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FINAL

AIR SPARGING GUIDANCE DOCUMENT

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ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
bgs	below ground surface
BTEX	benzene, toluene, ethylbenzene, and total xylenes
CA	corrective action
CAA	Clean Air Act
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
cfm	cubic feet per minute
COC	contaminant of concern
CWA	Clean Water Act
DCA	dichloroethane
DCE	dichloroethene
DNAPL	dense, nonaqueous-phase liquid
DO	dissolved oxygen
DoD	United States Department of Defense
EIS	Environmental Impact Statement
EPCRA	Emergency Planning and Community Right-to-Know Act
ESA	Endangered Species Act
FIFRA	Federal Insecticide, Fungicide, and Rodenticide Act
GAC	granular activated carbon
GIS	Geographic Information System
HASP	health and safety plan
ID	inner diameter
IDW	investigation-derived waste
LNAPL	light, nonaqueous-phase liquid
MACT	Maximum Achievable Control Technology
MC	methylene chloride
MCL	maximum contaminant level
MCLG	maximum contaminant level goal
MTBE	methyl *tert*-butyl ether
MW	molecular weight
NAAQS	National Ambient Air Quality Standards
NAPL	nonaqueous-phase liquid
NAVFAC	Naval Facilities Engineering Command
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
ND	not detected
NEPA	National Environmental Policy Act

NFESC	Naval Facilities Engineering Service Center
NHPA	National Historic Preservation Act
NPL	National Priorities List
O&M	operations and maintenance
OD	outer diameter
OSHA	Occupational Safety and Health Administration
PCE	tetrachloroethylene
POTW	publicly owned treatment works
ppb	parts per billion
ppm(v)	parts per million (by volume)
psi(g)	pounds per square inch (gage)
PVC	polyvinyl chloride
QA	quality assurance
QAPP	Quality Assurance Project Plan
QA/QC	Quality Assurance/Quality Control
RAO	remedial action objective
RBCA	risk-based corrective action
RCRA	Resource Conservation and Recovery Act
ROD	Record of Decision
RPM	Remedial Project Manager
SARA	Superfund Amendments and Reauthorization Act
SDWA	Safe Drinking Water Act
SF_6	sulfur hexafluoride
SIP	State Implementation Plan
SOW	Statement of Work
SVE	soil vapor extraction
SVOC	semivolatile organic compound
TCA	trichloroethane
TCE	trichloroethene
TPH	total petroleum hydrocarbons
TSCA	Toxic Substances Control Act
USACE	United States Army Corps of Engineers
U.S. EPA	United States Environmental Protection Agency
UST	underground storage tank
VC	vinyl chloride
VOC	volatile organic compound
WBS	Work Breakdown Structure

1.0 INTRODUCTION

This document was developed by the Naval Facilities Engineering Service Center (NFESC) to provide guidance on selection, design, installation, operation, optimization and shutdown of air sparging systems. This guidance document is intended for use by Navy, Marine Corps, and other Department of Defense (DoD) Remedial Project Managers (RPMs) and their contractors. The manual applies the results from full-scale systems, field studies, and research to provide a concise yet complete life-cycle approach to air sparging design and implementation.

1.1 Background

Air sparging is an innovative in situ treatment technology that uses injected air to remove volatile or biodegradable contaminants from the saturated zone. The primary application of air sparging entails the injection of air directly into the saturated subsurface to remove volatile contaminants such as solvents and gasoline from the dissolved phase to the vapor phase through air stripping. The stripped compounds are then biodegraded and/or removed via soil vapor extraction (SVE) in the vadose zone. For semivolatile contaminants, such as diesel and jet fuels, air stripping is not the removal mechanism. Rather, the primary removal mechanism is stimulated microbial activity caused by the introduction of dissolved oxygen, which increases the biodegradation rate of the contaminant in the saturated zone. The major components of a typical air sparging system, shown in Figure 1-1, include an air sparge/injection well, a compressor or blower to supply air, monitoring points and wells, and an optional SVE system.

For sites contaminated with halogenated and nonhalogenated volatile organic compounds (VOCs) as a result of leaking underground storage tanks, pipelines, or other accidental releases, air sparging is a viable remedial option. The use of air sparging to remove VOCs has been demonstrated successfully; in fact, in many cases, air sparging is the most cost-effective remedial alternative. As with any in situ technology, well-engineered design followed by proper installation and operation are essential for achieving remedial goals and site closure.

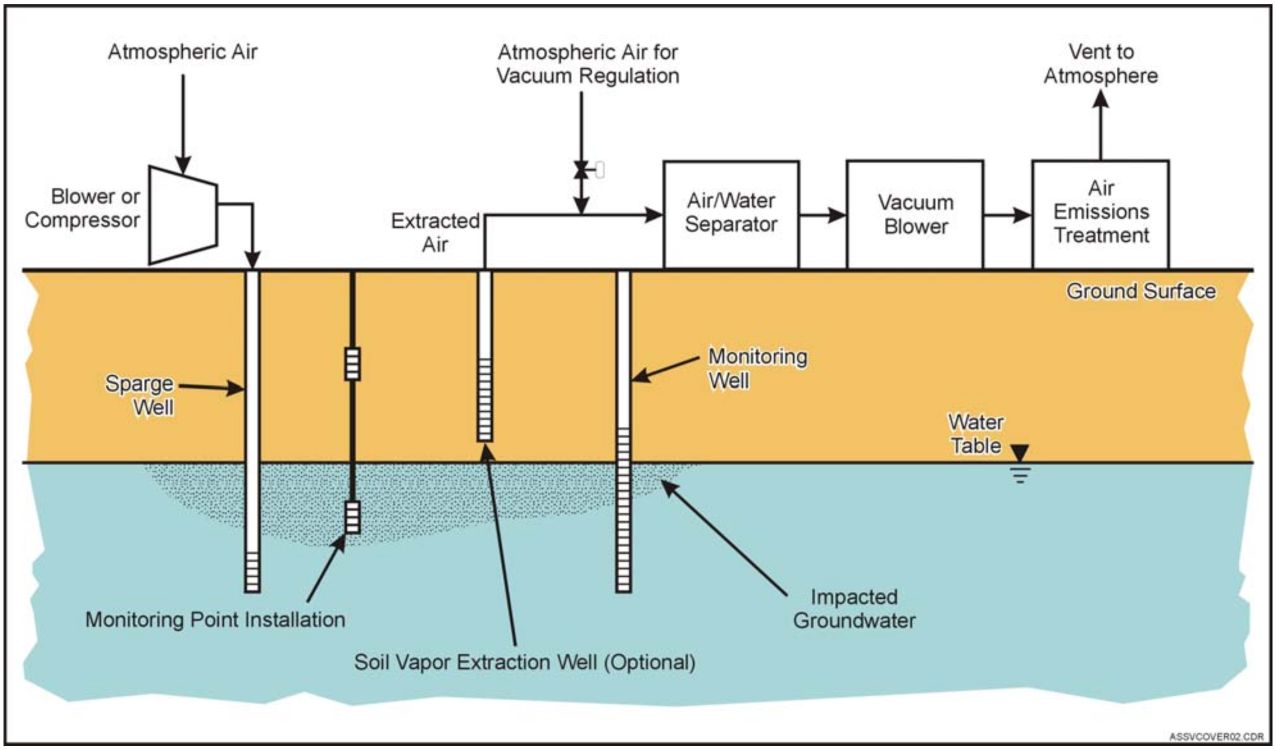


FIGURE 1-1. Air Sparging Conceptual Diagram

1.2 Scope of Document

The primary goal of this document is to provide RPMs and others with a management resource for the selection and cost-effective implementation of air sparging groundwater remediation systems. As such, the document provides detailed information covering all aspects of air sparging including feasibility analysis, regulatory and permitting issues, pilot testing, system design and construction, operation and maintenance, and site closure. The need for a life-cycle approach to system design, optimization, and long-term monitoring is also addressed. In general, this document attempts to answer the most common questions an RPM might have with respect to air sparging. Table 1-1 provides a quick reference to finding answers to these questions within the document. Figure 1-2 is a flowchart showing the general approach to implementing air sparging at a site.

TABLE 1-1. Where to Locate Answers to Common Questions on Air Sparging

Question	Answer Location
1. Will air sparging work at my site?	**Section 2.0. Site Characterization and Feasibility Analysis:** Provides information regarding site characterization requirements as well as the effect of site-specific data, such as contaminant type and geology, on air sparging effectiveness, implementability, and cost. **Appendix C. Properties of Selected VOCs:** Provides physical properties of VOCs necessary in evaluating air sparging feasibility. **Appendix D. Soil Properties:** Provides soil properties to aid in evaluating air sparging feasibility.
2. How much will it cost?	**Appendix E. Air Sparging Economics and Cost Estimating Worksheet:** Summarizes air sparging economics and provides a worksheet to quickly estimate budgetary costs.
3. Where can I find more information on the field application of air sparging at other sites?	**Appendix A. Focused Literature Review:** Provides the results and lessons learned from other air sparging field applications.
4. Is air sparging the best technology for my site?	**Appendix B. Compendium of Competing Remedial Technologies:** Evaluates competing remedial technologies to air sparging.
5. What regulatory and permitting issues do I need to consider when using air sparging?	**Section 3.0. Regulatory Issues and Permitting:** Identifies potentially applicable federal, state, and local regulations and permitting requirements. **Appendix F. Overview of Applicable Federal Environmental Regulations:** Summarizes federal regulations that may be applicable at air sparging sites.
6. How are air sparging systems designed?	**Section 4.0. System Design and Construction:** Describes pilot-scale testing requirements and full-scale design and construction considerations.
7. Does air sparging require predesign (pilot) studies?	**Appendix G. Air Sparging Pilot-Scale Testing Activity Matrix:** Summarizes pilot-scale testing activities and interpretation of pilot study data.
8. How long will it take to achieve cleanup goals?	**Section 5.0. System Operation, Monitoring, and Optimization:** Provides information on how to ensure that the air sparging system is operating in a cost-effective manner and how to evaluate progress toward achieving cleanup goals. **Section 6.0 System Shutdown, Long-Term Monitoring, and Site Closure:** Describes when and how to stop system operation and methods to obtain site closure.
9. How do I know if the system is operating effectively and efficiently?	
10. When can I stop operating the system?	
11. The system is not operating/ performing as intended. What's wrong?	**Appendix H. Troubleshooting Operation Matrix:** Provides a list of common problems encountered during air sparging operation and a recommended solution.
12. What are the key issues for my contractor to focus on?	**Appendix I. Air Sparging Statement of Work Guidance:** Provides guidance for preparation of a statement of work for an air sparging site.

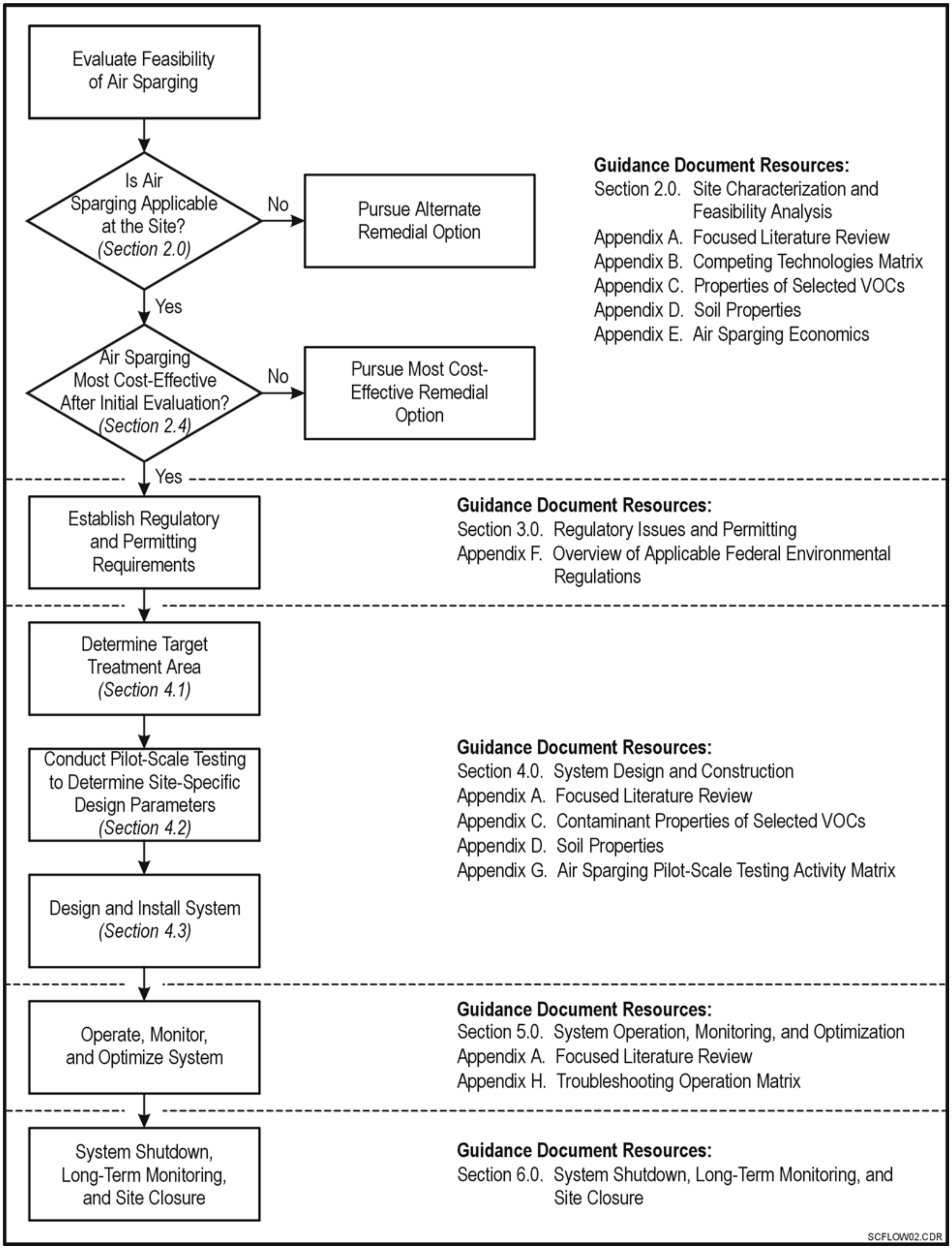


FIGURE 1-2. Air Sparging Project Flowchart

In addition, the following appendices are designed to expand on the main text and guide the RPM in other aspects of air sparging project management:

