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A Technology Assessment of Soil Vapor Extraction and Air Sparging

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A TECHNOLOGY ASSESSMENT OF SOIL VAPOR EXTRACTION AND AIR SPARGING

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of materials, that, if improperly dealt with, may threaten both human health and the environment. The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's land, air, and water resources. Under mandate of national environmental laws, the agency strives to formulate and implement actions leading to a compatible balance between human activities and the ability of natural resources to support and nurture life. These laws direct the EPA to perform research to define our environmental problems, measure the impacts and search for solutions.

The Risk Reduction Engineering Laboratory is responsible for planning, implementing and managing research, development, and demonstration programs to provide an authoritative, defensible engineering basis in support of the policies, program and regulations of the EPA with respect to drinking water, wastewater, pesticides, toxic substances, solid and hazardous wastes, and Superfund-related activities. This publication presents information on current research efforts and provides a vital communication link between the researcher and the user community.

The impacts associated with uncontrolled releases of petroleum hydrocarbons from underground storage tank systems present a major concern to the Risk Reduction Engineering Laboratory. Air sparging, an innovative technology, is being used at increasing numbers of sites to remediate impacted groundwater and soil in the saturated zone. This document provides general information on air sparging technology for remediating soils and groundwater contaminated with petroleum products. It also identifies the research needed to advance the development and application of this innovative technology.

E. Timothy Oppelt, Director
Risk Reduction Engineering Laboratory

ABSTRACT

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 adsorbed to 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.

The design of an air sparging system requires system component compatibility, optimal selection of blowers, efficient well configuration, and appropriate air emissions treatment. The technology can treat soil and water contaminated by gasoline, solvents, and other volatile compounds. Air sparging systems, always coupled with soil vapor extraction, provide control of the subsurface air flow. Proper hydraulic control prevents the migration 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.

This report covers research done between June and August of 1991. The work was completed in April 1992.

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ABBREVIATIONS AND SYMBOLS

A	Active (recycling facility)
ABN	acid/base neutral
BTEX	Benzene, toluene, ethyl benzene, xylene (combined analysis)
CDM	Camp Dresser & McKee, Inc.
CGI	combustible gas indicator
CPVC	chlorinated polyvinyl chloride
DCE	dichloroethylene
DO	dissolved oxygen
DRE	destruction and removal efficiency
EPA	U.S. Environmental Protection Agency
GAC	granular activated carbon
GC	gas chromatograph
HSWA	Hazardous and Solid Waste Amendments
lb	Pound (weight)
LEL	lower exposure limit
LNAPL	light non-aqueous phase liquid
MTBE	methyl tert-butyl ether
NA	not available
NAPL	non-aqueous phase liquid
NPDES	National Pollution Discharge Elimination System
O&M	operation and maintenance
ORD	Office of Research and Development
OUST	Office of Underground Storage Tanks, U.S. EPA
OVA	organic vapor analyzer
PCE	perchloroethylene
PP	polypropylene
PVC	polyvinyl chloride
RCB	Releases Control Branch
RCRA	Resource Conservation and Recovery Act
RREL	Risk Reduction Engineering Laboratory
scfm	standard cubic feet per minute
SVE	soil vapor extraction
TCA	trichlorethane
TCE	trichloroethylene
TCLP	Toxicity characteristic leaching procedure
THA	total hydrocarbon analyzer
TPH	Total petroleum hydrocarbons
TSDs	Transportation/storage/disposal facilities (for hazardous waste)
VOC	Volatile organic compounds
UEL	upper exposure limit
UST	Underground storage tank
$/t	Dollars per ton

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SECTION 1
INTRODUCTION

The U.S. Environmental Protection Agency (EPA) through the Hazardous and Solid Waste Amendments of 1984 (HSWA) and its land ban regulations, has encouraged the use of remedial action alternatives to excavation and land based disposal of contaminated soils resulting from leaking underground storage tanks (USTs).

EPA, through its Risk Reduction Engineering Laboratory's (RREL) Releases Control Branch (RCB), has initiated research and development efforts to expedite the remediation of contaminated soil impacted by leaking USTs. This work includes the investigation of emerging and innovative remedial technologies, such as air sparging used in combination with soil vapor extraction (SVE), as alternatives to pump-and-treat technology.

PUMP-AND-TREAT

Pump-and-treat processes have comprised a primary form of groundwater remediation. They employ groundwater extraction wells, a groundwater treatment system, and a discharge location for treated water. The treatment system for volatile organic compounds (VOCs) typically consists of air stripping and carbon adsorption equipment. In designing pump-and-treat systems, the remedial manager may experience difficulty in obtaining the required state and local permits for discharging the treated water. Several states restrict recharging treated water back into the aquifer; they make obtaining a National Pollution Discharge Elimination System (NPDES) permit for surface water discharge a long, difficult process. In addition, further restrictions limiting aquatic toxicity apply to surface water discharge.

Several factors control the effectiveness of pump-and-treat systems, such as the following rates:

- withdrawal of water from the ground
- contaminant diffusion

- desorption and dissolution of contaminants
- dissolution of non-aqueous phase liquids (NAPL)

Pump-and-treat is a slow method of remediating groundwater, with predicted clean-up times ranging from 10 to 30 years, or even longer due to the presence of NAPL and other physicochemical limitations as stated above [Mercer et al. 1990]. These long clean-up times increase costs for extraction, water treatment, and monitoring. Such limitations have promoted great interest in technologies which can achieve concentration goals in significantly less time than pump-and-treat. Sites treated with air sparging have achieved clean-up levels in time periods less than that expected via pump-and-treat systems.

AIR SPARGING SYSTEMS

This innovative technology sends air into a contaminated aquifer in order to force pollutants to leave subsurface soil and groundwater for soil pore spaces, where SVE can remove them. SVE systems always accompany air sparging treatments because they can capture the VOCs that air sparging strips from the saturated zone.

REPORT FORMAT

To accommodate the reader with a specific interest; the report will cover six different facets of air sparging as an innovative treatment for soil and groundwater contaminated by leaking USTs:

- a process description of air sparging and a review of the literature on the subject
- the components of the system and the factors that affect their performance
- case studies of documented applications
- the process design
- the economics of implementing air sparging
- the need for future research in this innovative area

Much of the information presented in this report emerged from a review of available literature on air sparging technology including case studies and theoretical papers presenting process mechanisms. The report describes air sparging system components, discusses the subsurface mechanism controlling the system's effectiveness, and outlines the various factors determining its applicability at a particular site. It also compares air sparging to conventional pump-and-treat treatment for groundwater remediation.

A case study section synopsizes over 20 air sparging applications, focusing on five which highlight various remedial conditions and the results achieved. Next the report describes the process layout and equipment requirements for an air sparging system. This section addresses contaminant removal and system performance.

A costs section presents capital, operational, and monitoring costs for soil vapor extraction and air sparging systems. It also provides costs for vapor emissions treatment and other significant cost factors associated with air sparging technology.

The final section forecasts the data and research efforts that are needed to further advance this technology and its application to the remediation of soil and groundwater impacted by the release of petroleum products from leaking USTs.

SECTION 2
AIR SPARGING

PROCESS DESCRIPTION

Air sparging, also called "in situ air stripping" and "in situ volatilization," is a technology utilized to remove VOCs from the subsurface saturated zone. It introduces contaminant-free air into an impacted aquifer system, forcing contaminants to transfer from subsurface soil and groundwater into sparged air bubbles. The air bubbles are then transported into soil pore spaces in the unsaturated zone where they can be removed by SVE.

Air sparging systems must operate in tandem with SVE systems that capture volatile contaminants stripped from the saturated zone. Using air sparging without accompanying SVE could create a net-positive, subsurface pressure extending contaminant migration to as-yet-unaffected areas. Thus the treatment could increase the overall zone of contamination. Without SVE, uncontrolled contaminated soil vapor could also flow into buildings (i.e., basements) or utility conduits (i.e., sewers), creating potential explosion or health hazards.

REMEDIATION MECHANISMS

The SVE system alone may affect the rate of volatilization of VOCs from the saturated zone [Marley, Walsh and Nangeroni, 1990]. However, transport of immiscible contaminants from the saturated zone to the vadose zone necessitates channeling them to the air/water interface for removal by an SVE system. Thus, the rate of contaminant transport from groundwater to soil vapor phase has increased with the addition of air sparging to an SVE system.

The effectiveness of combined SVE/air sparging systems results from two major mechanisms: contaminant mass transport and biodegradation. Depending on the system configuration, the operating parameters, and contaminant types found on-site, one mechanism usually predominates. In both remediation mechanisms, oxygen transport in the saturated and unsaturated zones plays a key role.

Although the exact nature of the saturated zone vapor phase is not completely understood, sparging seems to create air bubbles, which move through the groundwater to the unsaturated soil, like bubbles in an aeration basin [Ardito and Billings, 1990; Brown and Fraxedas,1991]. Other theories trace the movement of air through irregular pathways in the saturated zone and, ultimately, to the surface of the water table [Middleton and Hiller, 1990]. These theories suggest that the air would move as pockets through soil pathways, rather than forming bubbles, because groundwater travels in a porous medium.

The nature of air transport affects mass transfer to and from the groundwater regime. Bubbles exhibit higher surface area for transfer of oxygen to the groundwater and for volatile migration to the unsaturated zone, than the area provided by continuous, irregular air-flow pathways.

Mass Transfer

Mass transfer employs several mechanisms that move contaminants from saturated zone groundwater to unsaturated soil vapors. Figure 1 illustrates the following major mechanisms: (a) dissolving soil-sorbed contaminants from the saturated zone to groundwater; (b) displacing water in soil pore spaces by introducing air; (c) causing soil contaminants to desorb; (d) volatilizing them, and (e) enabling them to enter the saturated zone vapor phase. Due to the density difference between air and water, the sparged air migrates upwards in the aquifer. The pressure gradient resulting from the creation of a vacuum in the unsaturated zone pulls the contaminant vapors toward and into the SVE wells.

The action of the air passing through the saturated zone in response to sparging leads to turbulence and mixing of the groundwater. This in turn increases the rate at which contaminants adsorbed to the saturated zone soils dissolve into the groundwater. Light non-aqueous phase liquids (LNAPLs) floating on the water table are also subject to increased rate of transfer to the unsaturated zone because they are volatilized by the air sparging process.

In summary, air sparging increases the speed at which the following occur:

- volatilization of contaminants from the groundwater to the vadose zone;
- desorption and dissolution of adsorbed contaminants from the soil into the groundwater; and
- dissolution of NAPLs due to mechanical mixing.

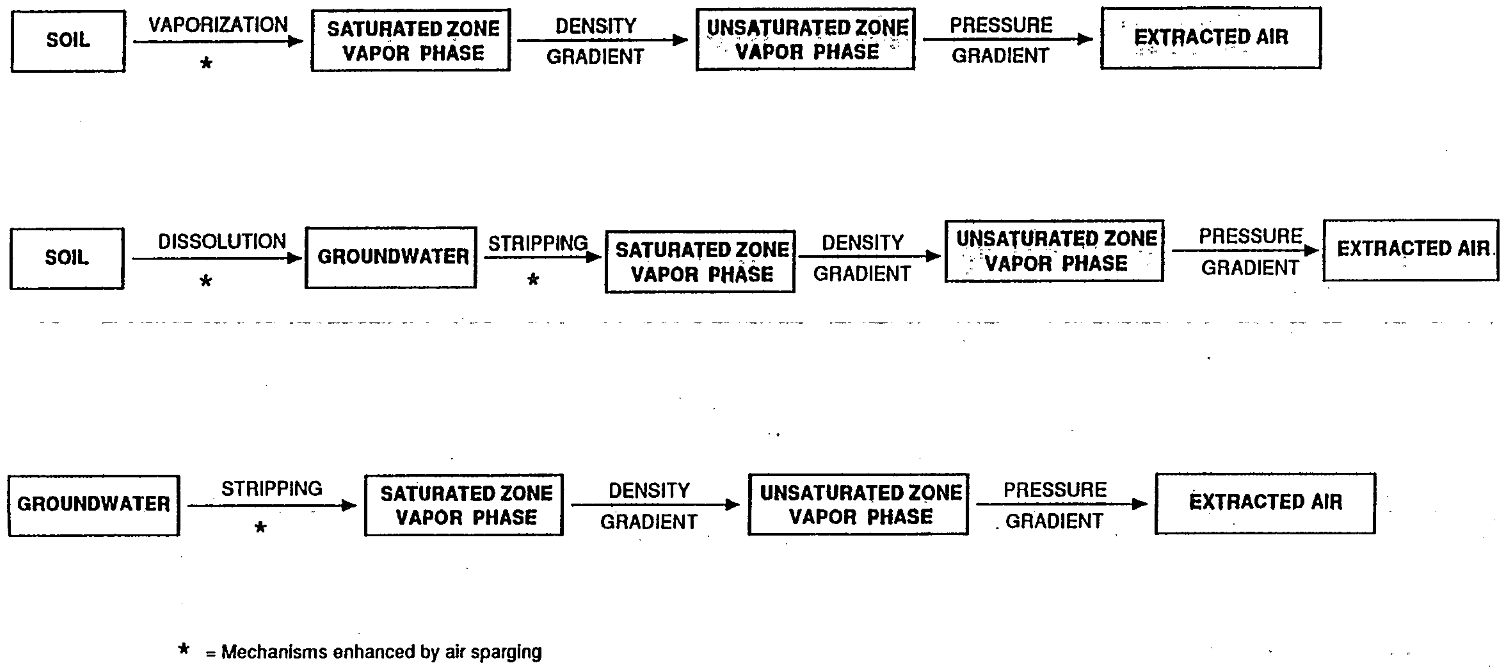

Figure 1. Mechanisms of mass transport during air sparging.

The mass transfer of contaminants may be further enhanced by heating the air prior to sparging. The increase in air temperature will increase the rate of volatilization of contaminants.

Biodegradation Mechanism

Aerobic biodegradation of contaminants by indigenous microorganisms requires the presence of a carbon source, nutrients, and oxygen. Air sparging increases the oxygen content of the groundwater thus enhancing aerobic biodegradation of contaminants in the subsurface. Certain organic contaminants, such as petroleum constituents, serve as a carbon source for microorganisms under naturally occurring conditions. The rate of biodegradation can be enhanced by optimizing nutrient status of the system.

