated) and saturated zone, with vacuum extraction of volatile and semi volatile organic contaminants from the soil. Results of the composite soil samples received to date show the presence of dioxins and dibenzofurans, petroleum hydrocarbons, volatile organics, semi volatile organics, and polychlorinated biphenyls in the waste fill material. Results of the treatability testing indicate that: (1) low concentrations of dioxins and furans were mobilized by the steam condensate; (2) high concentrations of hydrocarbons were reduced by one order-of-magnitude by the steam; and (3) dioxins and furans appeared to be dissolved mainly in the hydrocarbon nonaqueous phase liquid (NAPL) phase. Petroleum hydrocarbon and dioxin concentrations were not high enough to preclude a pilot scale test.

34A

Two U.S. EPA Bioremediation Field Initiative Studies: Evaluation of In Situ Bioventing, Eighteenth Annual Risk Reduction Engineering Laboratory Research Symposium, Conference Literature.
Sayles, G. D.; Brenner, R. C.; Hinchee, R. E.; Vogel, C. M.; and Miller, R. N., Eighteenth Annual U.S. Environmental Protection Agency (EPA) Risk Reduction Engineering Laboratory Research Symposium, Cincinnati, OH, April 1992.

Bioventing is the process of supplying oxygen in situ to oxygen-deprived soil microbes by forcing air through contaminated soil at low air flow rates. Unlike soil venting or soil vacuum extraction technologies, bioventing attempts to stimulate biodegradative activity while minimizing stripping of volatile organics. The process destroys the toxic compounds in the ground. Bioventing technology is especially valuable for treating contaminated soils in areas where structures and utilities cannot be disturbed because the equipment needed (air injection/withdrawal wells, air blower, and soil gas monitoring wells) is relatively non-invasive. The U.S. EPA Risk Reduction Engineering Laboratory, with resources from the U.S. EPA Bioremediation Field Initiative, began two parallel 2 year field studies in collaboration with the U.S. Air Force. The field sites are located at Eielson Air Force Base (AFB) near Fairbanks, Alaska, and Hill AFB near Salt Lake City, Utah. Each site has jet fuel JP-4 contaminated unsaturated soil where a spill has occurred in association with a fuel distribution network. With the pilot-scale experience gained in these studies and others, bioventing should be available in the very near future as an inexpensive, unobtrusive means of treating large quantities of organically contaminated soils.

34B

U.S. Environmental Protection Agency's Superfund Innovative Technology Evaluation of Pneumatic Fracturing Extraction^{SM}, Journal Article: Published in *Air & Waste Management Association Journal*, v44, October 1994.
Frank, U., U.S. Environmental Protection Agency, Edison, NJ.

This document describes the field demonstration of Pneumatic Fracturing Extraction (PFE)^{SM} performed by EPA, in cooperation with Accutech Remedial Systems and the New Jersey Institute of Technology. This demonstration focused on extracting chlorinated volatile organic compounds (VOCs) from vadose zones of low permeability. This document describes the demonstration, and indicates the estimated cost of using PFE and the favorable extraction rates obtained with this technology.

34C

Using Geophysical Techniques to Control In Situ Thermal Remediation, Symposium.
Boyd, S.; Daily, W.; Ramirez, A.; Wilt, M.; and Goldman, R., Lawrence Livermore National Laboratory, CA, U.S. Department of Energy, Washington, DC, January 1994.

NTIS Document Number: DE94-006722/XAB

Monitoring the thermal and hydrologic processes that occur during thermal environmental remediation programs in near real-time provides essential information for controlling the process. Geophysical techniques have played a crucial role in process control as well as characterization during the recent Dynamic Underground Stripping Project demonstration. The demonstration removed several thousand gallons of gasoline from heterogeneous soils both above and below the water table. Dynamic Underground Stripping combines steam injection and electrical heating for thermal enhancement with groundwater pumping and vacuum extraction for contaminant removal. These processes produce rapid changes in the subsurface properties including changes in temperature, fluid saturation, pressure, and chemistry. Subsurface imaging methods are used to map the heated zones and control the thermal process. Temperature measurements made in wells throughout the field reveal details of the complex heating phenomena. Electrical resistance tomography (ERT) provides near real-time detailed images of the heated zones between boreholes both during electrical heating and steam injection. Borehole induction logs show close correlation with lithostratigraphy and, by identifying the more permeable gravel zones, can be used to predict steam movement. They are also useful in understanding the physical changes in the field and in interpreting the ERT images. Tiltmeters provide additional information regarding the shape of the steamed zones in plan view. They were used to track the growth of the steam front from individual injectors.

OTHER RESOURCE GUIDES

34D

Bioremediation Resource Guide.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington, DC, September 1993.
(see abstract below)

EPA Document Number: EPA/542/B-93/004

35A

Ground Water Treatment Technology Resource Guide.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington, DC, September 1994.
(see abstract below)

EPA Document Number: EPA/542/B-94/009

35B

Physical/Chemical Treatment Technology Resource Guide.
U.S. Environmental Protection Agency, Office of Solid Waste and Emergency Response, Technology Innovation Office, Washington, DC, September 1994.
(see abstract below)

EPA Document Number: EPA/542/B-94/008

35C

Soil Vapor Extraction (SVE) Treatment Technology Resource Guide.
U.S. Environmental Protection Agency, Office of Solid Waste And Emergency Response, Technology Innovation Office, Washington, DC, September 1994.

EPA Document Number: EPA/542-B-94/007

These documents are intended to support decision-making by Regional and State Corrective Action permit writers, Remedial Project Managers (RPMs), On-Scene Coordinators, contractors, and others responsible for the evaluation of innovative treatment technologies. These guides direct managers of sites being remediated under RCRA, UST, and CERCLA to bioremediation, ground-water, physical/chemical, and soil vapor extraction treatment technology resource documents; databases; hotlines; and dockets, and identify regulatory mechanisms (e.g., Research Development and Demonstration Permits) that have the potential to ease the implementation of these technologies at hazardous waste sites. Collectively, the guides provide abstracts of over 300 guidance/workshop reports, overview/program documents, studies and demonstrations, and other resource guides, as well easy-to-use Resource Matrices that identify the technologies and contaminants discussed in each abstracted document.