Appendix A: Focused Literature Review
Appendix B: Compendium of Competing Remedial Technologies
Appendix C: Properties of Selected VOCs
Appendix D: Soil Properties
Appendix E: Air Sparging Economics and Cost Estimating Worksheet
Appendix F: Overview of Applicable Federal Environmental Regulations
Appendix G: Air Sparging Pilot-Scale Testing Activity Matrix
Appendix H: Troubleshooting Operation Matrix
Appendix I: Air Sparging Project Statement of Work Guidance

2.0 SITE CHARACTERIZATION AND FEASIBILITY ANALYSIS

Air sparging is a relatively simple and effective treatment technology that has a proven record of successful performance when properly applied. This section is designed to aid RPMs in determining if air sparging will achieve objectives at a given site based on the results of site characterization and technical considerations such as contaminant type, geology, hydrogeology, and other factors. Technical feasibility issues are addressed by considering effectiveness, implementability, and costs of air sparging systems.

A feasibility analysis is a necessary first step in determining if air sparging will be the best technology for remediation at a site, and typically is accomplished as part of a Feasibility Study or Corrective Action Plan. In order to make an informed decision as to whether or not air sparging is the most appropriate remedy, it also is necessary to evaluate other competing treatment technologies. Although technology evaluation is not the focus of this document, a compendium of competing technologies with their advantages and limitations respective to air sparging is provided in Appendix B, and serves as a starting point for evaluation.

2.1 Site Characterization

Site conditions and contaminant characteristics, as defined by the conceptual site model, drive decisions determining whether or not air sparging is the most appropriate and effective technology for a site. Current and site-specific data are necessary for the feasibility analysis and, if a good conceptual site model has not been developed, additional data will need to be collected. Figure 2-1 shows the elements of a good conceptual site model.

A conceptual site model (CSM) is a useful engineering management tool that summarizes all available site history, site characterization, receptor survey, and land use data into a form that helps decision makers. For existing data, the project manager must determine whether the data set was collected properly and if it is current enough to be useful. For example, if the most recent assessment of contaminant concentrations is more than five years old, additional, more recent contaminant data are likely to be needed prior to remedy selection. The existing data set should be reviewed to ensure that it is sufficient for site screening and design purposes. The following issues are common reasons for failure of site investigation programs:

☐ Inadequate preparation and planning can cause cost overruns and incomplete site characterization.

☐ Inexact definition of geology/hydrogeology can cause the selection of an inefficient remediation method.

☐ Poor definition of contaminant distribution leads to incomplete site remediation.

☐ Inadequate collection of chemical data can cause the selection of an inappropriate remediation method.

To avoid the difficulties listed above, Table 2-1 identifies the site characterization parameters needed for the feasibility analysis of an air sparging site.

2.2 Air Sparging System Effectiveness

Effectiveness is a measure of the remediation technology's ability to meet remedial objectives based on site-specific conditions. The potential effectiveness of air sparging at a site must be carefully evaluated during the feasibility analysis. Figure 2-2 is a flowchart that serves as an initial screening methodology for determining if air sparging is appropriate for a given site.

The following sections summarize contaminant, geology, and hydrogeology-related issues that impact the effectiveness of air sparging.

2.2.1 Contaminant-Related Issues

☐ Air sparging is typically effective at removing dissolved VOCs, and has potential application for low levels of light, nonaqueous-phase liquid (LNAPL), or dense, nonaqueous-phase liquid (DNAPL). If recoverable free product is present at a site, it should be removed to the extent practicable and the site should then be evaluated for groundwater remediation requirements. LNAPL free-product recovery can be evaluated by methods described in Hoeppel and Place (1998).

Background Information

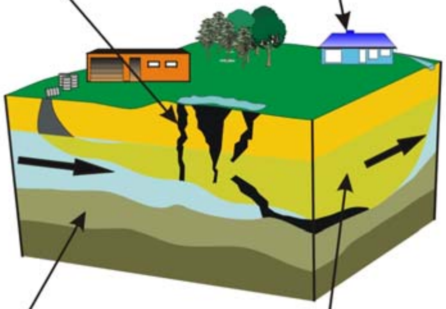
- Location of water supply wells.
- Groundwater classification.
- Nearby wellhead protection areas or sole-source aquifers.
- Locations of potential receptors exposure points.

Contaminant Source and Release Information

- Location, nature, and history of previous contaminant releases or sources.
- Locations and characterizations of continuing releases or sources.
- Locations of subsurface sources (e.g., DNAPLs).
- Flux of contamination.

Risk Assessment

- Current and future receptors.
- Exposure scenarios.
- Completed pathways?
- Exposure concentrations.



Geologic and Hydrologic Information

- Description of regional and site geology.
- Physical properties of subsurface materials (e.g., porosity, bulk density).
- Stratigraphy, including thickness, lateral extent, continuity of units, and presence of depositional features, such as channel deposits, that may provide preferential pathways for, or barriers to, contaminant transport.
- Geologic structures that may form preferential pathways for contaminants migration or zones of accumulation.
- Depth to groundwater.
- Hydraulic gradients (horizontal and vertical).
- Hydraulic properties of subsurface materials (e.g., hydraulic conductivity, storage coefficient, effective porosity) and their directional variability (anisotropy).
- Spatial distribution of soil or bedrock physical/hydraulic properties (degree of heterogeneity).
- Seasonal changes in hydrologic conditions
- Groundwater recharge and discharge information.
- Groundwater/surface water interactions.

Contaminant Distribution, Transport, and Fate Parameters

- Properties of contaminants that affect transport (e.g., composition, effective constituent solubilities, density, viscosity).
- Phase distribution of each contaminant (gaseous, aqueous, sorbed, free-phase NAPL or residual NAPL) in the unsaturated and saturated zones.
- Estimates of subsurface contaminant mass.
- Temporal trends in contaminant concentrations in each phase.
- Partitioning coefficients and migration rates.
- Contaminant natural attenuation processes (destructive and nondestructive).

Modified from U.S. EPA, 1993

SITEMODEL01.CDR

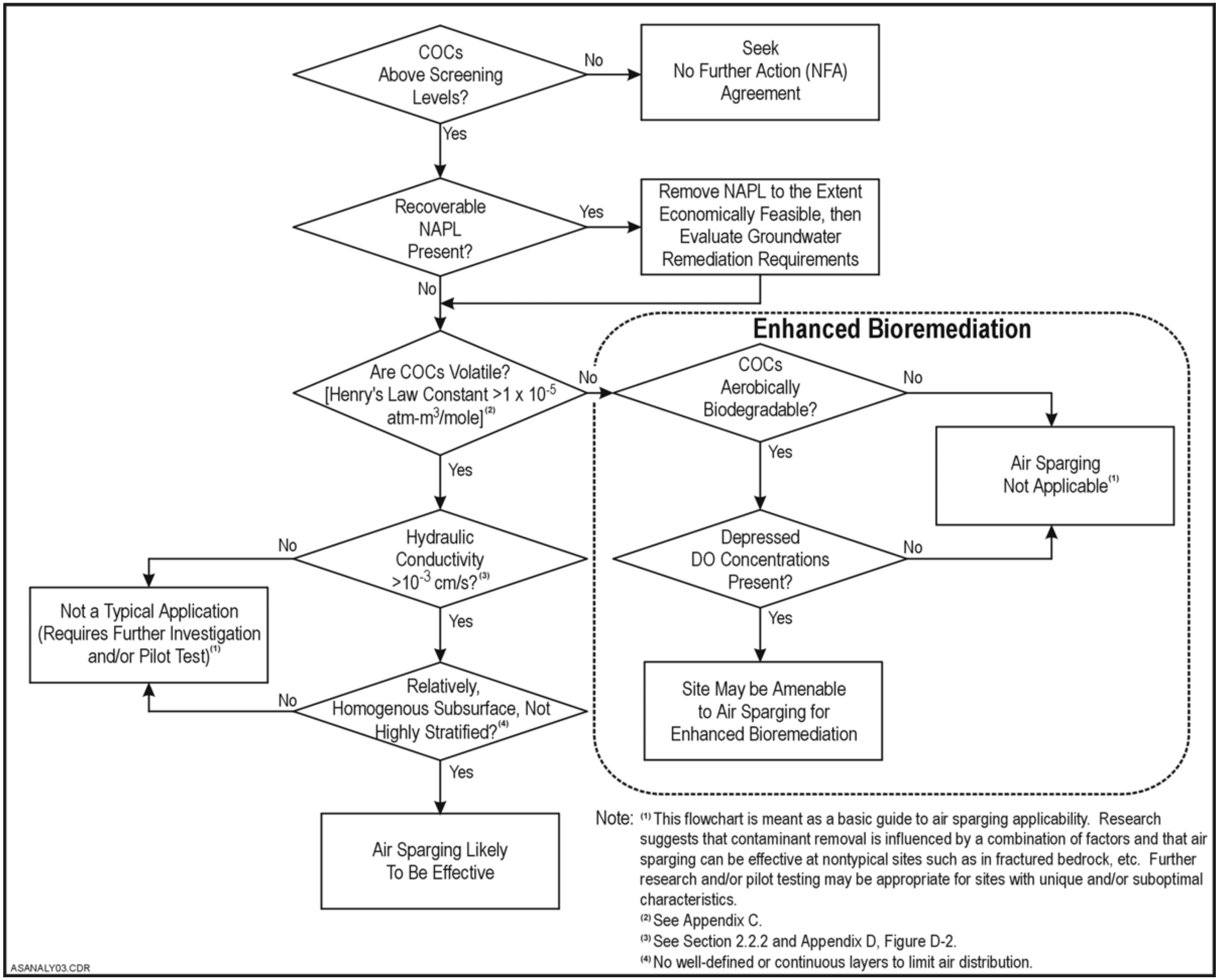
FIGURE 2-1. Conceptual Site Model

TABLE 2-1. Site Characterization Parameters for Assessing Feasibility of Air Sparging

Objective	Parameter	Comments
Site history	Site engineering plans	The primary purpose of this assessment is to determine which parameters have already been characterized and which must still be collected.
	Chemical inventory records	
	Contaminant release records	
Site geology/ hydrogeology	Subsurface geology	Collect data within the target treatment area. This can involve collecting soil cores, installing groundwater wells, performing aquifer characterization tests, and monitoring groundwater elevations. It is useful to take water-level measurements at several times during the year and over several years so seasonal and long-term variations in groundwater flow velocity and direction can be evaluated.
	Soil type/stratification	
	Groundwater depth	
	Groundwater velocity	
	Groundwater direction	
	Hydraulic gradient	
Contaminant type and distribution	Contaminant type	It is necessary to collect data that is sufficient to define the extent of the contaminant plume both horizontally and vertically, as well as to understand plume movement over time. Contaminant distribution data should be plotted on isocontour maps and on cross-section profiles to visualize the lateral and vertical extent of the plumes.
	Contaminant(s) of concern	
	LNAPL thickness (if present)	
	LNAPL recovery potential (if present)	
	Volume of contaminant released	
Geochemical assessment	Dissolved oxygen	Define horizontal and vertical distribution through multilevel wells for thicker contaminant plumes; Define horizontal distribution for thinner contaminant plumes. These parameters are optional for most air sparging sites, but critical when the application is meant to enhance bioremediation.
	Redox potential	
	pH	
	Conductivity	
	Nitrate	
	Fe(II)	
	Methane	
Receptor assessment	Identify potential receptors of groundwater contamination	Conduct a site visit and examine site boundaries. Identify persons or resources that could be impacted by the contamination and remediation process.
	Identify potential receptors of vapor migration	
Political assessment	Identify regulatory authorities and define the remedial action objective (RAO).	Early contact with the appropriate regulatory agencies is encouraged, as regulatory guidelines may exist that must be followed during site characterization.