Remediation of an aquifer via the biodegradation mechanism has distinct advantages since a portion of the contaminants will be biologically degraded to carbon dioxide, water, and biomass -- yielding a lower level of VOCs in the extracted air. This in turn can substantially reduce vapor treatment costs. The possibility of off-site contaminant vapor migration is also reduced when sparged vapors entering the vadose zone contain lower levels of contaminants.

Certain contaminants, such as chlorinated solvents, can undergo biodegradation under anaerobic conditions. Air sparging, in these instances, could adversely affect this biodegradation process.

TECHNOLOGY APPLICABILITY

Although air sparging is a relatively new technology for contaminated subsurface soil remediation, it has been applied at hundreds of sites in the United States and Europe since 1985. However, the design of these systems has been, for the most part, empirically based [Marley, 1991].

The effectiveness of air sparging depends on various site conditions. Table 1 lists these factors, which are discussed below.

Depth to Groundwater

Air sparging has been effective in an aquifer 150 ft below surface [Looney, Kaback and Corey, 1991]. There appears to be no depth limit at which air sparging would not be effective, but significant cost implications may accompany the installation of an air sparging system in a very deep aquifer. However, a

TABLE 1. CONDITIONS AFFECTING APPLICABILITY OF AIR SPARGING

Air sparging applicability factor	Favorable conditions	Unfavorable conditions
Depth to groundwater	>5 ft	<3 ft
Volatility of contaminants	High volatility	Low volatility
Solubility of contaminants	Low solubility	High solubility
Biodegradability	High biodegradability	Low biodegradability
Permeability	$>10^{-3}$ cm/sec	$<10^{-3}$ cm/sec
Aquifer type	Unconfined	Confined
Soil type	Sandy soils	Clays, high organic soils
Presence of LNAPL	None or thin layer	Thick layer of LNAPL
Bedrock aquifer contamination	Highly fractured bedrock	Unfractured bedrock

water table located at a shallow depth (<5 ft), may increase the difficulty of recovering vapors with SVE. It could release VOC emissions to the atmosphere. Capping such a site with pavement or other impervious material might reduce atmospheric emissions.

Volatility of Contaminants

Enhancing mass transfer of contaminants from the soil and groundwater into the vapor phase, a key mechanism of the air sparging process, requires highly volatile contaminants. Volatility is directly related to the Henry's Law Constant of a compound and its vapor pressure -- the higher the Henry's Law constant, the higher the volatility. In general, compounds which are effectively removed from contaminated water by air stripping are sufficiently volatile for adequate air sparging treatment. Compounds with Henry's Law Constants of 10^{5} atm-m^{3}/mole or greater can be air stripped or sparged [Brown et al., 1991]. Due to their high volatility, petroleum compounds (e.g., benzene and toluene), and solvents (e.g., trichloroethylene) are very amenable to air sparging technology.

Solubility of Contaminants

The solubility of a contaminant in water determines its ability to be stripped by air sparging. In general, the more soluble a contaminant is in water, the greater the difficulty there is in using air sparging.

Biodegradability of Contaminants

Since biodegradation is enhanced by air sparging, compounds that are readily aerobically degraded are amenable to remediation by air sparging. Biodegradation of petroleum hydrocarbons, such as those found in gasoline and diesel leaks from USTs, has been significantly increased with air sparging. Prior to designing an air sparging system for bioremediation, electrolytic respirometry should be used to analyze samples of the soils and groundwater. This will make it possible to gauge the effectiveness of the indigenous microorganisms and their energy sources to metabolize the petroleum hydrocarbons.

Soil Permeability

Soil permeability, which measures the ease of fluid flow through the soil column, is a critical parameter in the design of air sparging systems. Injected air must flow freely throughout the aquifer to achieve adequate removal rates. In most aquifers, horizontal permeability is greater, by a factor of ten, than vertical permeability. Successful sparging systems require air flow in both horizontal and vertical directions [Brown and Fraxedas, 1991]. Vertical flow is particularly important since the contaminant must migrate to the vadose zone for removal by SVE.

If the geology restricts the vertical flow, contaminants may migrate laterally into previously uncontaminated areas. Hydraulic conductivity of 0.001 cm/sec or greater is required to obtain sufficient subsurface air flow [Middleton, 1990]. Bench-scale experiments have shown coarse sand (d_{50} = 0.8 mm) forming the dividing line between soils, which permits injected air to rise by hydraulic uplift alone from soil that required additional pressure to inject air and through which air escaped at only a few points [Wehrle, 1990].

Due to the heterogeneity of soils at all sites, it may be necessary to concentrate wells in areas with lower permeability. The spacing of the wells depends on the radius of influence. In general, highly permeable soils will have larger radii of influence and higher air flow rates than lower permeable soils.

Screen placement requires a good understanding of the stratigraphy of a site. Well layout should overlap the radii of influence. This will ensure the treatment of all soil areas.

Clogging of the injection well screen or the aquifer in the vicinity of the sparging wells could reduce permeability and, therefore, decrease the effectiveness of the method. Clogging may result from enhanced bacterial growth under increased oxygen levels. In addition, oxidation at sites with high iron and manganese levels could cause further clogging. Some applications have injected nitrogen instead of ambient air to minimize problems associated with fouling [MWR, 1990]. However, the use of nitrogen also prevents the enhancement of aerobic biodegradation.

Confining Layers

Some air sparging proponents point out that it can only achieve success at sites with water table (i.e. unconfined) aquifers. Confined aquifers, where a low permeability layer lies above the water-bearing zone, would inhibit the flow of air upward from the saturated zone to the vadose zone. The injected air in these situations would flow radially away from the injection point; the vapor extraction system would not recover it. Such a situation could build up pressure in the aquifer.

For unconfined aquifers, stratigraphic layers with different permeabilities will also affect air and water flow patterns as well as influence the air sparging system. In such situations, optimal air flow will occur in the more permeable zones [Wehrle, 1990]. Air flow may travel horizontally away from the injection point and create a wider zone of influence than would otherwise be expected [Bohler et.al., 1990].

Soil Characteristics

Air sparging systems are most applicable for sites with sandy soil, due to its permeability. Soil containing a large organic carbon fraction may impede the desorption of volatile organic contaminants, thus reducing air sparging effectiveness. In extraction wells, the presence of a large amount of monomers in the soil may cause clogging of well screens possibly due to polymerization.

Presence of LNAPL

Low-density (or light) nonaqueous phase liquids (LNAPL) floating on the water table presents a particular problem during air sparging. As Figure 2 shows, the air sparging action creates a mounding effect

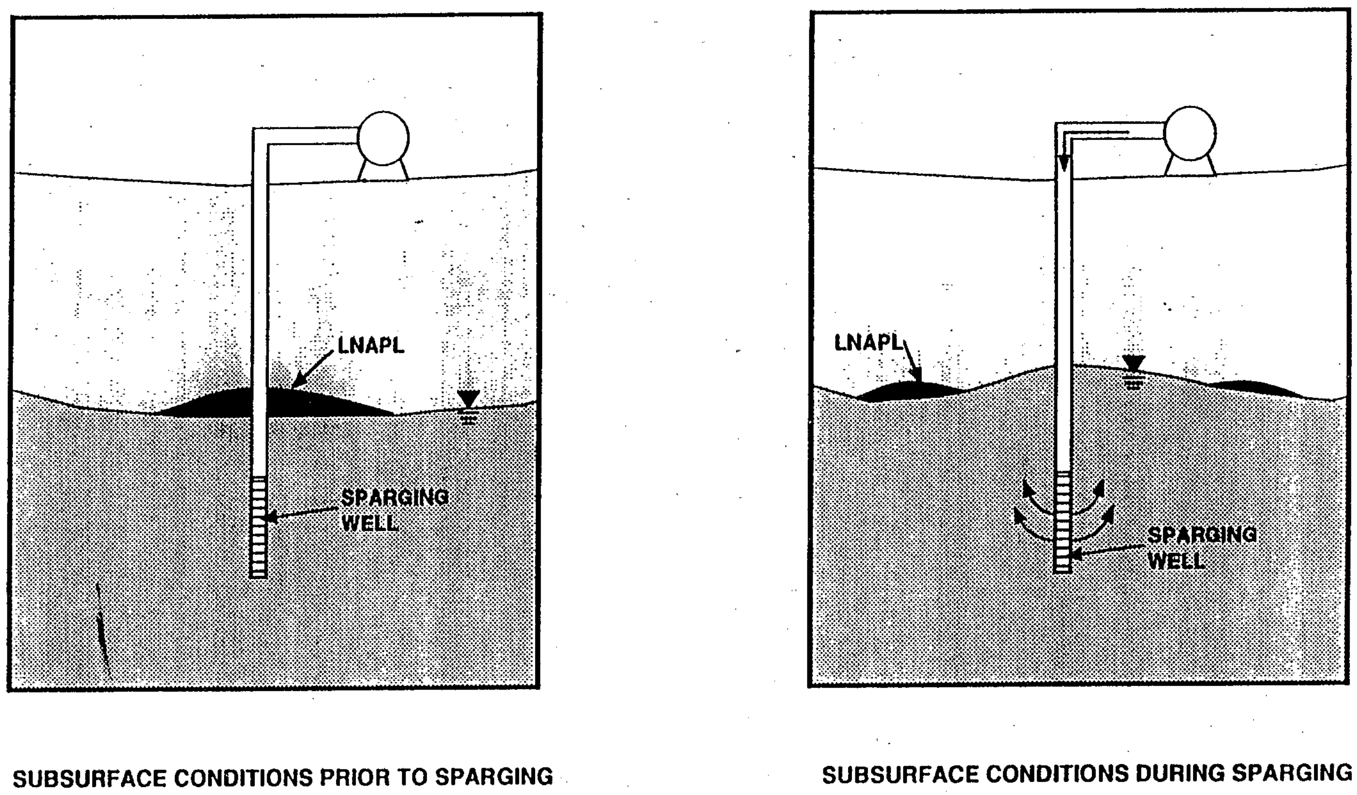

Figure 2. Migration of light non-aqueous phase liquids during air sparging.

in the proximity of the sparge well. In sites with steep hydraulic gradients, this mounding effect may be sufficient to move a plume of LNAPL, possibly contaminating clean areas. While it is possible to prevent the plume movement by modulating the sparged air pressure, it is more important to recover the mobile portion of the LNAPL to a residual saturation phase.

<u>Contamination in Bedrock Aquifer</u>

The effectiveness of air sparging hinges on the mass transfer of air to the groundwater and movement of the contaminants' vapor through the saturated zone upward into the unsaturated zone where they can be extracted. Unless the rock formation is highly fractured, with fractures vertically oriented, this technology will not provide sufficient mass transfer to effectively remediate a bedrock aquifer.

<u>Metals in Groundwater</u>

In addition to the possibilities of clogged well screens resulting from oxidation of metals in groundwater and the growth of bacteria previously discussed, precipitation of metals can also be an inhibiting factor. Since ambient air contains carbon dioxide, calcium carbonate precipitation may occur in some aquifers during air sparging. This may also reduce the air flow through the system.

<u>Contaminant Location</u>

Air sparging targets contaminants in the saturated zone and the capillary fringe. For compounds with a density less than water such as many petroleum constituents, much of the contamination may lie in the capillary fringe and just below the water table, depending on such factors as water table fluctuations, the amount of product released, contaminant density, and contaminant solubility. Dense non-aqueous phase liquids (DNAPL), such as trichloroethylene, often migrate through the aquifer to a lower confining unit and to greater depths. For dissolved contaminants in the aqueous phase, groundwater flow and direction will control the distribution of contaminants throughout the site. Depending on soil characteristics, air sparging would remediate DNAPL-contaminated soil as well.

<u>Combination with Other Technologies</u>

Air sparging is always used in conjunction with SVE. The implementation of SVE addresses the vadose zone contamination, and incorporates air sparging wells to treat saturated zones.

Groundwater extraction at air sparging sites may serve as a hydraulic control. Injected air may mobilize contaminants adsorbed to soil, either by displacement from the soil matrix or through increased dissolution of the adsorbed contaminant into the groundwater during mixing caused by air injection [Middleton and Hiller, 1990]. If this occurs and the rate of volatilization is insufficient, downgradient groundwater concentrations could actually increase. Air sparging may have fallen into disfavor in Germany due to increased downgradient dissolved contamination [Brown and Fraxedas, 1991]. To prevent this situation, a groundwater pumping system could hydraulically contain the site groundwater flow.

SECTION 3

AIR SPARGING CASE STUDIES

Air sparging technology is a relatively recent remediation method, applied at contaminated sites only within the past half decade. Early applications of this technique apparently occurred in Germany during the mid-1980's [Middleton and Hiller, 1990]. Due to the technology's short track record, the delay in publishing the results of field work, and the reluctance of some experts in revealing details about the technology for proprietary and competitive reasons, a relatively sparse body of information is available on air sparging. With increased application, the quantity and quality of this data should improve, disseminating helpful information to the remedial community.

Not surprisingly, documented air sparging experience has not been limited to one chemical group or soil type. The sites vary in contaminant treated, soil type, geological features, additional techniques used at the site, and other factors. A study of these sites, however, reveals that some share common characteristics, from which important insights can be drawn.

AIR SPARGING EXPERIENCE

Reviews of case histories for air sparging sites and visits to active sites in New Mexico contributed to the preparation of this report. A summary of the information gathered during these activities follows below. Table 2 lists 21 sites remediated by air sparging. It provides data on soil types, contaminant types, groundwater concentrations (initial and final), and the time needed to achieve those final levels. Table 3 presents construction and operations information for these case studies. Brief treatments of four case studies from the United States and nine European installations will illustrate how air sparging successfully remediates the saturated zone.

Contaminants Treated

At the sites studied, air sparging has been used exclusively to treat VOCs, including petroleum constituents and chlorinated solvents. Gasoline and industrial solvent applications targeted trichloroethylene (TCE) and perchloroethylene (PCE). In many instances such contamination originated in releases from USTs at service stations, tank farms, dry cleaners, manufacturing plants, and other industrial facilities. Among the case histories reviewed, nine sites were contaminated with gasoline, and twelve were impacted by the release of solvents. One of the nine gasoline-contaminated sites contained both gasoline and diesel fuel contamination.