- Table 2-2 lists contaminants that have been successfully removed via air sparging. In general, for air sparging to be effective, contaminants must be either sufficiently volatile to strip out of the groundwater, or aerobically biodegradable. Additional testing is required to evaluate sites with compounds for which there are no data supporting contaminant removal via air sparging.

- In many geological settings, groundwater contaminated with petroleum hydrocarbons and/or dissolved chlorinated solvents can be readily remediated through air sparging. These compounds generally exhibit good strippability as characterized by a high Henry's law constant. The Henry's law constant can be approximated by the ratio of a compound's vapor pressure to its aqueous solubility (see Table C-1). For example, tetrachloroethylene (PCE) has a relatively high Henry's law constant (1.8×10^{-2} atm-m^3/mol) due to both its high volatility and low aqueous solubility. Even though acetone has a relatively high vapor pressure (180 mm Hg), it has a low Henry's constant (3.88×10^{-5} atm-m^3/mol) due to its high water solubility (1,000,000 mg/L). In general, compounds like acetone and MTBE, with relatively low Henry's constants will be more costly to treat with air sparging because a greater flowrate of injected air and/or extended treatment duration are likely to be required to achieve remedial objectives.



Note: (1) This flowchart is meant as a basic guide to air sparging applicability. Research suggests that contaminant removal is influenced by a combination of factors and that air sparging can be effective at nontypical sites such as in fractured bedrock, etc. Further research and/or pilot testing may be appropriate for sites with unique and/or suboptimal characteristics.

(2) See Appendix C.

(3) See Section 2.2.2 and Appendix D, Figure D-2.

(4) No well-defined or continuous layers to limit air distribution.

FIGURE 2-2. Air Sparging Applicability Analysis

TABLE 2-2. Example Cases with Contaminants Amenable to Remediation Using Air Sparging

Compound(s)	Initial Maximum Concentration(a)	Reference
Benzene	811 μg/L	Covell and Thomas, 1997
BTEX	11 mg/L	Hartley et al., 1999
BTEX	11,701 μg/L	Klemm et al., 1997
BTEX	11,510 μg/L	Muehlberger et al., 1997
BTEX	38.1 mg/L	Klemm et al., 1997
BTEX; 1,1-DCA; 1,2-DCA; *cis*-DCE; *trans*-DCE; MC; PCE; 1,1,1-TCA; TCE; VC	470; 14; 0.052; 91; 0.93; 36; 69; 17; 3.6; 11 (all mg/L)	Maheux and McKee, 1997
BTEX; MTBE	2.0 mg/L; 7,010 μg/L	Damera et al., 1997
BTEX; TPH	22,000 μg/L; 9,300 mg/kg (soil)	Strzempka et al., 1997
Ethylbenzene; xylenes	41,000 μg/L; 150,000 μg/L	Kraus et al., 1997
MTBE	5.9(b) g	Bruce et al., 1998
PCE	20-50 μg/L	Marnette et al., 1999
PCE	489 μg/L	Dreiling, 1998
PCE; TCE; *cis*-DCE	6,670; 9,870; 26,400 (all μg/L)	Hughes and Dacyk, 1998
TCE	1.0 mg/L	Aubertin and Hise, 1998
TCE; DCE; VC	94 μg/L; 960 μg/L; 3,000 μg/L	Kershner and Theoret, 1997
TPH	>10,000 mg/kg (soil)	Basinet and Wollenberg, 1997

(a) Concentration in groundwater unless noted.
(b) Laboratory study in which 5.9 g of MTBE was injected into large-scale reactor.

BTEX = benzene, toluene, ethylbenzene, and total xylenes.
DCA = dichloroethane.
DCE = dichloroethene.
MC = methylene chloride.
MTBE = methyl-*tert*-butyl ether.
TCA = trichloroethane.
TCE = trichloroethene.
TPH = total petroleum hydrocarbons.
VC = vinyl chloride.

☐ At most air sparging sites, the volatilization process is the primary mechanism for mass recovery and can account for up to 99% of the mass removed (based on typical biodegradation rates of 8 kg/day vs. 810 kg/day for volatilization rates in Leeson et al., 2001). However, sites contaminated with SVOCs, such as diesel and jet fuels that cannot be removed effectively via volatilization, may be remediated through enhanced aerobic biodegradation. If the goal of the air sparging system is to enhance bioremediation by increasing groundwater dissolved oxygen (DO) concentrations, and the site already has DO concentrations greater than 2 mg/L, then air sparging may not be warranted.

2.2.2 Geology- and Hydrogeology-Related Issues

☐ Air sparging is best suited to sites with sandy soils and medium to shallow aquifer depths at less than 50 ft below ground surface (bgs).

☐ Site geological conditions such as stratification, heterogeneity, and anisotropy will prevent uniform airflow through the medium, thus reducing air sparging effectiveness. For in situ air sparging applications, good characterization of the geology in the area where the air sparging system is to be installed is critical. The subsurface geology should be evaluated by collecting at least one continuous soil core from ground surface to the bottom of the contaminated aquifer in the area where air sparging is being considered. A hydrogeologist should evaluate the soil core to determine the soil type and to identify the depth and location of distinct soil layers that may influence airflow.

☐ Figure 2-3 depicts the potential effect of geologic conditions on injected air distribution. If the subsurface is relatively homogenous, the airflow distribution pattern will tend to form a symmetrical, conical shape. If thick, continuous confining

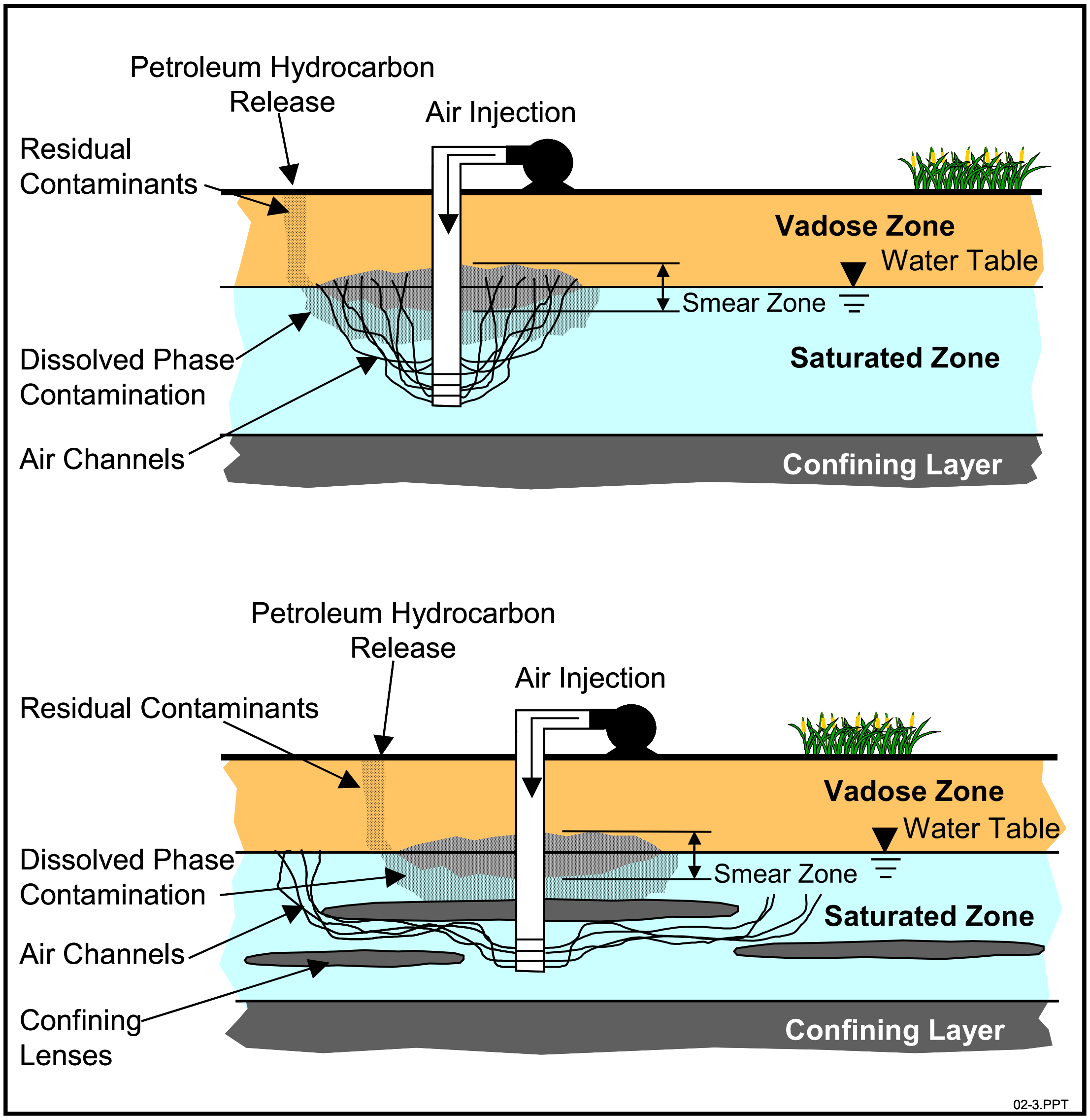


FIGURE 2-3. Effect of Heterogeneity on Injected Air Distribution

layers are present in the contaminated zone, they may prevent airflow from reaching the contaminants altogether. If thin, discontinuous layers are present, there will be less disruption to airflow, but preferential flowpaths may develop. Air flowpaths that are formed during air sparging are sensitive to small changes in soil permeability, so identification of layers of lower permeability material between the water table and greatest depth of contaminant penetration is important.

- Although stratification and heterogeneity may reduce effectiveness, their presence does not directly lead to the conclusion that air sparging is not the best remedial approach. In general, sites having high clay or silt content in soils with hydraulic conductivities less than 1×10^{-3} cm/s are not typical candidates for this technology. However, a recent pilot test has demonstrated successful contaminant removal using pulsed air sparging in a low permeability, highly stratified formation with hydraulic conductivities on the order of 6×10^{-7} to 3×10^{-4} cm/s (Kirtland and Aelion, 2000). In these suboptimal cases, pilot testing may still be warranted. Appendix D lists typical hydraulic conductivity values for a variety of soil types.

- At sites with LNAPL present, the majority of the contaminant mass is often contained in the smear zone or a band of residual product just above and below seasonal water table levels. If a smear zone is present, air sparging may be an effective approach because air moves vertically upward through this region. SVE alone would not be able to fully address the residual LNAPL source in the smear zone due to the seasonal submergence of this zone by the fluctuating water table.

2.3 Air Sparging System Implementability

Implementability is a measure of both the technical and administrative feasibility of the chosen remediation technology. Implementability issues relating to air sparging systems include the following advantages and limitations:

Advantages

- Application of the technology is widely recognized by the regulatory community as an effective remedial technology for removing volatile contaminants from groundwater.

- Implementation is relatively simple, because only readily available commercial equipment is utilized (i.e., polyvinyl chloride [PVC] well casing, compressors or blowers, etc.). The equipment is relatively easy to install and causes minimal disturbance to site operations.

- Cleanup times are relatively short, typically taking less than two years to achieve performance objectives.

- Use of low-cost, direct-push well installation techniques is possible. Direct-push technologies are most applicable in unconsolidated sediments and at depths of less than 30 ft. (Although, in relatively coarse-grained lithologies, direct-push rigs may experience some difficulty in obtaining good material recovery and specialized equipment may be needed to obtain relatively undisturbed samples from depths greater than 10 ft [Kram, 2001]). In soils where utilizing this technology is feasible, this option offers the advantage of being more rapid and less expensive than traditional drilling techniques such as the hollow-stem auger method.

- If SVE is not necessary, minimal operational oversight is required once the system is installed and no wastestreams are generated that require treatment. If SVE is required, soil vapor treatment prior to discharge to the atmosphere is likely to be required. This will necessitate obtaining an air discharge permit and additional manpower to operate and maintain the treatment equipment.

Limitations

- Because air sparging increases the rate of contaminant volatilization, it is important to be aware of the potential for migration of VOC-impacted vapor to human and/or ecological receptors at potential levels of concern. An SVE system can be used to reduce or eliminate vapor migration problems, but the proximity of the site to buildings or other structures should be taken into careful consideration. SVE is widely used and is one of the U.S. EPA's presumptive remedies for the remediation of VOC-contaminated vadose zone soils. SVE is relatively easy to implement, but depth to groundwater should generally be greater than 5 ft bgs to prevent SVE well submergence.

- If air sparging is applied to contain a dissolved phase plume, at a high air injection rate in a sparging barrier configuration, the injection of air into the subsurface can produce a zone of reduced hydraulic conductivity. If operation of the air sparging system is not managed properly, this could divert the plume away from the zone of air sparging influence and reduce treatment efficiency. Proper management includes pulsing air flow which allows water to flow through the sparged zone when the system is turned off.

2.4 Air Sparging System Costs

The potential economic benefit of air sparging has been an important driving force for utilization of this technology. The main categories of costs for air sparging projects are initial investment and operations and maintenance (O&M). Initial investment costs include expenditures such as additional site characterization, pilot-scale testing, design, and system construction, whereas O&M costs can include monitoring, vapor treatment, and site decommissioning costs. Although system design and installation costs may be comparable to other competing technologies, O&M costs may be significantly reduced due to the typically short duration of operation. Developing a life-cycle approach to system design and optimization can help to minimize equipment and O&M costs. Typically, full-scale air sparging remediation costs range from $150,000 to $350,000 per acre of groundwater treated (FRTR, 2001). The remaining sections of this document will highlight ways to improve system design and operation to ensure cost-effective implementation throughout the life of the project. Air sparging project costs are discussed in more detail and an initial cost-estimating worksheet is provided in Appendix E.

The following is a list of the major factors that impact project design and installation and O&M costs:

- ☐ Type of contaminant
- ☐ Area and depth of contaminant
- ☐ Depth of groundwater
- ☐ Site geology
- ☐ Air sparging/SVE well spacing
- ☐ Drilling method
- ☐ Required flowrate and vacuum and pressure
- ☐ Treatment duration
- ☐ Regulatory requirements (e.g., monitoring, permitting, etc.)
- ☐ Vapor treatment requirements.

The installation costs of an air sparging system are based primarily on the number of air sparging and SVE wells required to adequately cover the target treatment area. The required number of wells is controlled by the areal extent of the contamination and the subsurface air distribution characteristics. The costs for well installation and construction will also increase as the depth to the contaminated zone increases and the drilling becomes more costly. Capital equipment costs are impacted by the air injection and extraction flowrates, which relate to compressor and blower sizing, and by vapor treatment requirements, which determine the type and capacity of air pollution control equipment selected.

The O&M costs are influenced primarily by those factors that tend to increase the time required to reach remedial action objectives. The presence of nonaqueous-phase liquids (NAPLs) can significantly increase project duration because they provide a continuing source of groundwater contamination. Site subsurface characteristics are also important because the achievable air injection rate and/or extraction rate affects the rate of contaminant removal and therefore the project duration. The soil characteristics also impact the required operating pressure for injection and the required vacuum for extraction, which can increase energy use at the site. As discussed in Section 3.0, vapor treatment requirements are often the most significant O&M costs for an air sparging project coupled with SVE. The replacement and disposal of activated carbon or the need for supplemental fuel for thermal/catalytic oxidation plays a large role in project economics.

3.0 REGULATORY ISSUES AND PERMITTING

Numerous environmental regulations will impact the design, installation, and operation of an air sparging system. This section summarizes regulatory and permitting issues that must be considered for remediation projects using air sparging technologies. In the planning phase, it is important to research the regulatory framework involved because important issues such as limits on VOC emissions and stringent cleanup standards can significantly impact feasibility. Numerous federal regulations and executive orders may impact a remediation project (Appendix F provides a summary of these regulations), including:

☐ Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

☐ Superfund Amendments and Reauthorization Act (SARA)

☐ Emergency Planning and Community Right-to-Know Act (EPCRA)

☐ Resource Conservation and Recovery Act (RCRA)

☐ Clean Water Act (CWA)

☐ Safe Drinking Water Act (SDWA)

☐ Clean Air Act (CAA)

☐ Occupational Safety and Health Administration (OSHA) rules

☐ Endangered Species Act (ESA)

☐ Executive Order No. 11988, Floodplain Management

☐ Executive Order No. 11990, Protection of Wetlands

☐ Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)

☐ National Environmental Policy Act (NEPA)

☐ National Historic Preservation Act (NHPA)

☐ Toxic Substances Control Act (TSCA).

However, state and local regulations typically are the most critical because establishing site cleanup goals, permitting, and site closure negotiations take place under state and local jurisdictions. The majority of the regulatory compliance work will include obtaining permits from, and submitting reports to, state or local agencies. Although a detailed review of state and/or local regulations is beyond the scope of this guidance document, the following general considerations for establishing cleanup goals, performance objectives, and permitting requirements will apply to most sites.

3.1 Establishing Cleanup Goals

Remediation projects typically will fall under the jurisdiction of CERCLA, RCRA, or state and local underground storage tank (UST) programs. In most cases, the cleanup goals will consist of either site-specific risk-based levels or regulated concentrations, such as maximum contaminant levels (MCLs), established for contaminants in groundwater. The risk-based remediation goals usually are calculated based on industrial and/or residential exposure scenarios and derived using standard contaminant partitioning and transport equations. These risk-based approaches are presented in the American Society for Testing and Materials (ASTM) *Standard Guide for Risk-Based Corrective Action (RBCA*) at petroleum release sites (ASTM, 1996). Most states either have their own risk-based guidance for low-risk site closure or accept a RBCA-type approach. Progress towards remedial goals should be tracked and reviewed on a quarterly basis or as new compliance and system monitoring data become available. The following suggestions should be considered when establishing or reviewing cleanup objectives for an air sparging remediation project:

☐ Identify opportunities for modifying cleanup goals based on regulatory changes or updated contaminant toxicity information. Often stringent cleanup levels such as MCLs may be required initially, but through a site-specific risk assessment and negotiation with state/local regulators, more appropriate and/or feasible cleanup levels may be agreed upon.

☐ Utilize groundwater monitoring data or develop site-specific groundwater transport models to help negotiate cleanup levels or to demonstrate that levels of residual contamination at the site do not pose a threat to potential receptors.

☐ Identify sites where engineering and institutional controls can be used to reduce receptor exposure to contaminated soil or groundwater. For example, the cleanup requirements can be reduced with the use of appropriate deed restrictions which establish the site as a Brownfield, limit future land use, and prevent future residential development. These options must be discussed with legal counsel and the long-term use of the site should be considered. Land use controls may not always be feasible for federally owned sites.

☐ Where the contaminants of concern are petroleum hydrocarbons, attempt to remove remediation projects from RCRA or CERCLA authority and place them under state and local UST programs. This change results in fewer regulatory requirements and increased options for site-specific, risk-based cleanup.

3.2 Performance Objectives

The development of performance objectives for air sparging systems is critical to cost-effective remediation because air sparging alone may not achieve cleanup goals. Air sparging is effective at removing contaminant mass. Surveyed literature indicates that over half of air sparging systems achieve greater than 90% reduction in contaminant concentrations (Bass et al., 2000). However, permanent reductions in groundwater VOC concentrations greater than 90% can be insufficient to meet stringent cleanup standards. Table 3-1 shows that sites with similar percent reductions in total contaminant mass can have varying success towards achieving cleanup objectives. With a 92% reduction in TCE groundwater concentrations, the United States Army Corps of Engineers (USACE) could not meet the stringent cleanup standard of 5 μg/L (USACE, 1998). Alternately, a greater than 99% reduction of TCE concentrations in groundwater was reported by Glass (2000), which effectively met the 1,000-μg/L remedial objective.

As with any remediation technology, air sparging should be utilized when its operation is cost-effective. At sites where the air sparging system reaches asymptotic levels of VOC recovery and system operation loses its cost-effectiveness, a transition to other remedies (such as monitored natural attenuation) should be considered (see Section 6.0). To avoid regulatory bottlenecks, the performance objectives and the site closeout strategy should be discussed with regulatory authorities during system design and documented in the site's remediation work plan or Record of Decision (ROD) as appropriate. Some performance objectives or issues to consider include:

☐ Establish contaminant mass removal objectives rather than agreeing to meet stringent groundwater contaminant concentrations. For example, data from other full-scale air sparging systems indicate

TABLE 3-1. Example Percent Contaminant Reductions after Air Sparging Application at Selected Sites

Compound(s)	Remedial Action Objective	Percent Reduction for Each Contaminant	Duration of Operation	Reference
DCE, PCE, TCE, VC	TCE < 5 μg/L VC < 1 μg/L	DCE 100% TCE 92% VC 100%	12 months	USACE, 1998
DCE, PCE, TCE	PCE < 5 μg/L TCE < 5 μg/L	DCE 9% PCE 82% TCE 95%	9 months	Hughes and Dacyk, 1998
DCA, DCE, TCE, VC	TCE <1,000 μg/L	TCE 99.9%	8 months	Glass, 2000
BTEX	BTEX < 2 μg/L	BTEX 99.9%	15 months	Hartley et al., 1999
Ethylbenzene and Xylenes	E < 680 μg/L X < 1,750 μg/L(a)	E 98% X 99%	10 months	Kraus et al., 1997

(a) Remedial action objectives not provided for this site, so MCLs were added for comparison.

that the majority of systems achieve significant reductions in contaminant mass; therefore, 80% mass removal can be proposed as a performance objective.

- ☐ Establish criteria to trigger a transition to monitored natural attenuation once VOC recovery by the air sparging/SVE system has reached asymptotic levels and VOC levels in groundwater have been reduced compared to initial baseline levels.

- ☐ The SVE component of air sparging typically is the most costly aspect of system operation. Consider establishing performance goals for usage of the SVE system. Determine the contaminant loading where biological degradation in the vadose zone is sufficient to control contaminated vapor migration/releases and discontinue SVE operation at this point. (Discontinuing SVE operations may require increased vapor monitoring requirements to ensure safety and regulatory compliance.)

- ☐ Contaminant rebound following system shutdown is an important consideration in measuring air sparging performance. Consider leaving the air sparging system on standby (off, but still functional) for a 12- to 18-month period after turning off the system. If significant rebound occurs, reinitiate operation. This contingency will help ease regulatory concerns regarding discontinuation of system operation prior to achieving cleanup goals and yield substantial savings in mobilization and startup costs if reinitiation is required.

3.3 Permitting Issues

Permitting is an important aspect of air sparging regulatory compliance as well as a significant cost consideration. The following sections discuss the permits typically required for the installation and operation of an air sparging system including well installation and boring permits, air permits, and underground injection control permits.

3.3.1 Well Installation and Boring Permits

Local agencies, such as a county Department of Health, often require permits for subsurface installations. All sparge wells, SVE wells, soil vapor monitoring points, and groundwater monitoring wells typically will require well or boring permits. Applications for these permits usually request a description of the well construction details along with information regarding subsurface lithology. Right-of-way permits also may have to be obtained for the installation of monitoring wells off-site, near roadways, or on public property.

3.3.2 Permit to Construct and Operate an Air Pollution Control Device

Additionally, before the air sparging/SVE system is installed, both a permit to construct and a permit to operate an air pollution control device typically will be required. These permits can involve separate applications or a combined single application and usually are submitted to local Air Pollution Control Boards or Districts at the county level. The application for these permits typically include the following elements:

- ☐ Site location diagrams and system piping and instrumentation diagrams

- ☐ List of major pieces of equipment (e.g., blower, thermal oxidizer)

- ☐ List of stack parameters (e.g., height, diameter, flowrate)

- ☐ Description of flow monitoring and inlet/outlet vapor phase monitoring techniques

- ☐ Estimates of criteria air pollutant emissions (e.g., NO_2, SO_X, CO, particulate matter)

- ☐ Estimates of hazardous air pollutant emissions (e.g., benzene).