Contaminant Magnitude

Table 2 lists the initial contaminant concentration for each case history site. There appears to be no upper limit for expectations of air sparging effectiveness. Indeed, as the contaminant levels increase, air sparging should exceed the results achieved by groundwater pump-and-treat approaches, since the volatilization mechanism depends on a concentration gradient between the groundwater concentration and that of the (contaminant-free) introduced air.

Soil Characteristics

Like many in situ remediation technologies, the effectiveness of air sparging is significantly affected by soil characteristics. Table 2 shows the soil properties found at each site listed. Most of these sites contained permeable soil types, such as sand, silt, and gravel. The Nordrhein, Westfalen site presented fractured limestone. Such sites, with highly fractured rock formations, may also provide sufficient permeability for air sparging application, as noted before.

Depth to Groundwater Table

Air sparging has operated at sites where the depth to groundwater ranges from just two ft [Harress, 1989] to 135 ft [Looney, 1991]. Most of the sites studied, however, measured this depth from 8 to 20 ft (Table 3).

TABLE 2. SUMMARY OF PUBLISHED AIR SPARGING SITES

Site	Citation	Soil type	Contaminants	Cleanup time** (months)	Initial GW concentration (ppm)	Final GW concentration (ppm)
Isleta	Ardito & Billings, 1990	Alluvial sands, silts, clays	Leaded gasoline	2	MW-1 BTEX ~4 MW-3 BTEX ~18 MW-5 BTEX ~25	MW-1 BTEX ~0.25 MW-3 BTEX ~8 MW-5 BTEX ~6
Conservancy	Billings, 1990	Silty sand Interfering clay layer	Gasoline	5	Benzene 3 - 6	59% average benzene reduction after 5 months
Buddy Beene	Billings, 1991	Clay	Gasoline	2	*	8.5% reduction/month
Bernalillo	Billings, 1990	*	Gasoline	17	*	BTEX & MTBE <5.5
Los Chavez	Billings, 1990	Clay	Gasoline	9	*	40% benzene, xylenes reduction, 60% toluene reduction, 30% ethyl benzene reduction
Arenal	Billings, 1990	*	Gasoline	10	Benzene >30	Benzene <5
Dry cleaning facility	Brown, 1991	Coarse sand Natural clay barrier	PCE, TCE, DCE, TPH	4	Total VOCs - 41	Total VOCs - 0.897
Berlin	Harress, 1989	Sand, silty lenses Aquitard-clay	c-1,2-DCE, TCE, PCE	24	c-1,2-DCE - >2	c-1,2-DCE - <0.440
Bielefeld, Nordrhein - Westfalen	Harress, 1989	Fill, sand, silt Aquitard-siltstone	PCE, TCE, TCA	11	PCE 27; TCE 4.3; TCA 0.7	Total VOCs - 1.207
Munich, Bavaria	Harress, 1989	Fill, gravel, sand Aquitard-clayey silt	PCE, TCE, TCA	4	PCE 2.2; TCE 0.4; TCA 0.15	PCE 0.539; TCE 0.012; TCA 0.002
Nordrhein, Westfalen	Harress, 1989	Clayey silt, sand Aquitard-siltstone	Halogenated hydrocarbons	4 6	Location A: THH 1.5-4.5 Location B: THH 10-12	Location A: THH 0.010 Location B: THH 0.200
Bergisches Land	Harress, 1989	Fractured limestone	Halogenated hydrocarbons	15	THH - 80	THH - 0.4
Pluderhausen, Baden - Wurttemburg	Harress, 1989	Fill, silt, gravel Aquitard-clay	TCE	2	1.20	0.023

TABLE 2. (Continued)

Site	Citation	Soil type	Contaminants	Cleanup time** (months)	Initial GW concentration (ppm)	Final GW concentration (ppm)
Mannheim - Kaefertal	Herrling, 1991	Sand	PCE, chlorinated hydrocarbons	*	*	*
Gasoline service station	Kresge, 1991	Sand and silt	Gasoline	24	Total BTEX - 6-24	Total BTEX - 0.380-7.6
Savannah River	Looney, 1991	Sand, silt, and clay	TCE, PCE	3	TCE 0.5-1.81 PCE 0.085-0.184	TCE 0.010-1.031 PCE 0.003-0.124
Gasoline service station	Marley, 1990	Fine-coarse sand, gravel	Gasoline	2	Total BTEX - 21	Total BTEX <1
Solvent spill	Middleton, 1990	Quaternary sand and gravel	TCE, PCE	3	Total VOCs - 33	Total VOCs - 0.27
Solvent leak at degreasing facility	Middleton, 1990	Fill, sandy and clayey silts	TCE	2	0.200-12	<0.010-0.023
Chemical manufacturer	Middleton, 1990	Sandy gravel Aquitard-clay	Halogenated hydrocarbons	9	THH - 1.9-5.417	THH - 0.185-0.320
Truck distribution facility	MWR, 1990	Sands	Gasoline & diesel fuel	On-going	Total BTEX - 30	*

c-1,2-DCE - 1,2-cis-Dichloroethylene
TPH - Total petroleum hydrocarbons
TCE - Trichloroethylene
PCE - Tetrachloroethylene
TCA - Trichloroethane
BTEX - Benzene, toluene, ethyl benzene, xylenes
MTBE - Methyl tert-butyl ether
THH - Total halogenated hydrocarbons
* - Not specified

**** Cleanup times indicate the time interval between the initial and final groundwater concentrations reported in this table. Total site remediation time may have been longer.**

TABLE 3. PUBLISHED AIR SPARGING CONSTRUCTION DETAILS

Site	Citation	Depth to groundwater (ft)	No. of air spargers	Screen depth (ft)	Injection pressure (in H_2O)	Injection flow rate (cfm)	No. of vacuum wells	Other
Isleta	Ardito & Billings, 1990	6.5-16	27	*	*	*	27	Nested injection & extraction wells
Conservancy	Billings, 1990	6.5	35	*	*	*	35	Nested injection & extraction wells
Buddy Beene	Billings, 1991	*	67	*	*	*	67	Nested injection & extraction wells
Bernalillo	Billings, 1990	*	16	*	*	*	16	Nested injection & extraction wells
Los Chavez	Billings	*	*	*	*	*	*	Nested injection & extraction wells
Arenal	Billings, 1990	*	11	*	*	*	11	Nested injection & extraction wells
Dry cleaning facility	Brown, 1991	13	7 sparge only; 7 nested sparge/ vacuum	2' sparge 8'vacuum	277	225	1 extraction only 7 nested	40 in. H_2O, vacuum extraction flow rate - 500 cfm, (2) 1,800 lb GAC vapor treatment
Berlin	Harress, 1989	15-18	3	*	*	*	1	
Bielefeld, Nordrhein - Westfalen	Harress, 1989	2-8	5	*	*	*	2	
Munich, Bavaria	Harress, 1989	15	7	*	*	*	1	
Nordrhein - Westfalen	Harress, 1989	6-9	10	*	*	*	2	
Bergisches Land	Harress, 1989	90	8	*	*	*	2	
Pluderhausen, Baden - Wurttemberg	Harress, 1989	11	5	*	*	*	1	
Mannheim- Kaeferlal	Herrling, 1991	33	1 w/gw recirc. and extract.	*	*	*	1 combo inj. & ext. w/gw recirculator	19.7 in H_2O, vacuum extraction flow rate 300 - cfm, activated carbon vapor treatment
Gasoline service station	Kresge, 1991	8-13	8	2.5	*	*	*	20-30 in H_2O, vacuum extraction flow rate - 200 cfm, air injection - 8 hr/day
Savannah River	Looney, 1991	135	1 (horiz.)	300 (sparge) 205 (vacuum)	*	165-185	1 (horiz.)	130-145 in H_2O, vacuum extraction flow rate 935-1,020 cfm

TABLE 3. (Continued)

Site	Citation	Depth to groundwater (ft)	No. of air spargers	Screen depth (ft)	Injection pressure (in H_2O)	Injection flow rate (cfm)	No. of vacuum wells	Other
Gasoline service station	Marley, 1990	15.5-16	7 shallow 6 deep	18-20 25-27	28-55 166-222	3-6 2-6	2	Deep wells 6 hr on, 6 hr off, extraction flow rate - 100 cfm
Solvent spill	Middleton, 1990	27	5	*	*	30	2	Extraction flow rate - 475 cfm
Solvent leak at degreasing facility	Middleton, 1990	18-20	5	*	*	*	1	
Chemical manufacturer	Middleton, 1990	8	8	*	*	*	4	
Truck distribution center	MWR, 1990	12-14	13	*	*	*	4	

* Not available or reported.

CASE STUDIES

At many sites, the air sparging application has followed limited success with groundwater pump-and-treat operations [Marley, 1990; Ardito and Billings, 1990; Middleton and Hiller, 1990]. In effect, these sites were "retrofitted" with air sparging in the hopes of expediting the cleanup and achieving goals in a matter of months rather than years. In many cases, these goals have been met -- with several sites completing site closure. At most of these sites, SVE addressed vadose zone contamination; air sparging treated saturated zone contaminants. The following case studies (four in the United States and nine in Europe) describe sites where air sparging was successful.

Case Studies in the United States

Gasoline Service Station, Rhode Island--

A groundwater pump-and-treat and product recovery system, which was initially implemented at this gasoline spill site in Rhode Island, proved inadequate to meet the closure criteria established by the Rhode Island Department of Environmental Management [Marley, 1991]. In addition to groundwater extraction/treatment, a soil gas containment system was instituted to control the migration of gasoline vapors into nearby basements. The vapor containment system was subsequently upgraded to a soil vapor extraction/air sparging system by increasing vapor extraction flow with air injection into the saturated zone. A cost/benefit analysis was performed on three respective treatment schemes: two groundwater pump-and-treat processes and an air sparging process to be used in conjunction with the existing soil vapor extraction system. A geological study of the site showed fine to coarse sand and some fine to medium gravel; soil analyses revealed low levels of weathered gasoline constituents.

Based on the results of a pilot study, a full-scale air sparging system was designed. It employed seven shallow and six deep injection wells, with two vapor extraction wells. Pretreatment concentrations of benzene, toluene, ethyl benzene, and total xylenes (BTEX) in groundwater measured as high as 21,000 ppb. Full-scale air sparging treatment over a 60-day period lowered BTEX concentrations to levels well below the established closure criteria (only hundreds of ppb).

Dry Cleaning Facility--

A vapor extraction/air sparging treatment system was designed to remediate soil and groundwater contaminated by leaking USTs at a former dry cleaning facility. Groundwater contaminants included perchloroethylene (PCE), trichloroethylene (TCE), dichloroethylene (DCE), and total petroleum hydrocarbons.

The subsurface environment consisted of miscellaneous occurrences of fill material sporadically overlying a continuous sheet of naturally occurring Quaternary sediments [Brown, 1991]. A naturally existing barrier locally minimized the potential for downward migration of dissolved-phase total petroleum hydrocarbons and chlorinated VOCs from the shallow water-bearing zone to deeper water-bearing units.

A three-phase pilot study employed the following: vapor extraction only, air sparging only, and the simultaneous operation of both systems. The air sparging tests ran at pressure levels of 10, 15, and 20 psi with corresponding flow rates of 16, 24, and 37 cfm. Vacuum/pressure readings and OVA monitors measured system performance. The combined system was deemed effective because the OVA readings showed removals that exceeded those of the single processes.

Based on the results of the pilot study, a full-scale system was designed, consisting of seven nested vapor extraction/air sparge points, one (vapor) extraction-only well and seven injection-only wells. The vapor extraction system operated approximately one month prior to start-up of the air sparging system. Effluent samples indicated that concentrations of PCE and TCE decreased during vapor extraction start-up and then increased with start-up of the injection system. Initial groundwater concentrations were as high as 40,000 ppb total VOCs; after 125 days, they dropped by more than 98%.

Horizontal Wells, Savannah River Site--

Air sparging was demonstrated at a U.S. Department of Energy site as an innovative environmental technology capable of remediating unsaturated zone soils and groundwater containing VOCs [Kabek et al., 1991]. A 20-week pilot test evaluated the technology, utilizing two horizontal wells, one each for extraction and injection. Air injection flow rates and temperature were also used to evaluate the process. The horizontal wells were located along a process sewer line that was the apparent source of the contamination. The horizontal well configuration was chosen for this site because it would provide more surface area for the injection and extraction needed to treat the linear contamination. Since many water-bearing subsurface formations extend areally and because the site geology dictates the path of a contaminant plume, horizontal wells may draw vapors more efficiently from these horizontal formations.

The injection well, installed below the water table at a depth of 150-175 ft, extended 300 ft horizontally; the extraction well, installed at a depth of 75 ft (approximately 60 feet above the water table), extended 200 ft horizontally. Extensive characterization and monitoring determined that the highest concentrations of PCE and TCE in groundwater were found at depths greater than 180 ft below the zone of injection.

Helium tracer tests provided a better understanding of the vapor flow paths between the two wells. The results indicated connectivity between the two wells, although the recovery rates were slow. After 46 days, 45% of the helium had been recovered.

Microbial tests showed an increase in the activity of indigenous microorganisms, as measured by increased CO_2 levels during air injection at medium and high flow rates. This activity diminished at the conclusion of the air injection test. The injection of heated air had no apparent effect on the amount of contaminants nor the temperature of the vapors extracted. Comparison of extraction rates achieved in one vertical well during a vapor extraction test to rates from the air sparging horizontal well showed an increase of approximately 20% by the air sparging system.

Conservancy Site, Belen, New Mexico—

Contamination at the Conservancy Site consisted of a 6,500 gal gasoline leak from a leaking UST [Billings and Associates, 1991] . A free product layer as thick as 33 inches was found by monitoring wells, with groundwater benzene concentrations of up to 6 ppm. The soil is silty sand with a clay layer.

Free product recovery and air sparging systems were installed on-site. The air sparging system consisted of nested sparge and extraction wells, linked in a network. Since the depth to groundwater was only 6.5 ft, it was possible to manually install the extraction and sparging wells.