Several issues are involved in these permit applications that can impact the performance and economics of the air sparging remediation project. The selection of the type of air pollution control equipment has a substantial impact on project economics. Pilot test data can be used to select and size the air pollution control device (e.g., thermal or catalytic oxidizer or granular activated carbon system), but a practitioner must take into account the fact that the VOC removal rate will drop dramatically over time from the initial levels. Figure 3-1 illustrates the impact of decreasing mass removal rate on vapor treatment costs by displaying the following data versus time:

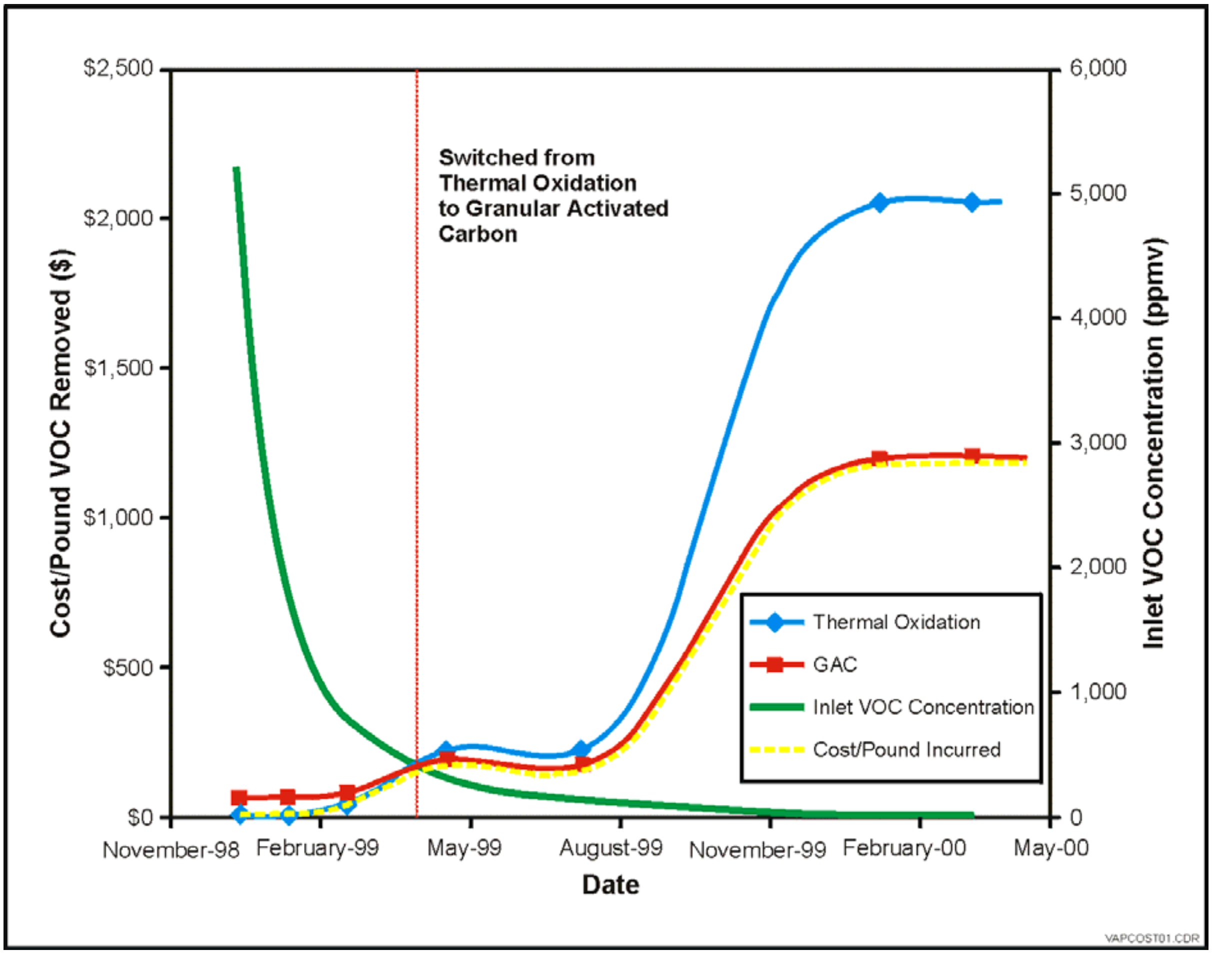


FIGURE 3-1. **True and Projected Vapor Treatment Costs Over Time at an Air Sparging/SVE Site**

- ☐ VOC extraction rate data from an air sparging/SVE system (green)
- ☐ True cost per pound of VOC extracted (yellow)
- ☐ Projected cost per pound of VOC extracted for thermal oxidation (blue)
- ☐ Projected cost per pound of VOC extracted for granular activated carbon (GAC) (red).

During the first three months of the project, thermal oxidation was the most cost-effective technology because VOC levels were high (5,000 to 500 ppmv) and significant heat value was present in the extracted soil vapor. As the VOC levels declined down to levels below 500 ppmv, the need for supplemental fuel continued to increase, and eventually thermal oxidation costs reached a level that made GAC purchase and disposal costs competitive. Figure 3-1 shows that it is important to optimize the selection of vapor treatment technology because system operating costs can be more than doubled if a less than optimal vapor treatment technology is used.

The permit should contain provisions to change out air pollution control equipment as the VOC extraction rates and the resulting vapor treatment required diminishes. Once granted, this permit will set emission limits and monitoring requirements for each pollution control device. The permit usually will require weekly or monthly monitoring and periodic submission of reports that document the required performance parameters of the air pollution control device.

3.3.3 Certificate of Exemption Permit

At sites where an air pollution control device is not required (i.e., SVE is not required), the local air pollution regulatory agency may require a Certificate of Exemption permit. This permit documents that direct discharge from the air sparging system will not impact air quality above certain allowable limits.

3.3.4 Underground Injection Control Permit

Some states regulate the injection of air into the subsurface through underground injection control programs. These programs often cover injection wells used for innovative remediation technologies such as air sparging, in situ oxidation, and enhanced bioremediation. The remedial project manager should determine if an underground injection control permit is required at the site. These permits typically include provisions for the following:

- ☐ Classification of the injection well(s)
- ☐ Classification and protection of the affected groundwater
- ☐ Requirements for abandonment, monitoring, and reporting.

4.0 SYSTEM DESIGN AND CONSTRUCTION

In a case study of 49 air sparging sites, Bass et al. (2000) reported that groundwater VOC concentration reductions ranged from 27% to almost 100%. The overall success of the systems varied due to differing designs, construction techniques, and operational conditions, which indicates that correct design and construction of an air sparging system is necessary for successful implementation. This section discusses the following aspects of air sparging system design and construction:

☐ Target treatment area definition
☐ Pilot-scale testing
☐ Air injection system design
☐ SVE system design
☐ Monitoring network placement and construction.

Air sparging relies upon two different mass removal mechanisms: (1) air stripping, and (2) aerobic biodegradation. The percentage of mass removed by these two mechanisms can vary widely and can be influenced by system design. At most air sparging sites, air stripping is the primary mechanism for VOC removal, and enhanced biodegradation through aquifer oxygenation is usually of secondary importance. The relative importance of the above mechanisms should be considered when designing an air sparging system. Air sparging systems can be designed and implemented in the following ways:

☐ Air sparging can be used to restore aquifer water quality at the source, throughout the plume, or as a barrier to prevent elevated concentrations from passing by a selected boundary.

☐ Air sparging, with SVE, can be designed to operate at high injection flowrates (6 to 20 cubic feet per minute [cfm]) to effectively partition contaminants from the groundwater into the vapor phase. The volatilized contaminants are then captured in the vadose zone by the SVE system and treated before release to the atmosphere.

☐ Air sparging, without SVE, can be used to partition VOCs from the groundwater into the vapor phase for aerobic biodegradation in the vadose zone. In this approach, soil vapor monitoring is necessary to establish that the system does not exceed the biodegradation capacity of the vadose zone and/or impact ambient air quality above the appropriate regulatory thresholds.

☐ Air sparging, without SVE, can be designed to deliver a mixture of oxygen to the saturated zone to stimulate microbial growth and therefore enhance aerobic biodegradation of target compounds dissolved in groundwater. This approach can be an option if the contaminants are aerobically biodegradable SVOCs.

4.1 Target Treatment Area Definition

The target treatment area is the area where the air sparging system will be installed to achieve the most effective treatment. The area will be defined based on the site characterization data and regulatory requirements. It may encompass the source zone, the dissolved plume, localized areas with elevated concentrations within the plume, or the downgradient boundary of the dissolved plume. In determining the target treatment area for an air sparging system, development of a conceptual site model is necessary as discussed in Section 2.1 of this manual. The conceptual site model will help determine the potential feasibility of air sparging, the most effective location for pilot testing and full-scale system installation, and facilitate understanding among all involved parties.

Most practitioners advocate targeting the source zone for remediation of petroleum-contaminated aquifers, while targeting the localized areas with elevated concentrations within the dissolved plume is recommended for chlorinated solvent-contaminated aquifers. In general, if the source zone can be located and remediated, then the remaining dissolved plume will dissipate rapidly through natural attenuation processes. Remediation outside the source area is warranted, however, when further migration of a recalcitrant chemical (e.g., TCE or MTBE) must be prevented.

Location of the target treatment zone is dependent on the contamination type, distribution, and the proximity to receptors. Contaminants commonly are classified into general types based on similar sources and chemical properties. These properties can affect the optimal density and location of sparging wells, as discussed in Sections 4.1.1 and 4.1.2.

4.1.1 Petroleum Hydrocarbons

For petroleum hydrocarbon contamination, the target treatment area is influenced by three factors:

- ☐ Typically, the more hazardous components (i.e., BTEX compounds) are volatilized fairly readily, and petroleum hydrocarbons are biodegradable under aerobic conditions.
- ☐ Petroleum hydrocarbon source zones often are relatively small in contrast to a dissolved-phase plume that may be much larger.
- ☐ Petroleum hydrocarbon dissolved-phase plumes often naturally attenuate readily, and additional plume control may be unnecessary.

Given these factors, the most economical air sparging installation may be one that is installed into the source zone to remove high concentrations of contaminants. Natural attenuation could then be implemented for remediation of the remaining dissolved-phase plume. If natural attenuation is not sufficient to control plume migration before the plume contacts potential receptors, an air sparging system can also be installed at the leading edge of the plume. This is sometimes referred to as a sparge curtain or wall.

4.1.2 Chlorinated Volatile Organic Compounds

For chlorinated solvent contamination, the target treatment area is influenced by three factors:

- ☐ Chlorinated solvents such as PCE and TCE degrade slowly or not at all under aerobic conditions, but are volatilized fairly readily.
- ☐ Chlorinated solvent source zones may be relatively large and difficult to locate due to the sinking and spreading of DNAPL in the aquifer.
- ☐ Chlorinated solvent plumes often are quite large because natural attenuation processes are relatively slow.

Given these three factors, chlorinated solvent source zone treatment may not be feasible due to a large and/or unknown location of the source zone. If the contaminant plume is very large, air sparging may be economically prohibitive due to the number of wells that would have to be installed. Therefore, the most appropriate air sparging system location may be treatment within localized areas of elevated concentrations throughout the plume and/or location of a system at the leading edge of the plume. If the source zone can be identified, treatment of the source zone is recommended to shorten the remediation time.

4.2 Pilot-Scale Testing

Pilot testing should be conducted in a portion of the target treatment area and should be performed to determine air sparging feasibility. If the target treatment area is very large, it may be necessary to conduct pilot testing in more than one location, particularly if site soils vary significantly throughout the site. The air sparging pilot test is designed to: (a) look for indicators of infeasibility; (b) characterize the air distribution to the extent practicable; (c) identify unexpected challenges; (d) identify any safety hazards to be addressed in the full-scale design; and (e) provide data to size the full-scale system.

In order to accomplish these objectives, pilot-scale testing typically includes the following activities:

- ☐ Baseline sampling
- ☐ Injection pressure and flowrate testing
- ☐ Groundwater pressure response testing
- ☐ Soil vapor sampling and off-gas sampling (with SVE)
- ☐ DO measurements
- ☐ Helium tracer testing
- ☐ Direct observations

In complex geologic conditions and where well spacing greater than 15 to 20 ft is being considered, additional tests, such as sulfur hexafluoride (SF_6)-distribution testing, neutron probe analyses, and geophysical testing, may be appropriate. Table 4-1 summarizes pilot-scale testing activities and the data objectives met by each activity. A more extensive discussion of pilot-scale testing activities and implementation can be found in the *Air Sparging Design Paradigm* (Leeson et al., 2001). An Air Sparging Pilot-Scale Testing Activity Matrix is provided in Appendix G and includes more discussion of the key issues related to pilot test activities as presented in Table 4-1.