The sparging system consisted of 2-in PVC wells and solvent-welded piping. The network was radially installed around the source of the contamination to minimize migration of the contaminant plume. Air injection and vapor extraction used several blowers, installed in parallel systems with manifolds and piping networks for operational flexibility.

The system operated intermittently for two months, and then continuously for three months. After the fifth month, groundwater benzene reductions throughout the site ranged from 37 to 100 percent with an overall average of 59 percent. The following average percent reductions of other parameters were achieved after the fifth month:

- benzene - 59%
- toluene - 66%
- ethyl benzene - 54%
- xylenes - 49%

Based on these reduction rates, the site might achieve the cleanup criteria established by the State of New Mexico in about 2.5 years as predicted by the engineer [Billings and Associates, 1991].

Developments and Applications of Air Sparging in Europe

Chief among the firms developing and applying SVE and air sparging technology in Europe are Hannover Umwelttechnik GmbH and Harress Geotechnik. Hannover Umwelttechnik (HUT) has developed an inexpensive and relatively effective technique for SVE and groundwater stripping in situ (Nunno and Hyman, 1988). Compressed air is pulsed into the aquifer through injection wells, stripping the volatile contaminants from the groundwater. The compressed air is introduced in a pulsed manner in order to prevent channelling or short circuiting.

Since 1985, in situ groundwater aeration has been used on over thirty sites in Europe (Middleton and Hiller, 1990). Following are detailed descriptions of two of these remedial installations and their operations. An additional seven brief case histories of installations in Germany are included.

Example 1--

In the example described here, soil gas measurements inside a building revealed concentrations of more than 500 ppm for both trichlorethylene (TCE) and tetrachloroethylene (PCE). Peak concentrations in soil samples were found to be as high as 2,800 mg/kg for TCE and 64 mg/kg for PCE.

The geology on the site was characterized by quaternary sand and gravel units of more than 110 feet in thickness, with an interlayer of silty sands at a depth of 44 to 47 feet. The depth to groundwater was about 27 feet measured from the floor of the building.

Two soil venting units, equipped with radial flow blowers, produced a volume flow of 475 cfm. Within 100 days a total of 5,100 lbs of solvents was removed from the soil. At that point, compressed air was injected into the groundwater using 5 injection pipes with a length of 37 feet each. The injected volume flow was about 6 cfm at each pipe.

Exhaust air VOC concentrations decreased by approximately an order-of-magnitude in the first 100 days due to soil venting. Air injection started at day 100. An increase in the exhaust air VOC concentrations from a total of 800 mg/m^3 to more than 10,000 mg/m^3 was observed within 2 hours after the start of the aeration. From this peak, the VOC concentration again decreased along the typical slope of an air extraction curve.

Soil venting and groundwater aeration removed a total of more than 8,900 lbs VOC from the unsaturated and the saturated zone within 240 days. After 3 months of aeration, the concentrations in the groundwater were reduced from an initial 33,000 μg/L to 270 μg/L.

Example 2--

Groundwater contamination was discovered on the site of a chemical manufacturer. Initial analyses revealed concentrations of more than 5,000 μg/L of solvents in the groundwater. Following the discovery, several wells were established up- and downgradient of the contamination sources which had been previously defined by soil gas investigations.

The geology of the site was characterized by uniform sandy gravels down to a depth of approximately 36 ft. The sandy gravels were underlain by marly clays, which form the base of the aquifer. The water table was at a depth of 8 ft. Soil venting was chosen as the process to clean up the vadose zone, starting in June 1986. For the remediation of the contaminated groundwater, eight air injection points were installed at the base of the aquifer in the immediate vicinity of the soil venting systems. Injection of air into the aquifer commenced in July 1986.

Groundwater quality was monitored using wells located along the property line downgradient of the contaminated areas. Within 9 months of operation, the concentration of solvents in the well, which was located directly downgradient, decreased from 5,417 μg/L to 320 μg/L. By May 1990, the concentration had further decreased to less than 10 μg/L. In another downgradient well, the concentrations decreased from 1,990 μg/L in August 1987 to around 150 μg/L in May 1990. During the same period, the contaminant concentration in the exhaust air decreased from initial levels of up to 500 ppm to values of 1 ppm and less. No groundwater was pumped during the period of the remediation.

Following are brief case histories of air sparging installations at seven locations in Germany (Harress Geotechnik, Inc., 1989). The operations all began with an SVE installation in the vadose zone. After the VOCs in the vadose zone were reduced to asymptotic levels, the air injection systems were installed in the saturated zones within the zone of influence of the SVE systems.

<u>Case History No. 1</u>

Location: Augsburg, Bavaria
Soil conditions: 36 ft sandy gravel, aquitard - clay
Depth to groundwater: 8 ft
Number of air injection points: 8 at 50 ft spacing

Number of vapor extraction points: 4
VOC contaminant: halogenated hydrocarbons
Initial groundwater concentration: (in downgradient monitoring wells B2 and B4)
B2 - 1,900 ppb
B4 - 5,417 ppb
Effectiveness of VE/GA^{sm} System: Within 9 months in B2 to 185 ppb, B4 to 320 ppb

Case History No. 2

Location: Berlin
Soil conditions: 115 ft of sand, with silty lenses from 9 ft to 36 ft below grade, aquitard - clay
Depth to groundwater: 15 - 18 ft
Number of air injection points: 3
Number of vapor extraction points: 1
VOC contaminant: mostly 1,2-DCE-cis, with TCE and PCE
Initial groundwater concentration: 1,2-DCE-cis >2,000 ppb
Effectiveness of VE/GA^{sm} System: Reduced to 1,000 ppb after 10 months, reduced to 440 ppb after a total of 2 years

Case History No. 3

Location: Bielefeld, Nordrhein-Westfalen
Soil conditions: 5 ft to 15 ft (thickness varying) of fill and sandy to silty sediments, aquitard - siltstone
Depth to groundwater: approximately 2 ft to 8 ft
Number of air injection points: 5 at 30 to 60 ft spacing
Number of vapor extraction points: 1, plus 1 at 100 ft distance
VOC contaminant: PCE, TCE, TCA
Initial groundwater concentration: PCE - 27,000 ppb, TCE - 4,300 ppb, TCA - 700 ppb
Effectiveness of VE/GA^{sm} System: Reduction to total VOC concentration of 1,207 ppb after 11 months of operation

Case History No. 4

Location: Munich, Bavaria
Soil conditions: 6 ft fill, 14 ft gravel, 6 ft fine grained sand, 9 ft gravelly sand, aquitard - clayey silt
Depth to groundwater: approximately 15 ft
Number of air injection points: 7 at 60 - 80 ft spacing
Number of vapor extraction points: 1
VOC contaminant: PCE, TCE, TCA
Initial groundwater concentration: PCE - 2,200 ppb, TCE - 400 ppb, TCA - 150 ppb
Effectiveness of VE/GA^{sm} System: Within 3 months, PCE - 622 ppb, TCE - 13 ppb, TCA - 3 ppb. After an additional month, PCE - 539 ppb, TCE - 12 ppb, TCA - 2 ppb

Case History No. 5

Location: Nordrhein-Westfalen
Soil conditions: 6 ft clayey silt, 30-45 ft sand (fine to medium grained), aquitard - siltstone
Depth to groundwater: 6 - 9 ft
Number of air injection points: 10
Number of vapor extraction points: 2
VOC contaminant: halogenated hydrocarbons

Initial groundwater concentration:	Sublocation A: between 1,500 and 4,500 ppb Sublocation B: (downgradient monitor well) between 10,000 and 12,000 ppb
Effectiveness of VE/GA[sm] System:	Reduction in Sublocation A: to 25 ppb within 1 month to 10 ppb within an additional 4 months; B: to 200 ppb within 6 months

Case History No. 6

Location: Nordrhein-Westfalen (Bergisches Land)
Soil conditions: Limestone, fractured
Depth to groundwater: 90 ft
Number of air injection points: 8
Number of vapor extraction points: 2
VOC contaminant: halogenated hydrocarbons
Initial groundwater concentration: 80,000 ppb
Effectiveness of VE/GA[sm] System: 2,500 ppb to 4,900 ppb after 6 months, 400 ppb after 15 months

Case History No. 7

Location: Pluderhausen, Baden-Wurttemberg
Soil conditions: 2 ft fill, 7 ft silts, 10 ft gravel, aquitard - clay
Depth to groundwater: approximately 11 ft
Number of air injection points: 5 at 10 - 15 ft spacing
Number of vapor extraction points: 1
VOC contaminant: trichloroethene (TCE)

Initial groundwater concentration:	20,000 ppb; reduced to 1,200 ppb after approximately 10 months of groundwater extraction and treatment
Effectiveness of VE/GA[sm] System:	Starting at 1,200 ppb, a 90% reduction (to 120 ppb) after 5 days of operation, and a further reduction to 23 ppm after an additional two months

SECTION 4
DESIGN CONSIDERATIONS

The design of air sparging systems depends on various elements, such as well configuration, blower capacity, compressor size, and vapor treatment systems. The proper placement of process equipment, gauging, and instrumentation are crucial to monitoring the process. Only then can adjustments ensure optimal effectiveness. Air sparging systems are diverse in terms of design and operational factors. These characteristics are discussed below.

INJECTION WELL CHARACTERISTICS

Installation of air injection wells usually employs conventional vertical drilling methods, although horizontal drilling techniques are gaining increased acceptance. Some contractors drill wells using a truck-mounted hollow-stem auger [Kresge and Dacey, 1991]; others install wells without, using hand augers [Billings and Associates, 1991]. At sites where the depth to groundwater is shallow and site conditions favorable, hand-held, gasoline-powered augers or pneumatic hammers can be used.

Wells typically utilize PVC, galvanized steel, or stainless steel casing and screen/s. Steel pipe is necessary when injected air will be heated to high temperatures. PVC (Schedule 40 or 80) for ambient air injection offers the advantage of lower cost. Two-inch diameter pipe can transmit the usual air flow rates.

Screen lengths vary, depending on the zone to be remediated, from 2 ft to 10 ft. A shorter screen allows greater control over the injection point, whereas a longer screen provides more air dispersion.

Contractors usually backfill screens with sand or gravel packing from 6 in to 2 ft above the screen. A bentonite seal above the screen is essential to prevent short-circuiting of the injection air. The remainder of the borehole annulus is then grouted to the surface. The bottom of the casing is plugged.

Spacing

The spacing of injection points is a key design parameter. Well spacing must be sufficient so that the sparging system affects the entire zone of contaminated aquifer. Locating the wells too tightly will add unnecessary cost. Too few wells may bypass some areas. In most cases, well spacing is determined by the results of pilot studies and site-specific conditions. Either the radius of influence for that site or professional judgment based on soil type, soil layering effects, depth to groundwater table, and contaminated saturated zone thickness, determine the spacing of the wells.

Radius of Influence

The radius of influence of an air sparging well describes the contaminated areas that the well can adequately remediate. The radius depends on several factors including the soil type, soil homogeneity, depth of injection below the water table, injection air pressure and flowrate, and groundwater flow rate. For example, the higher the soil permeability, the larger the radius of influence for either a sparging or vacuum well. The cases studied radii identified from five ft to 177 ft; typically it is less than 25 ft. In one sparging system, the radii of influence of the sparging wells were 72 ft, 76 ft, and 177 ft at injection pressures of 10 psi, 15 psi, and 20 psi, respectively [Brown et al., 1991]. This shows the effect of additional pressure on the measured radius of influence.

The literature studied did not describe the radius of influence for a horizontal injection well. However, it was indirectly measured by a helium tracer at the Savannah River Site. It has also been determined by monitoring levels of dissolved oxygen (DO) in groundwater. In one case, a three-fold increase in DO concentrations occurred in wells located in the vicinity of air injection wells; it documented an average radius of influence of 10 to 15 ft per injection well [Kresge and Darcy, 1991].

Air Injection

Using an injection well, a blower or compressor introduces air into the subsurface. The connection can be made to the top of the well casing (Middleton, 1991) or directly into the well using packers to seal off the area of injection. The choice of blower, compressor, or vacuum pump depends on the air flow rate and injection pressure desired. Injection at greater depths may require a rotary lobe unit rather than a regenerative blower. Values for injection pressure were rarely reported but ranged from 3 psi to 20 psi.

Air flow rates correspond to air injection pressures. Not all case studies report pressure values. Generally they described ranges from 2 to 16 cfm per injection point. Greater air flow rates could cause greater turbulence and mixing in the saturated zone, leading to increased volatilization.

Several sparging experts noted that the volume of extracted air should exceed the volume of injected air to maintain a margin of safety and to prevent subsurface pressure buildups. Wisconsin requires at least a 4:1 ratio of extracted air to injected air when the injection well is in a source area [Mickelson, 1991]. Another system maintained a volume ratio of 5:1 [Marley, 1990].

PROCESS LAYOUT AND EQUIPMENT

The first step in implementing an air sparging system consists of designing the well configuration and selecting the process equipment. Figure 3 shows the aboveground components of a typical system.

The major components of the air sparging system include the following:

- injection wells
- oil-free compressor
- vacuum blower
- air/water separator
- air emissions treatment
- piping and valves
- instrumentation

As Figure 3 illustrates, an air sparging system can operate with a single passage of ambient air, or with multiple passes of recycled extracted air. Recycling eliminates the need to discharge the extracted air.

The selection of blowers should take into account the site-specific type of operation. Treating flammable gases such as gasoline vapors may require the installation of non-sparking vacuum pumps. This requirement is overcome in many installations by locating the vapor treatment system, such as activated carbon adsorption, upstream of the vacuum pump. The air sparging blowers are not required to be of non-sparking construction.

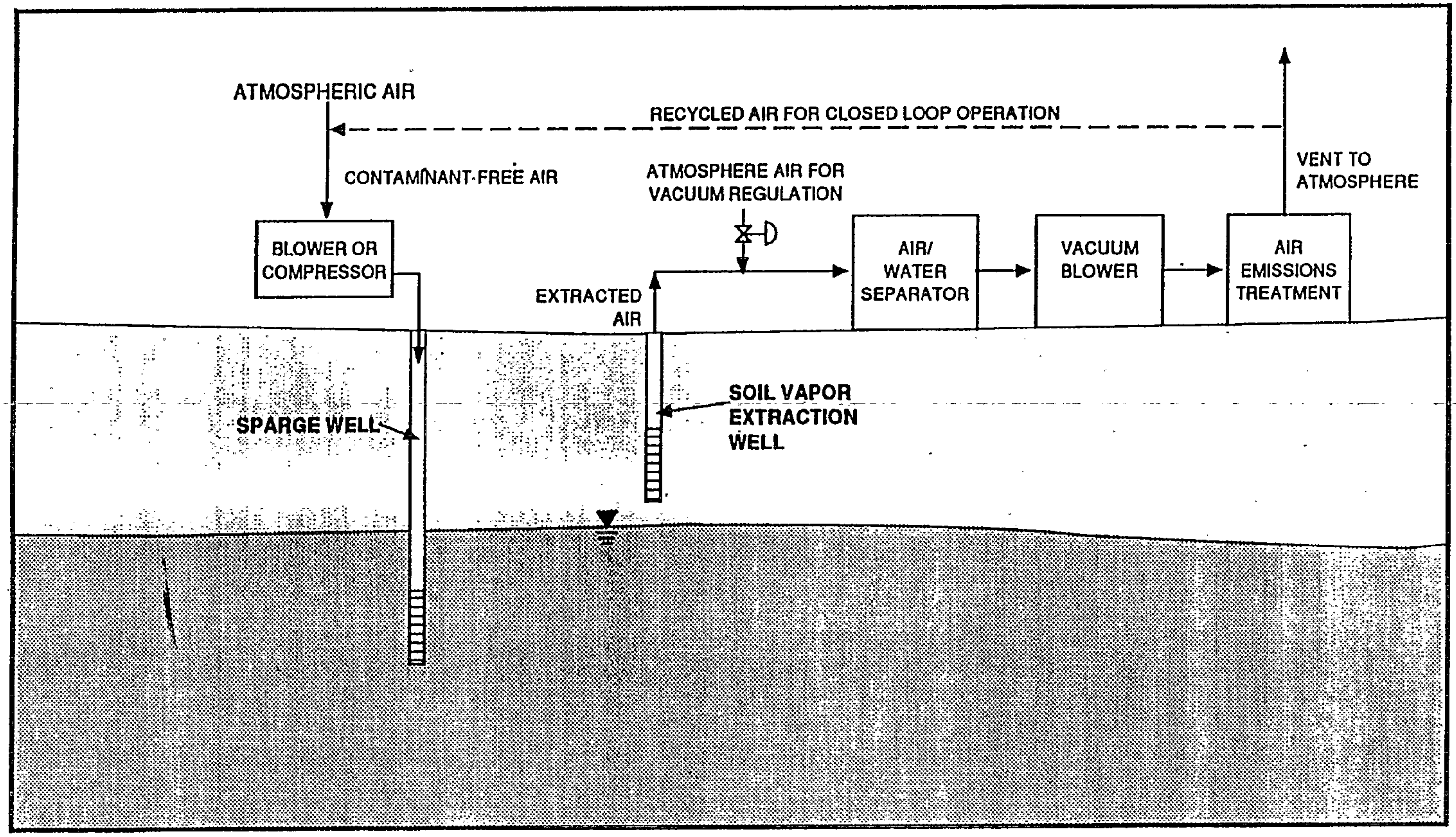

Figure 3. Air sparging process schematic.

Well Configuration

Perhaps the most important design element of an air sparging system is the configuration of the well system. Both well design and layout play important roles. The placement of air sparging and vapor extraction wells must take into account factors such as depth to groundwater, hydraulic conductivity, contaminant/s, and the extent of contamination. Various configurations, as shown in Figure 4, alter the design of air sparging systems. Each configuration can present its own unique advantages and disadvantages in conjunction with site-specific soil/aquifer characteristics and project objectives.

Vertical Well Configuration --

Based on their radius of influence, placement of vertical extraction and sparging wells throughout the site should cover the zone of contamination. Pilot tests, with two to four wells in a portion of the site provide the best means of determining the radius of influence.

Nested Wells --

Nested wells are extraction and sparging wells that are placed in the same borehole, thus saving drilling costs. However, proper grouting of the borehole to prevent short circuiting of air is very important. The primarily vertical pressure gradient is another difficulty presented by nested wells. It can lower the radius of influence per well in comparison with other well configurations.

Horizontal Wells --

Advancement in drilling techniques have made horizontal wells feasible for air sparging systems. This configuration is particularly effective at sites that present shallow aquifers and long, thin contaminant plumes, such as those caused by leaking pipelines. In some cases, horizontal wells may increase extraction efficiency over vertical wells by a factor of five [Looney, Kaback and Corey, 1991]. A horizontal well provides uniform pressure throughout the length of the well, and more surface area for sparging than a vertical well. Such wells can reach under buildings and into other hard to reach areas. Also, since less wells are required, they result in cost savings associated with piping, manifolds, and trenching.

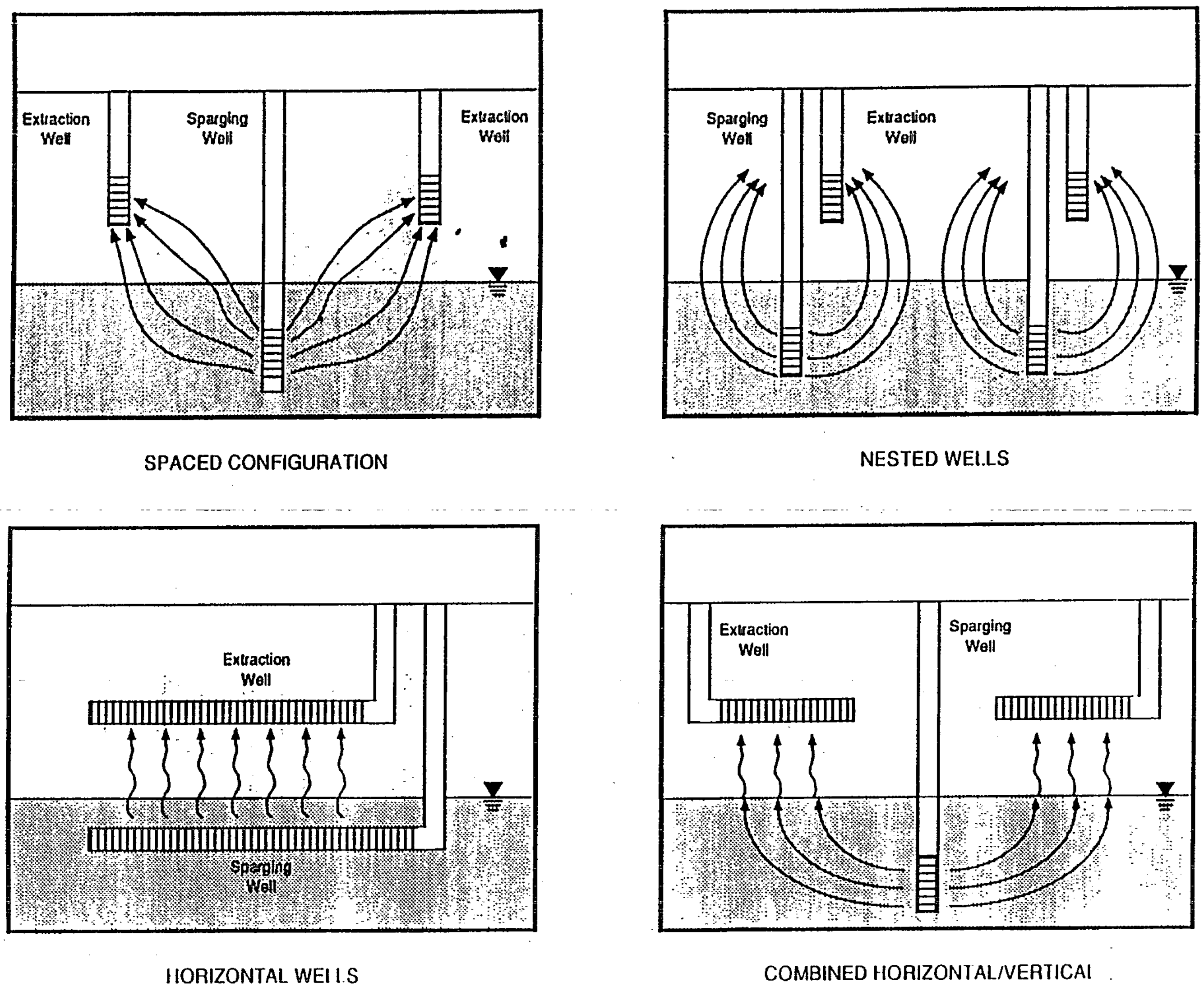

Figure 4. Air sparging well configurations.

Combined Horizontal/Vertical Wells --

Depending on site conditions, the combination of vertical and horizontal wells may be advantageous. Conditions such as depth to groundwater, soil permeability, and confining layers will determine whether a combination of horizontal and vertical wells would be the optimal configuration.

Well Radius of Influence

Soil permeability, among other factors, determines the radius of influence for sparging and extraction wells. The radius of influence, in turn, determines the well spacing and numbers needed for the site. The number affects not only the cost, but also the design of an air sparging system.

Air sparging experts have suggested several methods of determining the radius of influence for a sparging well. These methods study the following:

- pressure at various distances from sparging points
- dissolved oxygen concentration of the aquifer
- groundwater elevations in response to injection
- groundwater contaminant concentration isopleths

Pressure measurements provide the most common method for determining the radius of influence of a sparging well. Some experts state that pressure declines exponentially away from the injection well, and determining the radius can be accomplished by plotting the natural logarithm of the pressure versus distance [Brown et al., 1991]. Others measure dissolved oxygen concentrations in monitoring wells or at points throughout the expected zone of influence. This latter method requires measurements before and during system operation, but it may be a more relevant measurement of the sparging effect.

Well Installation

Sparging well construction should optimize the injection of air to the contaminated saturated soil and groundwater zone. The screen level should lie close to the water table in order to effectively capture the vapors sparged from the saturated zone. However, if the SVE screen is too close to the water table, the mechanical action will extract water, which will reduce system efficiency and require the use of an air/water separator to prevent blower damage.

Injection Depth Below Water Table

The air injection point e.g., the base of the aquifer or near the water table, depends on the location of the contaminants. For example, many chlorinated compounds in the DNAPL phase sink through the aquifer to a confining unit. Petroleum constituents (LNAPLs), on the other hand, may float on or near the water table. The density of the contaminants determines the location of the dissolved contaminant plume in the aquifer.

Ideally, the air should be injected just below the lowest level at which contaminants have been detected. This will ensure that the sparged air contacts all of the contaminant zone. Because injection pressure is a function of depth, excessively deep wells will require larger, more expensive blowers and vacuum pumps.

PROCESS MONITORING AND OPERATION

Proper operation and monitoring of the air sparging process are necessary to ensure that sparged volatiles are captured and that migration of groundwater contaminants is controlled. The following operating parameters should be monitored:

- sparging pressure
- vacuum pressure
- air flow rates
- radius of influence for both vacuum and sparging wells
- dissolved oxygen in groundwater
- contaminant concentration in extracted air
- continuity of blower and compressor operation

The air sparging process, coupled with SVE, enhances both mass transfer and biodegradation of subsurface contaminants. Depending on the mechanism desired and the type of contaminant present, the operating and monitoring procedures will differ. Regardless of the targeted mechanism, the design must minimize off-site migration of gases. It is necessary to discuss the steps used to prevent off-site migration, and specific monitoring requirements in terms of the mechanism they will enhance.

Mass Transfer Enhancement

Mass transfer systems are characterized by high-vacuum, high-flow wells operations. A high vacuum provides a large driving force that increases the removal of contaminants. Adequate pressure monitoring assures net-negative pressure in the subsurface during operations.

Heating the sparging air can enhance mass transfer. The higher air temperature raises the Henry's Law Constant, thus improving the stripping of contaminants from groundwater and increasing the volatilization rate of contaminants.

Biodegradation Enhancement

The key to enhancing biological activity is adequate oxygenation of the groundwater to maintain an optimal environment for microorganism growth. However, the addition of nutrients and supplemental carbon to the subsurface may also be necessary to maintain a healthy microorganism population.

In a successful biodegradation scenario, extracted, sparged gases have relatively low contaminant concentrations as compared to gases extracted from mass-transfer-enhanced systems. However, it is still important to maintain a net-negative subsurface pressure (with vapor extraction wells) to control contaminant migration. Extracted vapor treatment may still be required.

Monitoring this type of system is similar to that of any in situ biodegradation system. The dissolved oxygen level in the groundwater determines the effectiveness of oxygen mass transfer. A dissolved oxygen level of 3 ppm is a good indicator of process performance [Billings and Associates, 1991]. Hydrocarbon and carbon dioxide levels in the extracted air also monitor the biological process.

Contaminant Migration Minimization

An air sparging system must operate in a manner that will minimize further migration of contaminants. As previously mentioned, vapors could travel horizontally in the vadose zone and LNAPL plumes could extend due to mounding effects in the water table during sparging. Increased vapor migration could also result from the concentration of the contaminant exceeding the equilibrium concentration in the vadose zone. Untreated soil pores in the unsaturated zone contain air in equilibrium with the contaminated soil. The contaminant concentration in the untreated soil will register at a relatively high level. SVE replaces the saturated air with cleaner air, as shown in Figure 5; this causes an exponential decline in soil vapor concentration. If the sparging wells are started too soon, a surge of contaminated air from the saturated zone could cause the vapor concentration in the vadose zone to exceed the equilibrium concentration. Resulting concentration gradients could cause further contaminant migration.

To prevent vapor migration, an SVE system should be in operation prior to start-up of the sparging wells. Once the vapor concentration has leveled off, the sparging wells should then be activated. The injection of air will cause a new concentration peak, which will ultimately level off in an exponential manner, as shown in Figure 5. The plateau for contaminant concentration in the extracted air of a sparging/extraction system is regulated by various factors, such as the rates of dissolution and desorption of contaminants in the vadose zone, and the rate of dissolution, desorption, and volatilization of contaminants in the saturated zone. In addition, the rate of vapor migration in the saturated zone vapor phase will influence the concentration of extracted vapor. In order to fully capture the sparged vapors, the extracted air flow rate should exceed the injected air flow rate.