TABLE 4-1. Summary of Pilot Test Activities

Activity	Question(s) Answered
Baseline sampling • Pressure • DO • Groundwater COCs • Soil vapor • Geophysical	What are aquifer and vadose zone conditions prior to air sparging startup?
Injection pressure/ flowrate test	Is it possible to achieve desired flowrate at safe and reasonable pressures?
Groundwater pressure response test	What are the general characteristics of the air distribution? a) Semiconical air distribution or b) Irregular distribution with preferential channels
Helium tracer test	What is the lateral extent of the air distribution? Are there indications of preferential flowpaths?
Soil vapor/SVE off-gas sampling	What is the volatilization rate? Are there any obvious safety hazards?
Dissolved oxygen measurements	What is the lateral extent of the air distribution? Are there indications of preferred directions?
Direct observations	Are there any odors, noise, or other factors present that make system operation less acceptable?
SF_6 distribution test	What is the vertical and lateral extent of the air distribution in the target treatment zone? What are the oxygen transfer rates to groundwater?
Other geophysical tools (e.g., neutron probes, electrical resistance tomography)	What is the vertical and lateral extent of the air distribution in the target treatment zone?

4.2.1 Pilot-Scale Testing Equipment

Figure 4-1 shows the typical components of an air sparging system. The following equipment typically is needed to conduct pilot test activities:

- ☐ At least one air injection well equipped with a wellhead pressure gauge, flowmeter, and control valve.

- ☐ An air supply system consisting of an air filter, air compressor, and pressure vessel. The air compressor should be capable of providing at least 20 cfm at pressures up to 10 to 15 pounds per square inch (gage) (psig) above the calculated hydrostatic pressure.

- ☐ Three or more groundwater piezometers or monitoring wells.

- ☐ Three or more multilevel groundwater/vadose zone monitoring points.

- ☐ A soil vapor extraction system may be needed to reduce the potential for adverse vapor migration impacts (or it may be required by regulation). The SVE system consists of control valves, sampling ports, air/water separator, air filter, blower, and vapor treatment equipment.

The air injection well should be designed the same as wells intended to be used for full-scale implementation (see Section 4.3.1). A typical air injection well is a 1- to 4-inch-diameter vertical well having a 1- to 2-ft-long screened interval installed 5 ft below the lowest depth of observed contamination. For drilled wells as opposed to direct-push wells, it is important to ensure a good annular seal between the top of the screened interval and the water table to prevent vertical airflow within the borehole.

To the extent possible, existing groundwater monitoring wells and other monitoring installations should be incorporated into the design. The piezometers and groundwater sampling points ideally should be screened only within the target treatment area. Groundwater wells should be designed and installed such that the length of screen exposed above the water table is minimized.

Vapor monitoring points should be screened over a narrow interval (1 to 2 ft maximum) and placed just above the capillary fringe. Seasonal water table fluctuations should be considered when selecting appropriate depths for vapor monitoring points. For shallow sites (i.e., depth to groundwater <30 ft bgs), monitoring networks like these are often quickly and cost-effectively installed with direct-push methods. At deeper sites, or sites with access restrictions, practical considerations may dictate the use of fewer wells or multilevel samplers.

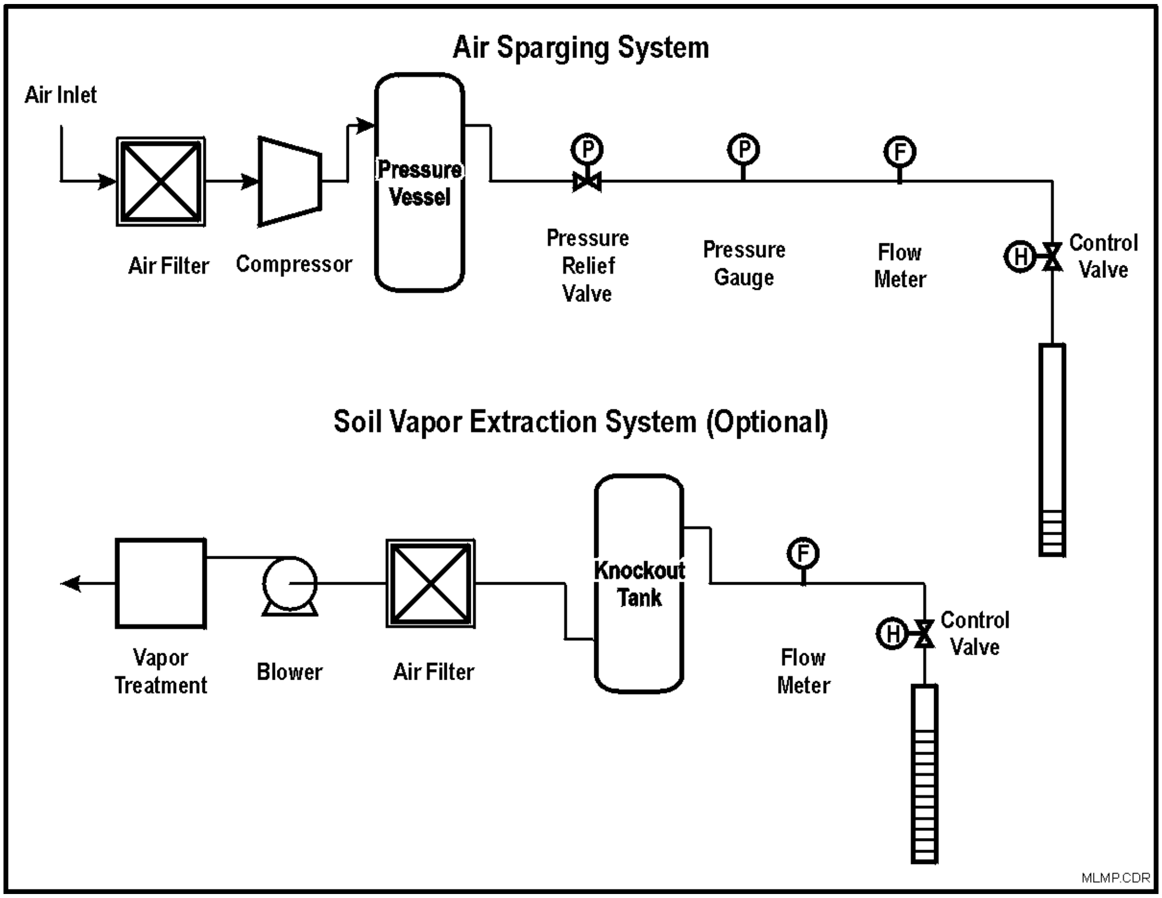


FIGURE 4-1. Components of a Typical Air Sparging System

4.2.2 Pilot-Scale Testing Layout

A sample pilot test layout is shown in Figure 4-2. When determining the vapor monitoring point layout, it is important to recognize that air distributions often have unpredictable preferred directions. Vapor monitoring points should be spatially varied and placed at several different angles from the sparge well because preferential flow and channeling make the air distribution pattern unpredictable and a straight line of vapor monitoring points might provide inadequate or nonrepresentative data (Bruce et al., 2001). Furthermore, the locations should reflect the hydrogeologic setting and the preferred well spacing. In most circumstances, the vapor monitoring points should not be installed more than 10 ft away from the injection well to obtain adequate data to characterize the injected air distribution. The groundwater monitoring wells should be located at three different distances, no more than 20 ft out from the injection well, to obtain good pressure transducer measurements.

4.2.3 Pilot-Scale Test Evaluation

The data from pilot-scale testing should be evaluated and a decision made about whether or not air sparging is an effective remedial option for the site. The results of the pilot test can sometimes be a challenge to interpret because no site will have completely homogeneous flow around an air sparging well. However, the following is a list of some pilot test results that would indicate that air sparging is infeasible or less than optimal at a specific site. It should be noted that some of the following results may also be caused by the lithology in a highly localized region of the site and the results of the test could change if the injection point is moved to a new location.

☐ If air could not be injected into the aquifer at a flowrate of 5 to 20 cfm at a pressure that does not exceed the soil overburden, then air sparging system design requires more engineering effort.

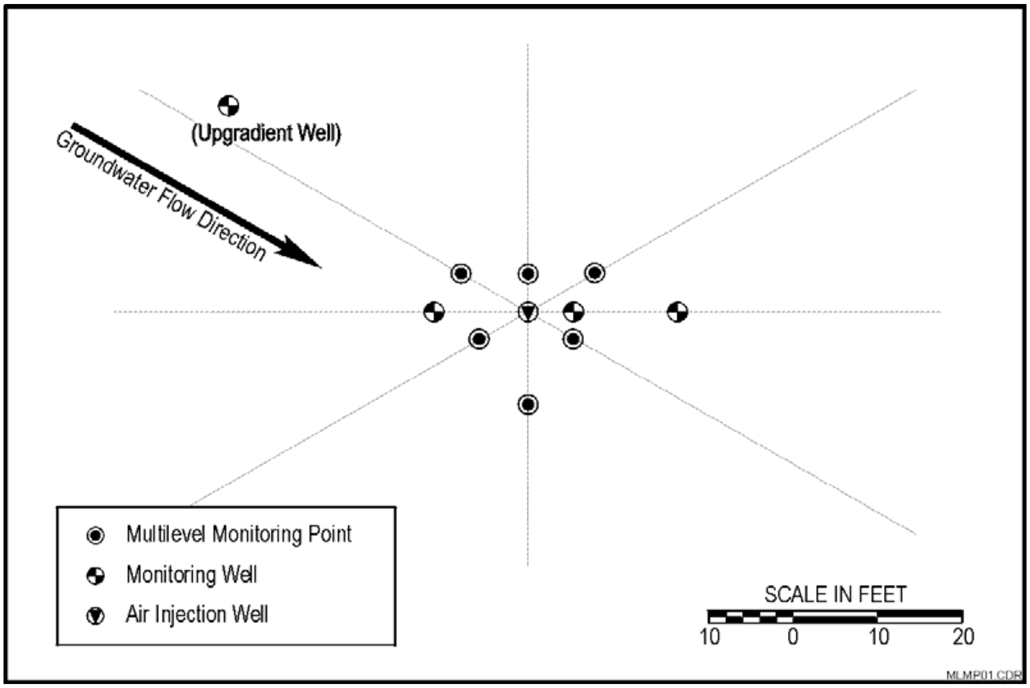


FIGURE 4-2. Sample Pilot Test Layout

- If mass removal rates during the pilot test are very low, then there should be considerable concern about the viability of air sparging at the site. If pilot sparging wells are placed in high concentration areas, pilot test data typically represent the maximum achievable removal rate observed over the lifetime of the air sparging project.

- If all of the injected air appears to be conducted through a channel of high permeability based on tracer testing, then air sparging either may be infeasible or site-specific system design enhancements may be necessary to avoid and/or compensate for this channeling.

- If the groundwater pressures remain elevated for more than 8 hours, it can be assumed that the injected air is trapped or limited by subsurface stratification and may not be reaching the targeted treatment zone.

- For sites with SVE systems, if helium recovery is low (less than 20%), the air is most likely being trapped by less permeable lenses or layers that conduct it beyond the SVE system or out of range from monitoring wells (Figure 4-3). This indication of poor air distribution may impact mass recovery, but could also limit air sparging implementability, if buildings and/or other potential receptors are located nearby.

- Odors caused by the contaminants, noise caused by the equipment, or other environmental factors may not make air sparging infeasible from a technical standpoint, but may make the system less acceptable for the community or property owner.

4.3 Full-Scale Implementation

If results from pilot testing are favorable, then the full-scale design may be developed and implemented. If buildings or underground corridors may be impacted, vapor migration management must be accommodated in the system design. This topic is discussed in detail in Leeson and Hinchee (1996). The engineering design process can be divided into these categories:

- Air injection system
- Vapor extraction and treatment system (if applicable)
- Monitoring network.

Table 4-2 summarizes the critical design considerations involved in full-scale implementation of an air sparging installation.