If properly coordinated, remedial activities at sites containing LNAPLs can minimize migration of the floating product by implementing a product recovery system prior to sparging, or hydraulically controlling the depression of the water table. This method, however, adds a need for posttreatment of the groundwater residuals, thus defeating the purpose of an in situ groundwater remediation program.

Adjusting the pressure at which the air sparging wells operate can minimize vapor migration. The minimum sparge pressure required to overcome water column is 1 psi for every 2.3 ft of hydraulic head [Brown and Fraxedas, 1991]. To transfer air into the saturated zone, well pressure must remain above this minimum. However, a pressure too high may move the vapor horizontally, rather than vertically toward the vadose zone. As shown in Figure 6, this can decrease vapor capture by the extraction system and inhibit treatment of some saturated zone areas by air sparging.

Process Operation

In most cases, the concentration of extracted vapors levels off after the sparging wells have been operating for a period of time. However, the high costs of treating extracted vapors create a need to extract less vapor volume at a higher concentration. This can be achieved by pulsing the vacuum and sparging

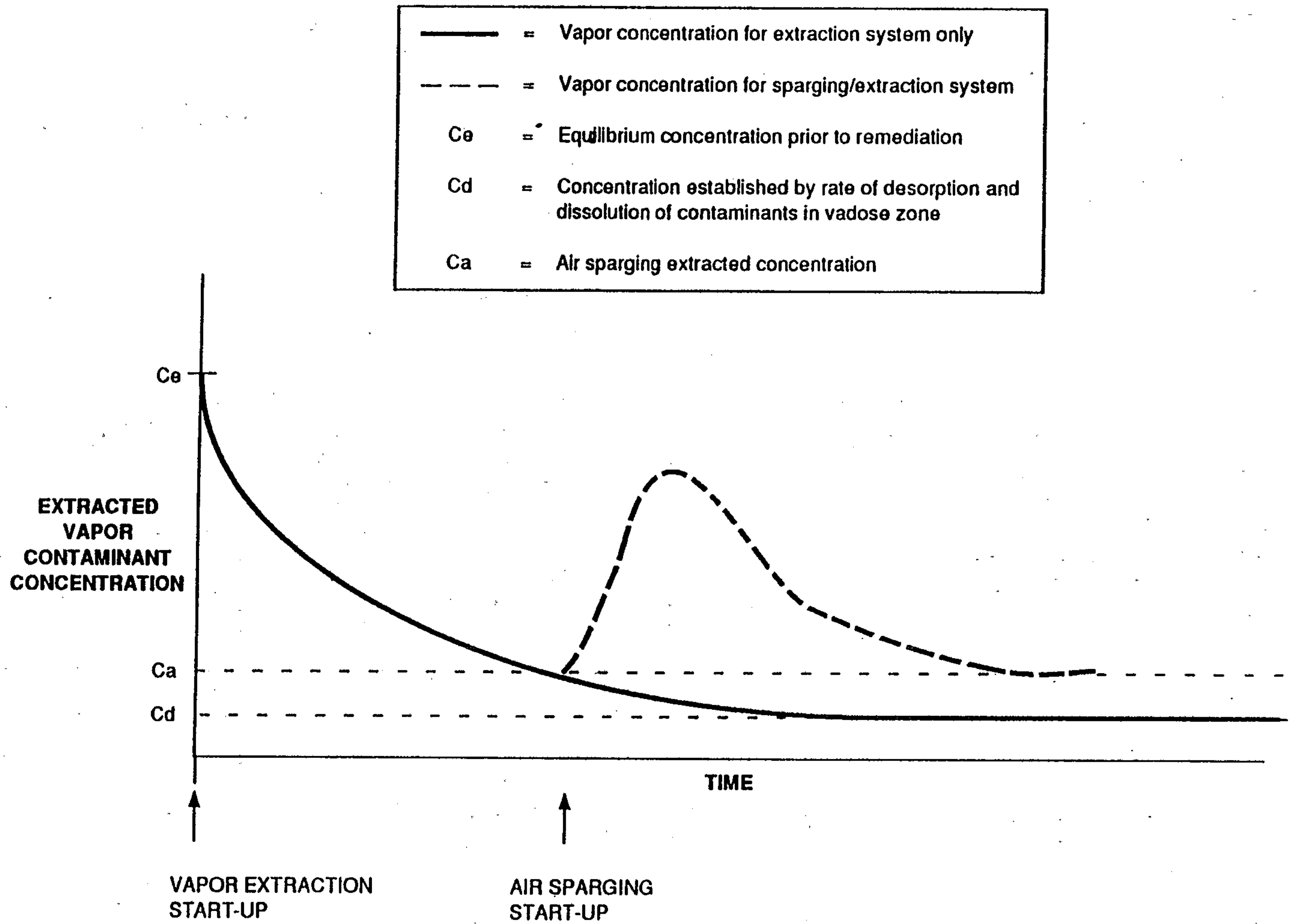

Figure 5. Extracted vapor concentration of air sparging system.

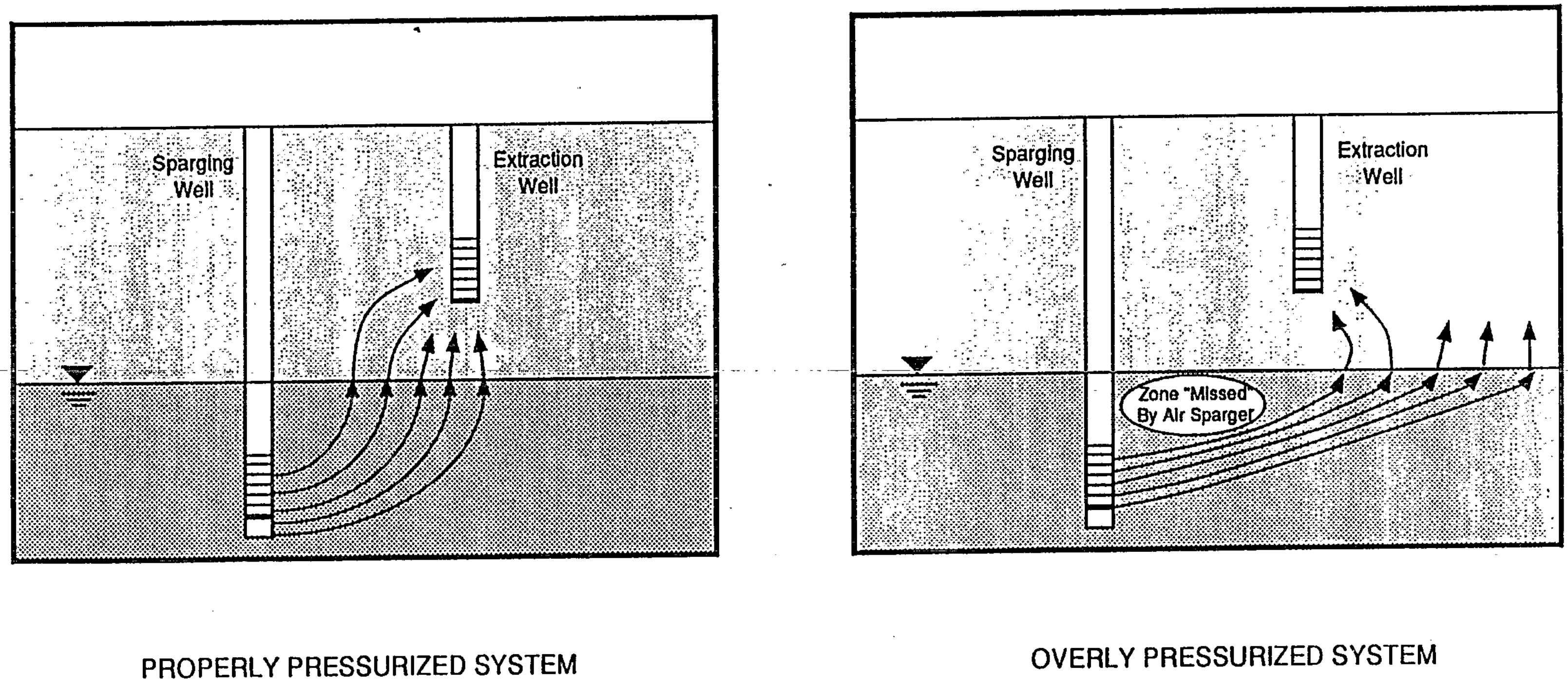

Figure 6. Effect of pressure on air sparging system.

wells. Shut-down time allows the soil, groundwater, and soil vapor to equilibrate, increasing the vapor concentration. The system can then restart (vapor extraction wells first, then sparging wells) to pull out the more highly concentrated soil vapor.

SECTION 5

AIR SPARGING SYSTEM COSTS

The published literature on air sparging technology includes little discussion on the costs of designing, building, and operating a system. However, equipment for air sparging technology is very similar to that used for soil vapor extraction, and hence, the costs are comparable. There are 3 major cost elements for an air sparging system: capital, operating, and monitoring costs.

CAPITAL COSTS

Capital costs for an air sparging system encompass design, engineering, permitting, contingencies, equipment procurement, installation, and instrumentation. Some components contribute significantly to the capital costs of a complete air sparging system:

- Wells (extraction, sparging, and monitoring wells) - installation, piping, and trench construction
- Mechanical equipment - blowers, compressors, and vacuum pumps
- Instrumentation - flow meters, pressure gauges, and analytical equipment for vapor testing
- Vapor treatment equipment - includes air/water separator, emissions control (usually activated carbon devices, or others such as incineration and catalytic oxidation), and water treatment systems

In addition to these major components, cost estimates for site remediation must also include funds for a thorough site investigation that is required prior to the remedial design.

Well Installation

Sparging and extraction wells, which are very similar in design, normally use schedule 40 PVC (polyvinyl chloride) piping in various diameters (2-in to 12-in). Polypropylene (PP) or chlorinated polyvinyl chloride (CPVC) pipes are more rigid; they provide an alternative where stronger piping is required. A typical 30-ft well installation will cost from $2,000 to $4,000. Of this cost, materials such as casing (riser), well screen, plugs, filter pack materials, bentonite, and cement grout may total from $500 to $2,000 per well, depending on the method of construction. Table 4 shows the range of costs for various sparging and extraction well components. PVC piping, for example, costs as little as $2 per linear ft with a 2-in diameter casing up to $12 with a 6-in casing. Similarly, PVC screens cost from $2 to $15 per linear ft, depending on diameter. Ball valves (PVC) cost from $60 for a 2-in riser to $300 for a 6-in riser.

Well configuration can achieve savings or add costs to the items described above. For example, nested wells can cut drilling costs by placing both sparging and extraction wells in the same hole. Horizontal wells cost several times more than vertical wells, but may increase the VOC extraction efficiency by a factor of five [Looney, Kaback, and Corey, 1991].

System piping can lie aboveground, or buried in trenches. Aboveground piping can realize savings if the site is inactive and if barriers to access are acceptable. However, water carried in aboveground piping may freeze during winter operation, causing operational problems and pipe damage. Pipe freezing problems may be overcome by applying heat tracing and insulation. This adds a significant cost to the piping installation. Installation costs will also increase significantly if the piping is buried in trenches.

Mechanical Equipment

Air is sparged into the subsurface saturated zone by mechanical compression equipment. Vacuum pumps extract the sparged air in addition to the induced air flow that they produce through the vadose zone. The type of mechanical compression equipment used is a function of the flow rate and pressure required. An important feature of the equipment employed is that the air injected by the machine be oil-free.

Some of the types of compression equipment that may be employed with the air sparging technology include:

- oil-free rotary screw machines
- centrifugal blowers
- regenerative and rotary lobe blowers
- reciprocating compressors

Single-stage oil-free rotary screw compressors are commercially available with flow capacities as low as 420 scfm, capable of achieving a discharge pressure of 50 psig (Table 4). Rotary lobe machines have a wide application in soil remediation both as air injection compressors and as vacuum pumps. The rotary lobe air compressors listed in Table 4 are single-stage units with a discharge pressure of 18 psig. The rotary lobe vacuum pumps are capable of achieving vacuums of 15" Hg absolute for the flow rates listed. Regenerative blowers are available and are used as air injection machines for very low pressure applications (5 psig), as well as in vacuum blower applications.

Centrifugal blowers and reciprocating compressors are limited in their application. The practical lower limit of capacity for centrifugal blowers in air injection service is approximately 8000 scfm. Reciprocating compressors would only be employed if pressures higher than 50 psig were required. The reciprocating machine becomes prohibitively expensive at lower pressures since the cylinders must be non-lubricated in order to supply the oil-free air required for injection.

Instrumentation and Monitoring

Instruments for monitoring of the process and the extracted vapor stream are vital to air sparging design and operation. Monitoring equipment should measure the vacuum air flow, vapor characteristics, and contaminant concentrations.

Vacuum can be measured with a magnehelic gauge. These gauges are typically located at each extraction well and upstream of the blower. The cost for each magnehelic gauge can range from $50 to $75. A quick-coupling sampling port may substitute for gauges at each well. Air flow, expressed in standard cubic feet per minute (scfm) to normalize flow readings taken at different pressures, can be measured in-line by an annubar flow meter or at flow ports using portable equipment. Air flow should be measured at each well and upstream of the blower. Annubar flow meters cost about $300. Quick-coupling sampling ports with two or three connections are available for $25.

Monitoring of the composition and concentrations of the extracted vapors is critical in determining vapor treatment alternatives and operating procedures. An organic vapor analyzer (OVA), a total hydrocarbon analyzer (THA) or a combustible gas indicator (CGI) can determine the quantitative vapor concentration of VOCs. A gas chromatograph (GC) can identify vapor components and concentrations.