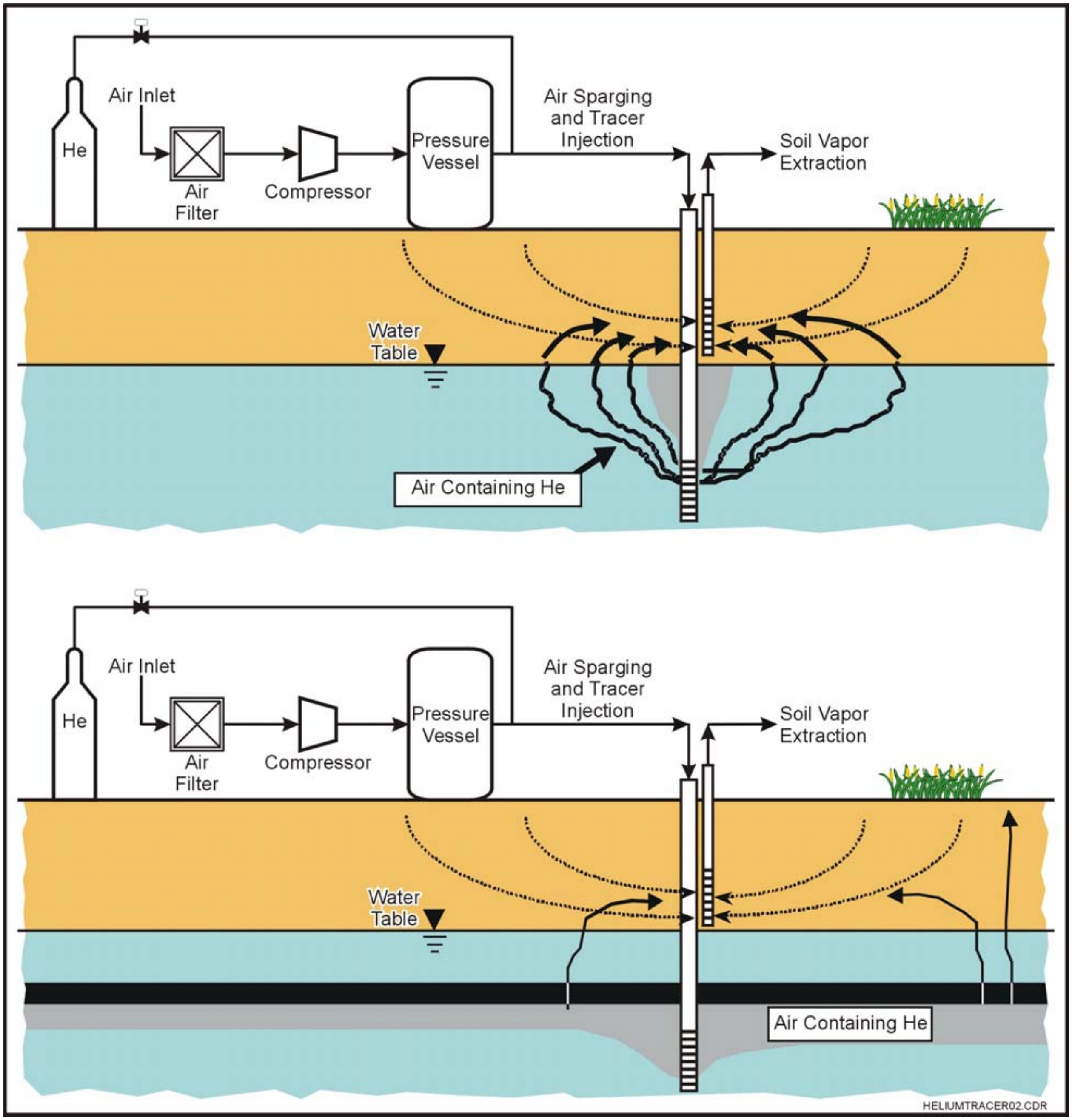


FIGURE 4-3. **Helium Tracer Test Results with Optimal and Suboptimal Site Geology**

4.3.1 Air Injection System

The air injection system is the primary component of the air sparging system and consists of an air compressor with pressure vessel, air filter, piping, valves/controls, and injection wells (see Figure 4-1). The following sections discuss injection well placement and design as well as air compressor selection.

4.3.1.1 Injection Well Placement

Starting with a plan view map, air injection wells are placed in locations consistent with the selected well spacing within the target treatment area. A relatively dense well spacing of 15 to 20 ft, as shown in Figure 4-4, is recommended (Leeson et al., 2001; Bass et al., 2000). The study by Bass et al. (2000) showed that the most

TABLE 4-2. Critical Design Considerations for Air Sparging Installations

Installation	Design Parameter
Air injection system	Injection well screen begins approximately 5 ft$^{(a)}$ below target treatment area.
	Separate pressure control and flowmeter for each injection well.
	Competent annular well seal immediately above injection well screen (if drilled installation).
	Flowrate between 5 to 20 ft^3/min. Note that 20 ft^3/min has been found to be the most effective.
	Pulsed injection in banks of 2 to 5 wells.
Vapor extraction and treatment system	Extract 2 to 3 times the volume of air injected and maintain vacuum in soil vapor monitoring points.
	If VOC concentrations in the extracted vapor exceed 150 ppmv, consider thermal treatment (i.e., thermal or catalytic oxidation). GAC treatment is typically cost-effective for concentrations below 150 ppmv.
	Refer to standard design manuals (USACE, 1995).
	Option for colocating extraction wells in same borehole as injection wells.
Groundwater monitoring wells	Refer to standard design manuals (USACE, 1998).
	Diameter at least 2 inches to allow for insertion of pressure transducer.
Multilevel groundwater and vapor monitoring points	At least two sampling depths: • In contaminated groundwater area • In vadose zone approximately 1 to 2 ft above water table.
	Discrete sampling intervals: 0.5 to 1 ft in length and 0.25 to 0.5 inches in diameter.

(a) If site stratigraphy does not allow for a separation of 5 ft, the injection screen can be installed at lesser distances below target treatment zone. However, the shorter the distance from the target treatment zone to the top of the injection well screen, the greater the chance that portions of the target treatment zone will not receive direct contact with air channels.

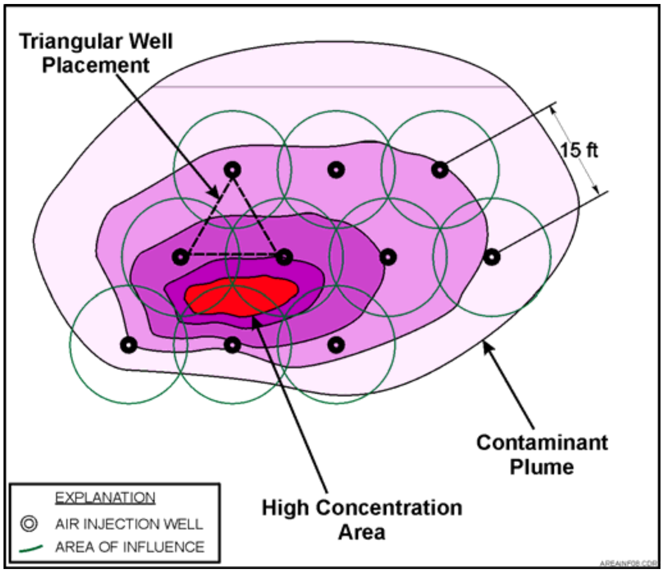


FIGURE 4-4. Standard Design Approach to Injection Well Placement

successful air sparging systems consisted of multiple wells spaced less than 30 ft apart. Typically, a triangulated spacing is preferred because it increases the amount of overlap of the influence of the individual wells.

4.3.1.2 Injection Well Design

The critical design parameters for air injection wells are the depth of the injection well screen, the use of flowmeters, and the annular well seal. Figure 4-5 illustrates a typical air sparging injection well design.

The vertical air injection well should be constructed of 1- to 4-inch-diameter, schedule 40 PVC well casing with a slotted screen. For vertical wells, the well screen interval should typically be about 1 to 2 ft long and placed entirely below the groundwater table. Longer well screens generally are not necessary, but may be appropriate for some sites where greater air flowrates are desired and the formation is relatively tight. The specific screen depth at any given site is based on considerations of the contaminant depth and subsurface stratigraphy. Performance data demonstrates that placing the top of the injection screen approximately 5 ft below the bottom of the contaminated zone is preferable (Leeson et al., 2001). If the source is a DNAPL that results in dissolved contaminants through the entire saturated interval, sparging well screens should be installed such that the bottom of the screen is at or just above the aquitard underlying the aquifer (assuming fairly homogenous soils). Injection well screens that are

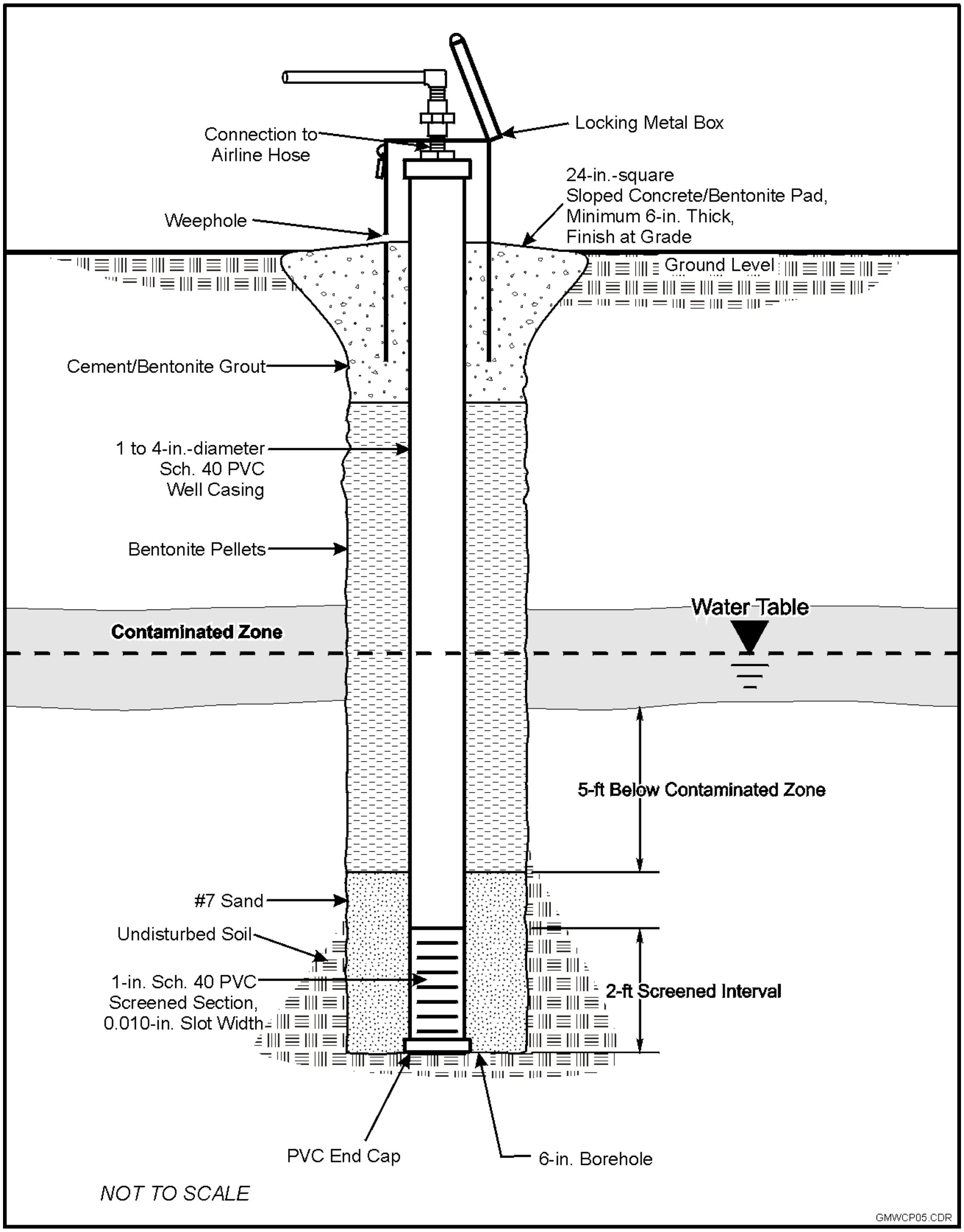


FIGURE 4-5. Typical Sparge Well Construction

installed much greater than 5 ft below the target treatment zone run the risk of air bypassing the contaminated area. Likewise, injection wells installed too shallowly will likely result in air channels not contacting the lower portions of the contaminated area. If confining layers are present, they may prevent airflow from reaching the contaminants. However, this negative impact can be avoided by modification of well screen depths or well spacing. Subsurface stratigraphy may force the practitioner to install the injection well screens closer to the bottom of the target treatment zone than 5 ft.

Injection wells should be installed with a competent annular seal in the borehole above the screened interval, using a bentonite-and-grout slurry. However, bentonite chips can be used if hydrated continuously during installation. In the absence of a good seal, the injected air will flow up along the well bore and the well will be ineffective. At some sites, driven points can be used without injecting grout; site soils will dictate this use.

The piping and manifolding of the wells need to be designed such that each injection well has its own dedicated pressure control and flowmeter. This design allows observation and optimization of airflow into each well, and unless flow can be regulated to each individual injection well, air injection will not be uniform throughout the system.