TABLE 4.
SVE AND AIR SPARGING SYSTEM COMPONENTS CAPITAL COSTS

Component	Type	Size	Capital costs ($)	Notes
Extraction well construction			12-15/ft	Matthews Manufacturing
Casing	PVC	2 in 4 in 6 in	2-3/ft 3-5/ft 7-12/ft	SCH. 40 PVC
Screen	PVC	2 in 4 in 6 in	2-4/ft 5-7/ft 10-15/ft	Matthews Manufacturing SCH. 40 PVC Any slot size
Sand pack Gravel pack			15-20/cu ft 0.74/cu ft	
Piping	PP	2 in 4 in 6 in	2.10/ft 5.60/ft 10.00/ft	
	PVC	2 in 4 in 6 in	0.4/ft 1.10/ft 2/ft	SCH. 40 PVC
	CPVC	2 in 4 in 6 in	2.50/ft 6.70/ft 12/ft	SCH. 80 PVC
Valves (ball)	PVC Single union	2 in 4 in 6 in	65 300 700	Vendor - M&T Plastics SCH. 40 PVC, 2 in & 4 in threaded socket, 6 in flange and connection
Joints (elbow)	PVC 90 degrees - slip	2 in 4 in 6 in	3 16 51	M&T Plastics, SCH. 40 PVC, threaded, socket end connections
Surface seals	Bentonite 6 in Bentonite 4 in Polyethylene 10 mil HDPE 40 mil asphalt 2 in		0.37/sq ft 0.25/sq ft 0.25/sq ft 0.56/sq ft 1.03/sq ft	
Air compressor	Single stage Rotary screw	450 scfm (75 HP) 1120 scfm (200 HP) 2000 scfm (350 HP)	60000 80000 90000	Vendor - Atlas Copco
	Rotary lobe	100 scfm (15 HP) 450 scfm (75 HP) 1000 scfm (125 HP) 2000 scfm (250 HP)	3000 10000 30000 33000	Vendor - Roots Dresser
Vacuum pump	Rotary lobe	100 scfm (5 HP) 450 scfm (25 HP) 1000 scfm (50 HP) 2000 scfm (125 HP)	3000 6500 9500 20000	Vendor - Roots Dresser

TABLE 4. (Continued)

Component	Type	Size	Capital costs ($)	Notes
Air/water separator		20 to 800 gal	1,500-2,400	
	Knockout pots	800 gal 20 gal 35 gal 65 gal 105 gal 130 gal	11,600 1,470 1,560 1,750 2,150 2,350	Vendor - Water Resources Assoc., installation 33% of capital costs
Instrumentation Vacuum gauge (magnehelic) Flow (annubar)			 50-75 300	
Sampling port	Brass T		20-30	
Concrete pad			$450/yd^3$	
Flame arrestor	w/o SS element w/SS element		665 735-930	Vendor - Stafford Tech.
Air relief valve			225	Vendor - Stafford Tech.
Soil gas probe			30-50	Vendor - K.V. Assoc.
Engineering/design			8-15% of system cost	
Diffuser stacks	Carbon steel	4 in 6 in	8/ft 10/ft	Add 40% for installation
	Stainless steel	4 in 6 in	30/ft 40/ft	

Analysis of the vapor CO_2 concentration can track the subsurface biological activity. Monitoring of the vapor composition usually occurs between the demister (or knockout pot) and the blower. In carbon adsorption systems, monitoring may also check the exhaust from the carbon bed.

Vapor Treatment

Air/Water Separator –

Air/water separators ("knockout pots") decrease the velocity of the vapor stream and allow the gravity fallout of water droplets and sediment. They can be very simple (e.g., a 55-gallon drum) or may be sophisticated in terms of level controls and other instrumentation. The size depends on the flow rate (to reach a minimum residence time), ranging from 800 to 1,200 gal. Construction materials vary, including cast iron, stainless steel, or similar material. Demisters are often incorporated into the vapor pretreatment process. These screens remove particles down to microns in size by coalescing droplets on the demister material.

Duvall Industries, Inc. manufactures a variable-sized demister ranging in cost from $700 to $1,000 for flow volumes of 100 to 1,000 scfm. Water Resources Associates, Inc. manufactures knockout pots for use with their incineration/SVE systems. The cost for knockout pots may range from $1,500 to $2,500, according to size and flow rate capabilities.

Liquids that accumulate in the air/water separator must be treated on-site, disposed off-site (according to regulations, possibly to a sewer line), or removed by truck. On-site water treatment can employ liquid phase granular activated carbon (GAC). Small, easily installed carbon units are appropriate for the small flows expected from vapor pretreatment units.

Emissions Control –

Vapors removed from the subsurface normally require treatment prior to release to the atmosphere, depending on local regulations. Several options are available: carbon adsorption, catalytic oxidation, thermal incineration, combination systems, and internal combustion engines. Where vapor treatment is not required, diffuser stacks can provide safe emission of the extracted vapors. Vapor phase concentration will determine which options are appropriate.

Vapor treatment can comprise a significant portion of the total air sparging system cost. Care must be taken to ensure that the most cost-effective option is used, based on the vapor discharge standards, the extracted vapor concentration, the expected mass removal over the life of the system, and several other variables. The operating costs for vapor treatment may dominate the system cost, especially for GAC systems. For this reason, the forecast of expected removal rate becomes even more important.

Carbon Adsorption –

Carbon adsorption is widely used for vapor treatment in industrial and air sparging settings. It applies to a variety of vapor contaminants and can achieve very high removal rates. Carbon is only economical for relatively low mass removal rates; high mass removal rates make the cost of replacing/ regenerating the carbon prohibitive. In addition, the heat of adsorption may present an explosion hazard in the treatment of combustible VOCs.

Numerous vendors offer carbon adsorption systems in a large variety of sizes. Table 5 shows a partial list of these vendors and their respective products. These systems range from very small systems (55-gallon drums holding less than 200 lbs) through larger, skid-mounted systems (up to 5,700 lbs). For very large installations, vendors can customize carbon to the specific requirements of the site. Carbitrol offers G-1,G-2, G-3, and G-5 canisters that are rated for various air flows. These drum systems contain 200, 170, 140, and 2,000 lbs of activated carbon, respectively. The G-1 system, rated at 100 scfm, costs $695; the G-2 (300 scfm), $985; and the G-3 (500 scfm), $985. The G-5 system which is rated for 600 scfm is available with a 304 stainless steel (SS) vessel for $11,000 or an epoxy-lined carbon steel vessel for $7,700. TIGG Corporation offers the Nixtox Series N500 DB, N750 DB, and N1500 DB (deep bed) systems that contain 1,900, 3,200, and 5,700 lbs of virgin carbon, respectively. Calgon Carbon Corporation also offers a large variety of carbon adsorbers. The Ventsorb canister can handle average flows up to 100 cfm or high flows from 400 to 11,000 cfm. The high-flow model is available skid-mounted with a fan, flexible connectors, and a damper. The canisters range in price from $760 to $6,330; the skid-mounted models cost from $5,400 to $10,700.

The carbon may be virgin or reactivated. Purchase of reactivated carbon usually saves three to thirteen percent off the price of virgin carbon. For example, the virgin G-1 (200 lb) canisters offered by Carbitrol sell for $660; a reactivated canister sells for $640. Larger containers are usually charged on a weight basis. Environtrol reactivated carbon sells for $1.15 per lb plus transportation costs. A one-time RCRA Toxic Characteristics Leaching Procedure (TCLP) test is required ($2,800 to $3,000) for hazardous materials.

TABLE 5. VAPOR TREATMENT COSTS*

Treatment	Vendors	Model	Maximum flow (scfm)	Capital costs ($)	Rental $/mo	Lease period (mo)	Operation	Equipment included	Notes
Carbon adsorption	Carbtrol	SVX	105	18,400	1,540	12 + deposit	hp x kw/hr	A skid mounted system including a blower, demister, controls, gauges, valves, and flow ammeter	Uses G-1 or G-5 carbon
			250	21,900	1,830	12 + deposit			
			500	30,000	1,900	12 + deposit			
	Continental Recovery Systems	Manual beds							
		1 bed		20,000	2,400		5 hp	Includes controls, blowers, and steam regenerator	
		2 beds		26,000	2,900				
		3 beds		32,000	3,325				
		4 beds		38,000	3,650				
		5 beds		44,000	3,875				
		6 beds		50,000	4,000				
		Automatic regenerable beds		149,000	7,500	6		Fully remote monitored trailer	
	Calgon	High flow Ventsorb							
		28 in dia	400	5,400			0.5 hp	Skid-mounted system includes fan, flexible connector, and damper	
		36 in dia	600	8,550			3 hp		
		48 in dia	1,100	11,000			5 hp		
Catalytic oxidation	Dedert Corp.	Catox	1,000	85,000			Fuel	Skid-mounted system includes reactor, blower, heat exchanger, boiler, and water heater	
			5,000	200,000					
	CSM	Model 2B Torvex	200	37,500				Skid-mounted system includes burner, catalyst, control panel, and blower	Treats chlorinated solvents, air dilution system - $20,000, trailer - $8,500
		Model 5A + heat ex.	500	60,000					
		Model 5B Torvex	500	50,000					
		Model 10B Torvex	1,000	70,000					
	ORS	Catalytic Scavenger							
		1282001	200	63,000	6,600/11,584	12/6	20 kw	Skid-mounted includes installation, heater, control module, heat exchanger, and catalyst	No chlorinated solvents, catalyst replacement - $2,800
		1282002	500	78,000			35 kw		

TABLE 5. (Continued)

Treatment	Vendors	Model	Maximum flow (scfm)	Capital costs ($)	Rental $/mo	Lease period (mo)	Operation	Equipment included	Notes
		1282008	300	90,000	15,000 9,900/17,377	1 12/6	20 kw	Additionally includes (2) 5 hp blowers, (2) catalysts, piping, filters, gauges, valves, flame arrestor, enclosure, and trailer	
	Water Resources Associates	AB15-5-SVS AB19-10-SVS AB22-10-SVS AB24-10-SVS AB22-15-SVS	100 210 320 420 570	11,200 15,300 18,400 20,100 22,900					No warranty or process efficiency is extended when flow rates are in excess of design capabilities of not more than 12,000 ppm total hydrocarbons
		AB15-5-SVS AB19-10-SVS AB22-10-SVS AB24-10-SVS AB22-15-SVS	100 210 320 420 570	23,000 28,000 32,000 36,000 40,000	3,850 4,675 5,350 6,000 6,675		Fuel 1.5 hp	Includes burner, blower, flame arrestor, gauges, valves, filters, knockout pot, and sampling port, skid-mounted w/enclosure, fence, and control panel	
Carbon Cannisters	Carbtrol	G-Series cannisters							Carbon can be reactivated at 3-13% discount from original purchase price
		G-1 200 lb	100	650					
		G-2 170 lb	300						
		G-3 140 lb	500						
		G-5 2,000 lb	600	11,000					
		1,800 lb	1,000	5,600					
		Ventsorb Cannister	100	764					
		Highflow Ventsorb cannister 28 in	400	1,700					
		36 in	600	4,000					
		48 in	1,100	6,400					
	TIGG	Nixtox Series							Deep bed units
		N500DB	500	7,050					
		N750DB	750	11,850					
		N1500DB	1,500	19,150					
		BOXSORBER 6x6	2,200	13,750					
		BOXSORBER 8x8	4,000	20,500					

* 1989 Estimates. Contact vendor for actual prices.

A recycling carbon system is an alternative to the replacement of canisters and off-site reactivation. Such systems regenerate the carbon in place, usually using steam to desorb the contaminants. The contaminant/steam mixture is then drawn off and treated or sent for proper disposal. Continental Recovery System Inc. offers this type of system; it comes in several sizes, using from one to six carbon beds.

Manually-operated systems cost from $20,000 (one bed) to $50,000 (six beds). A fully automated, remotely-monitored, trailer-mounted system sells for $150,000 or leases for $7,400 per month on a 6-month lease. The cost effectiveness of the system depends on the mass removal rate. The system initially costs more than non-regenerative systems, but reduced carbon usage may make it a cheaper option on a long-term basis.

Use of carbon for vapor treatment may develop a need for a heat exchanging unit to cool extracted vapors heated by compression from the blower. This treatment will ensure maximum contaminant uptake. Alternatively, GAC can be placed upstream of the blower in a treatment train.

Incineration –

Incineration of contaminant vapors offers an excellent treatment option for high vapor concentrations. At temperatures of 1,000 to 1,400°F or higher, vapor combustion destroys over 95 percent of the contaminant concentration.

Fuel supplements may be required to maintain the requisite temperatures for adequate removal. The amount of supplementary fuel depends on the vapor concentration. Some vendors report that, at gasoline concentrations above 12,000 ppm, the flame is self-sustaining; at concentrations below this figure, greater amounts of fuel are needed in proportion to the contaminant. The operating cost of an incineration system is greatly affected by the need for supplementary fuel. Propane, which costs about $1.00 per gal, is often used for this purpose.

While higher contaminant concentrations make this method cheaper, safety concerns increase with higher concentrations. Highly volatile contaminants (such as gasoline) become explosive in certain concentrations. This range is limited by the lower explosive limit (LEL) and the upper explosive limit (UEL). Fresh air must be mixed with the extracted vapors at very high concentrations to reduce the concentration to a safe level.

Table 5 shows the cost for various incineration units. These prepackaged units include the burner, blowers, sampling valves, and other appurtenances. Capital costs depend on the flow rate to be treated; they range from $23,000 (for 100 scfm) to $40,000 (570 scfm) from one vendor. A smaller unit (70 scfm) costs $12,000. A heat recovery system, which uses the exhaust to preheat the incoming vapors, can realize a substantial energy and cost savings.

Catalytic Oxidation –

Catalytic oxidation systems employ a catalyst to facilitate the oxidation of the contaminants. Thus, they operate at much lower temperatures (600 to 800°F) than direct incineration while achieving destruction and removal efficiencies (DREs) above 85 percent. The catalyst is a precious metal formulation (typically platinum or palladium), which can exist either in the form of beads or a honeycomb bed.

Although most commonly applied to petroleum contamination, special catalysts enable catalytic oxidation to treat chlorinated contaminant vapors. However, hydrochloric acid, formed during the oxidation, requires additional treatment processes (scrubbers, neutralization, etc.).

Catalytic oxidation requires careful monitoring to prevent overheating and destruction of the catalyst. If the concentration of vapors in the extracted air exceeds 3,000 ppm, the vapor stream must be diluted with fresh air to remain below the cutoff level. At lower concentrations, supplemental fuel (propane) may be needed to maintain the required temperatures. Safety is also a concern for catalytic oxidation. This method is best suited for concentrations below ten percent of the LEL.

Available catalytic oxidation units can handle flows from 30 scfm to more than 50,000 scfm. Hasstech offers a trailer-mounted unit (MCC-2) that can handle 30 to 40 scfm. ORS offers the Catalytic Scavenger in a 20 kw model (200 scfm) and 35 kw model (500 scfm) that sell for $60,000 and $75,000, respectively. Installation and training will cost $3,000 for these units. CSM Systems, Inc. produces the Torvex series Model 5A, 5B (500 scfm) and Model 10B (1,000 scfm) that sell for $50,000 and $70,000, respectively. A trailer ($8,500) and ADS dilution system ($20,000) are available for these models. Larger catalytic oxidation systems are also available from CSM and Dedert Corporation. Dedert sells field- ready units, rated at 5,000 scfm, for $200,000.

Diffuser Stacks --

Diffuser stacks, constructed of either carbon steel or stainless steel, merely direct vapors into the atmosphere. This system is simple and inexpensive, but only an option where treatment of the vapors is not required. The design of diffuser stacks should minimize health risks. Costs depend on the height required and the material of construction.

Other Costs

Implementation of an air sparging system will entail other costs that are neither strictly capital costs or O&M costs. These include system design, engineering, permit acquisition, contingencies and other miscellaneous costs. These costs are often treated as capital costs. Engineering and design fees often comprise 10 to 15 percent of the system cost, as do contingencies. These and other costs are highly site-specific, however, the figures quoted here are arbitrary.

OPERATION AND MONITORING COSTS

Operation and monitoring costs, depending on the duration of system operation, may comprise a significant portion of the overall air sparging remediation cost. These costs arise mainly from power for the blowers; vapor treatment, including fuel costs for incineration methods and GAC regeneration/replacement; monitoring and analyses for progress and cleanup attainment determination; and other on-going costs such as labor. Labor costs depend on whether the system is operated manually or by a microprocessor. These costs are discussed later.

Power Requirements

The cost of electric power depends on the power rating of the fan/s or blower/s, the hours of operation, and the local cost of electricity. The following formula determines the cost:

(0.75) x (fan horsepower) x (electricity cost in $/kw-hr) x (hours of operation)

For example, a 10-hp blower operated continuously would use electricity at $0.10/kw-hr. The daily cost for power would be 10 x 0.75 x $0.10 x 24 = $18.00 per day. Pulsed operation -- operating the blowers intermittently -- would save power costs by decreasing the hours of operation. Power may also be required for heat exchangers.

Vapor Treatment

The operating cost for vapor treatment depends on the method used, the concentration of contaminants, and the flow rate. Generally, GAC adsorption costs increase, while the cost for incineration and oxidation decreases with higher vapor concentrations. GAC treatment costs will be dominated by carbon replacement and regeneration; incineration and oxidation treatment will be dominated by fuel costs to sustain incineration.

Carbon Adsorption --

Adsorption of contaminants from the vapor phase concentrates the contaminants onto the carbon. When the carbon's capacity to hold contaminants has been exceeded, the carbon is considered "spent" and must be replaced or regenerated. Obviously, higher mass removal rates (flow rate x concentration) will result in more frequent carbon replacement and higher costs.

Carbon costs vary according to the type and quantity ordered. They may range up to $2.00/lb. Regenerated carbon costs 87 to 97 percent of virgin carbon cost. One vendor quoted $1.15/lb for large orders. Table 5 shows costs for virgin carbon units. One rule of thumb states that carbon costs about $20/lb ($130/gal) of gasoline removed [Hinchee et al., 1987].

Where carbon is used and mass removal rates are high, on-site regeneration may become economical. Continental Recovery Systems offers a unit that uses steam to regenerate carbon in place. Other vendors offer units that regenerate the carbon and then incinerate the contaminants. These combination units are initially more costly, but save on O&M costs. The determination of the most cost-effective option is site-specific; the pilot system results normally make the determination.

Incineration --

Incineration requires supplementary fuel (typically propane or LPG) for vapor concentrations below 12,000 ppm. This fuel costs about $1.00 per gallon. When the BTU value of the vapor feed cannot sustain the required temperature (about 1,400 to 1,600°F), fuel supplements must maintain proper temperatures.

Catalytic Oxidation --

This method requires much lower temperatures (600 to 800°F) than incineration; and, it is therefore less costly to operate. Optimal vapor phase concentration for catalytic oxidation is about 3,000 ppm. Higher concentrations require dilution (to protect the catalyst from destruction), while lower concentrations may require supplemental fuel. ORS quotes the cost of a 200 scfm Catalytic Scavenger at about $800/mo to operate with no incoming hydrocarbons (i.e., just air). As the hydrocarbon concentration increases, the supplemental fuel requirements decrease.

SYSTEM MONITORING

For air sparging to gain wide acceptance with regulatory agency personnel, consultants, and site owners, methods to confirm the system's success are required. Monitoring ensures that the air sparging system does not move contaminants away from the treatment zone, especially off-site. Several techniques have been used for these purposes.

The simplest method to assess effectiveness of an air sparging system, used by virtually all proponents identified in this project, monitors the extracted vapor stream for VOCs, O_2/CO_2, or other contaminants of concern. Another method analyzes and monitors dissolved oxygen (DO) in groundwater throughout the treatment zone. Groundwater concentrations in monitoring wells are measured before, during, and after air sparging to determine the actual effect on in situ contaminant levels, which are usually how the regulated endpoints are expressed (concentration of BTEX, TPH, or other parameter remaining in groundwater or soil). Downgradient wells can check whether the system is mobilizing contaminants. In most published case studies, both monitoring techniques, vapor sampling and groundwater sampling, have been used.

Monitoring and Analyses

Laboratory sampling for soil, groundwater, and vapor contaminant concentrations is relatively costly, but necessary to assess the effectiveness of the remediation. A comprehensive sampling and analytical plan using recognized and accepted methodologies is very important. Soil sample analyses will generally cost $150 for total petroleum hydrocarbons (TPH), $250 for volatile organic contaminants (VOCs), $100 for benzene, toluene, ethyl benzene, and xylenes (BTEX), $450 for acid/base neutral extractable compounds (ABNs), and $70 for routine soil parameters, which include organic carbon and particle size distribution.

Analyses for groundwater sampling cost $125 (TPH), $225 (VOCs), $100 (BTEX), $425 (ABNs), and $50 for general groundwater quality parameters, respectively. Soil gas analysis using a GC determines total hydrocarbons and other specific contaminants; it may cost as much as $250 at a laboratory.

Biological assay tests can monitor biological activity in the soil. Dissolved oxygen in groundwater should be measured on-site with a D.O. probe, which costs about $1,000.

CONCEPTUAL ESTIMATE FOR AN SVE AND AIR SPARGING INSTALLATION

Following is a conceptual estimate for a leaking underground storage tank site remediation using the air sparging technology. The site is contaminated in both the saturated and unsaturated zones by gasoline. The equipment that will be included for site remediation will be sufficient to act on a total of up to 10,000 cubic yards of contaminated soil. The depth to the water table is assumed to be 60 feet.

The capital costs are based on a configuration that includes two (2) vapor extraction wells, one (1) air injection well, and four (4) groundwater monitoring wells. The system also consists of a 25 HP rotary lobe vacuum pump, a 15 HP rotary lobe air injection compressor, two (2) air/water separators, a collection header and various piping connections. An off-gas emissions control system will be required to capture the BTEX hydrocarbon compounds. This will consist of canisters filled with granular activated carbon adsorbent. The size of the site dictates that on-site regeneration of the carbon will not be practical. The cost of carbon will be based on regeneration or reactivation off-site. The canisters containing the carbon will be rented from the supplier, so that the costs for the emissions control system will appear as an operations and maintenance cost.

Table 6 contains the equipment specifications required for the site remediation, Table 7 outlines the capital costs of the equipment items, and Table 8 contains a summary of the annual operating and maintenance costs.

TABLE 6. EQUIPMENT SPECIFICATIONS

A. Vacuum Blower	
Size	25 HP
Rating	500 scfm @ 10" Hg vac
Electrical	440 V, 3 phase
Compression ratio	1.52
Type	Straight lobe rotary (positive displacement), constant volume - variable discharge pressure
B. Air Compressor	
Size	15 HP
Rating	160 scfm, disch. press. 15 psig
Electrical	440 V, 3 phase
Type	Rotary lobe, positive displacement V-belt dirve with inlet filter, inlet silencer and discharge silencer
C. Air/Water Separators	
Size	800 gallons
Type	Stainless steel
Accessories	Sight glass 2-4" NPT connections (top) 1-4" NPT connection (bottom sealed to atmosphere)
D. Piping Network	
Type	4" PVC
Length	500 ft
Elbows	20
Caps	5
Valves (2")	6
Reducers	10
Type	2" PVC
Length	70 ft
E. Vacuum Well Construction	
Type	Rotary auger
No. of wells; Screen	Depth
3 10'	20'
3 15'	60' (to water table)
Hole size	6"
Casing	4"
F. Air Sparging Well Construction	
Type	Rotary auger
No. of wells	One
Depth	60'
Hole size	6"
Casing size	4"
Air line	2" PVC, well complete with bottom cap, bentonite seal and inflatable packer
G. Valve Boxes (4)	
Type	Below grade/cast iron construction
Size	2' x 2' x 1'
Additional features	Gravel packed bottom
H. Trench Construction	
Type	Cut and cover
Depth	1 foot below grade
Layout	4" PVC pipe
Length	50 feet
Cover	Concrete

TABLE 7. CAPITAL COSTS

Item/description	Install/labor cost ($)	Equip./matl. cost ($)	Total cost ($)
1. WELLS			
Air sparging well	2,000	1,000	3,000
Extraction wells	4,000	1,600	5,600
Monitoring wells	3,000	1,900	4,900
Valve boxes	1,500	1,000	2,500
SUBTOTAL	$10,500	$5,500	$16,000
2. EQUIPMENT			
Air compressor	1,500	3,000	4,500
Vacuum blower	2,500	9,500	12,000
Separators	11,600	23,200	34,800
Blower housing	2,500	5,000	7,500
SUBTOTAL	$18,100	$41,700	$59,800
3. MECHANICAL/PIPING			
Wellhead pits (4)	2,000	1,200	3,200
Well pipe & fittings	3,000	1,500	4,500
Pipe	5,500	4,000	9,500
Valves & fittings	1,500	2,100	3,600
Testing	500	500	1,000
SUBTOTAL	$12,800	$14,700	$27,500
4. ELECTRICAL/INSTRUMENTS			
Elec. & instr. - wells	1,000	1,500	2,500
Elec. & instr. - equip.	2,500	3,000	5,500
Elec. distribution	2,000	4,000	6,000
Main control panel	1,000	2,000	3,000
SUBTOTAL	$6,500	$10,500	$17,000
TOTAL	$47,900	$72,400	$120,300

TABLE 8. OPERATION AND MAINTENANCE COSTS

	Annual costs
Power	8,000
Off-gas emissions control[1]	120,000
Maintenance	5,000
Monitoring[2]	34,000
Labor	15,000
Contingency	10,000
TOTAL	$192,000

[1] Assumes an average usage of 2,000 lb per month of granular activated carbon. The price includes transportation and off-site regeneration.

[2] Assumes twice a month evaluation of extraction well concentrations with a portable GC.

SECTION 6
RESEARCH NEEDS

Air sparging, in combination with soil vapor extraction, promises to be a cost-effective, relatively simple technology for remediation of volatile organic contaminants in the saturated zone. The recent advent of this technology suggests the need for additional theoretical evaluation of the design of air sparging systems. A review of available literature on air sparging technology indicated that the technology, through a topic of research, employs systems that are designed according to the results of pilot studies or empirical data.

An understanding of the process, and of the important design parameters that go into the developmen of a predictive mathematical model, are essential prior to field implementation. Several attributes, mechanisms, and phenomena (such as dissolution, partitioning, etc.) related to air sparging require further research. For example, although it is clear that mass transfer plays the most important role in the remediation of chlorinated VOCs, the role of biodegradation during air sparging of petroleum-contaminated aquifers has not yet been fully demonstrated.

SATURATED ZONE VAPOR PHASE

The nature of the saturated zone vapor phase requires further definition. Conflicting opinions state that the air passing through the saturated zone travels in the form of bubbles or in a continuous phase passing through pathways in the soil, or in some other form.

Clearly, the transfer of oxygen to the saturated zone is key to bioremediation during air sparging. The transfer of contaminants from soil and water to the vapor phase is also important for removal of contaminants. If these transfer mechanisms can become effective, the rate of contaminant removal would increase significantly. For example, an increase in surface area between the vapor phase and the soils and groundwater would increase the rate of mass transfer.

Subsurface air injection requires additional study:

- What is the optimal well screen size for air injection?
- Does the injection of air in the form of microbubbles significantly improve the mass transfer?
- What is the correlation between soil permeability, aquifer depth, and optimal injection pressure?
- How much of the injected air is recovered in the SVE system, and what is the fate of the unrecovered air?

SYSTEM DESIGN AND INSTALLATION

Air sparging systems have used various well configurations and designs. Depending on the type of contaminants, location within the aquifer, and plume shape, some systems are more effective than others. Additional research should address the following issues:

- What is the optimal ratio of sparging to extraction wells?
- Should the system be designed differently to enhance biodegradation as opposed to enhancement of mass transfer of contaminants?

OPERATING CONDITIONS OF SYSTEM

Analyses of soil venting systems indicate the system is most cost effective during intermittent operations. This allows the soil to equilibrate with the soil vapor so that more contaminants can be removed with lower energy costs. Certainly, if a site remediation is to operate for several years, pulsing the blower operation can achieve a significant cost savings. Similarly, pulsed operation of an air sparging system may save energy. Several questions remain unanswered regarding this mode of operation:

- What is the optimal interval for operating the vacuum blowers and air injection equipment?
- Can the blowers and air injection equipment be pulsed simultaneously, or should they be pulsed at different intervals (i.e. operating the vacuum blowers longer than the air injection equipment) to prevent vapor migration to uncontaminated areas?
- What are the optimal injection and vacuum pressures?

RESEARCH METHODS

Many questions remain unanswered regarding air sparging technology. Various phenomena, such as air transport, can be studied on the bench scale. However, since air sparging is an in situ system, various operating conditions, such as pulsed operation and system pressures, must be analyzed in an actual field environment.

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