To understand the need for dedicated controls for each injection well in a network, it is necessary to understand how airflow is introduced into the saturated zone. First, a threshold pressure must be attained before the airflow can push through into the saturated zone. Enough pressure has to be applied to make room for the introduced air which involves overcoming the resistance to airflow contributed by the well screen, the packing material, the soil matrix, and the groundwater. Once the threshold pressure is achieved, very small changes in pressure can result in large flowrate changes (Rutherford and Johnson, 1996). The minimum pressure needed to achieve airflow into the saturated zone will be determined during the pilot-scale test. The practitioner should be aware of the fact that if the minimum pressure needed to induce flow is too high, there could be safety issues and practical operational difficulties to air sparging. It is important that the air injection pressure does not exceed safe levels since high pressures can damage air sparging well seals and cause fracturing in the formation. As a general guideline, to maintain the integrity of the injection well seal, practitioners should proceed with caution when operating in a range near the estimated fracturing pressure (P_{fracture}). This pressure is related to the overburden or weight of the soil matrix above the injection point (based on a bulk density of 105 lb/ft^3) and can be estimated with the following theoretical relationship:

$$P_{\text{fracture}}\,[\text{psig}] = 0.73 \times D_{\text{soil}}\,[\text{ft}] \tag{4-1}$$

where: D_{soil} [ft] = depth below ground surface to the top of the air injection well screened interval. The actual fracture pressure of the formation may be greater due to the resistance offered by friction along the margin of the overburden column and resistance offered by surface completion features (e.g., concrete pad).

Vertical Injection Wells

Air injection wells can be installed using either direct-push technology or traditional auger drilling techniques. Injection wells installed using direct-push technology tend to be less expensive; however, site soils or contaminant depth may necessitate the use of traditional auger drilling techniques.

Direct-push techniques are believed to minimize disturbance of the soil column and to eliminate the need for well packing material. In less permeable soils, sand pack installation and grouting below the water table may be necessary to prevent short-circuiting. If site conditions are suitable, direct-push is quicker than traditional auger drilling.

Direct-push wells are typically small diameter wells with pre-packed well screens. Air sparging injection wells can be constructed with standard off-the-shelf groundwater well systems. These pre-packaged systems are available in two sizes: 1.4 inches OD (outer diameter) (0.5 in or 0.75 in ID [inner diameter]) and 2.5 inches OD (1.0 in or 1.5 in ID). The pre-packed well screens typically consist of 20/40 grade sand. The small diameter well has a 0.50-inch Schedule 80 PVC riser and is installed with a 2.125-inch OD probe rod. The large diameter well uses a 1.0-inch Schedule 40 PVC riser pipe and is installed with a 3.25-inch OD probe rod. The wells are lowered to the required depth after the probe rod has been driven into the subsurface to the target depth. Once the well assembly has been lowered, and the probe rod retracted, a sand barrier is created directly above the well screen, which prevents grout from entering the screen. A granular bentonite or bentonite slurry is then installed in the annulus and the well is sealed and grouted according to EPA and ASTM D-5092 method requirements. Standard aboveground or flush-mount well protectors can be used with direct push wells.

If site geology and/or contaminant depth prevent the use of direct-push techniques, other drilling methods, such as hollow-stem augering, will be required. When using a hollow-stem auger, it is vital to have a good annular seal that begins well below the water table. Whenever possible, the diameter of the borehole should be at least two times greater than the sparging well outside diameter. The annular space corresponding to the screened interval should be filled with silica sand or equivalent. The annular space above the screened interval should be sealed with a bentonite-and-grout slurry to prevent short-circuiting of air to the vadose zone.

Existing groundwater monitoring wells are unlikely to be suitable for use as an injection well. Groundwater monitoring wells are frequently screened above the water, or may at least have a sand pack that extends above the water table. In these situations, the majority of the injected air will be delivered into the vadose zone with little or no air entering the saturated zone outside the borehole.

Horizontal Injection Wells

Horizontal wells are occasionally installed to inject air below structures within or through which drilling is not possible. However, horizontal wells have the disadvantage of higher installation costs and a high potential for nonuniform aeration. Wade et al. (1996) documents the difficulties with non-uniform aeration during the use of a 200-ft horizontal well as a barrier to the migration of a chlorinated solvent plume, although relatively successful implementations have been documented (Kershner and Theoret, 1997; Roth et al., 1998). Horizontal well installation for air sparging is not typically recommended.

4.3.1.3 Air Compressor Selection

An air compressor provides the driving force to move air through the sparging system. Compressors typically are selected during the pilot-testing phase based on expected injection flowrates and pressure requirements. According to current design practices, the practitioner should expect to inject air at flowrates ranging from 5 to 20 cfm per injection well at pressures 10 to 15 psig above the hydrostatic pressure. Compressor selection should be discussed with a reputable vendor and/or manufacturer. It is important that the unit(s) be capable of: (a) providing the necessary flow capacity of clean air at the design pressures, and (b) long-term continuous operation with minimal maintenance requirements. In selecting the compressor size, one must consider the required air flowrate and the total system pressure drop. System pressure drop includes the back-pressure due to the injection wells and formation in an air injection configuration plus any pressure drop in the system piping. Both oil-less, rotary vane compressors and reciprocating piston-type compressors are suitable for air sparging applications. Reciprocating piston air compressors are typically designed to deliver low flow at higher pressures than rotary vane compressors, so they can be used for sparging at deep sites or in low permeability soils. Figure 4-6 shows a typical performance curve for a 5-hp reciprocating piston air compressor.

Air compressors should be selected based on their ability to deliver the desired flow at a pressure that does not exceed 60% to 80% of the maximum pressure. The empirical data collected during pilot testing should be used to properly size the compressor for full-scale use. Proper sizing and selection of a compressor is essential to ensure that the unit can deliver the required airflow at the necessary pressure and that it operates properly. Choosing the wrong compressor can result in an inability to deliver sufficient air or a significantly shortened compressor life. It is best to select the compressor to allow operation near the middle of its performance range. A compressor operating near its maximum pressure is running inefficiently and under stressed conditions, thereby increasing operating costs and shortening its life. Selection of an oversized compressor reduces operating efficiency and increases design and installation costs unnecessarily.

Practitioners have varied opinions on the effect of changing air injection flowrates. Some believe that lower air injection rates favor biological treatment relative to volatilization, while others believe that increased injection rates can improve air distribution. Johnson et al. (2001) states that low air flowrates generally yield less extensive air distributions compared to high air flowrates. Laboratory-scale studies (Ji et al., 1993; Rutherford and Johnson, 1996) indicate that increasing the injection flowrate results in positive effects, especially in stratified geological settings, by allowing the air to break through soil layers under which it might normally be stratified, creating a dense air distribution network. Although a high injection rate is favorable, it will undoubtedly result in higher costs due to the necessity of selecting a larger compressor. The practitioner must weigh all these factors when selecting a compressor.

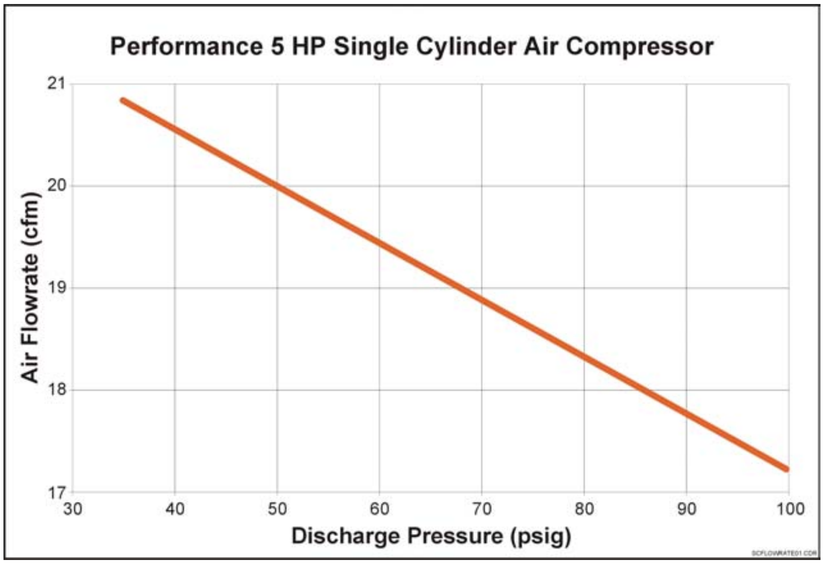


FIGURE 4-6. Example Air Compressor Performance Curve

4.3.2 Vapor Extraction and Treatment System

Vapor extraction systems are installed in conjunction with in situ air sparging systems when contaminant vapors must be recovered, or where there is concern that contaminant vapors could migrate to enclosed spaces (e.g., utility conduits, basements, buildings). An SVE system should not be installed when vapors, particularly petroleum hydrocarbon vapors, can be degraded in the vadose zone. In general, if safe and feasible, air injection into the aquifer with no SVE is the preferred and most economical configuration for full-scale air sparging systems. However, several conditions may require vapor collection and treatment:

- One or more of the target contaminants are not aerobically biodegradable (e.g., chlorinated solvents).
- Soil vapor monitoring indicates that contaminants are not adequately biodegraded in the vadose zone and could potentially impact utility conduits, basements, and/or buildings.
- Substantial contaminant mass remains in the vadose and/or smear zone through which the water table fluctuates (typically this condition exists in or near the source area).

SVE systems are routinely installed and design considerations are covered thoroughly in several manuals (including U.S. Army Corps of Engineers, 1995). The typical components of an SVE system include the vacuum blower, air filter, air/water separator, valves/controls, extraction wells, and vapor treatment system (see Figure 4-1).

The soil vapor extraction rate should typically be 2 to 3 times the air injection rate and should maintain adequate vacuum in the nearby soil vapor monitoring points. The number of SVE wells required will typically be less than the number of air sparging wells because the spacing for SVE wells is generally on the order of 30 ft or more, compared to the 15-ft spacing for a standard air sparging design. The minimum number of SVE wells required can be estimated by the ratio of target treatment area to the area of influence of the SVE well as follows:

$$N_{SVE} = \frac{A_{target}}{\pi(R_{SVE})^2} \tag{4-2}$$

where: N_{SVE} = minimum number of SVE wells
A_{target} = target treatment area
R_{SVE} = radius of influence for SVE well.

The radius of influence for SVE wells is typically around 20 ft for sandy/silty soil types and 30 ft or more for sand to gravel soil types.

The SVE wells can be located adjacent to an air sparging well or in between a network of air sparging wells. An additional option for SVE well placement is to colocate the extraction well and air sparging injection well in the same borehole. This strategy provides a conservative SVE well spacing, but will reduce installation costs.

Figure 4-7 is a diagram of a typical SVE well. The SVE wells should be screened above the seasonal high water table to avoid flooding of the wells. The SVE well should be constructed of 2- to 4-inch-diameter, schedule 40 PVC well casing with a slotted screen. After the screen and riser are installed, the annular space is filled with a silica sand mixture to a height of 2 ft above the screen. A 2-ft-thick (minimum) bentonite seal is placed on top of the sand pack and the remaining annular space filled with a bentonite-cement grout mixture. A flush-mount protective vault with a watertight, locking well cap is often placed over the well.

There are several options for the vapor treatment system such as: thermal oxidation, catalytic oxidation, and granular activated carbon. Thermal oxidation and catalytic oxidation rely on thermal destruction to combust the contaminants and convert them to carbon dioxide and water, while granular activated carbon relies upon adsorption of the contaminants onto a carbon substrate for later regeneration and/or disposal. If VOC concentrations in the extracted soil vapor exceed 150 ppmv, consider thermal oxidation or catalytic oxidation. Granular activated carbon is generally cost-effective for concentrations below 150 ppmv. However, each constituent has a different adsorption capacity ranging from 1.5g/100g GAC for VC to 54g/100g GAC for PCE. Catalytic oxidation is typically not suited to sites with chlorinated volatile organic compounds.

4.3.3 Monitoring Network

The monitoring network for an air sparging system consists of groundwater monitoring wells and multilevel monitoring points. Groundwater monitoring wells are traditional wells with a relatively large screened interval (approximately 5 ft) in the contaminated zone of the aquifer. Multilevel monitoring points are much smaller and are designed to collect water and soil vapor samples from discrete intervals in the groundwater and vadose zone.

4.3.3.1 Groundwater Monitoring Wells

Construction of groundwater monitoring wells is standardized and often dictated by local regulatory issues, and is defined in detail in several manuals (including U.S. Army Corps of Engineers, 1998). A typical groundwater monitoring well may consist of 4-inch-diameter PVC casing with the well screen in the saturated zone. The annular space outside the screened interval of the monitoring wells is filled with a medium-grade silica sand filter pack. The remaining annular space is sealed to the surface with a bentonite plug. A minimum well diameter of approximately 2 inches is required for use of most pressure transducers. Other design parameters of a standard groundwater monitoring well will allow for collection of pressure and contaminant data. The following issues should be considered regarding the use of groundwater monitoring wells:

- ☐ The location of groundwater monitoring wells should span the system treatment area from upgradient, through the treatment area, to downgradient of the area.
- ☐ Downgradient wells should include at least one sentinel well just upgradient of a defined compliance point.
- ☐ The number and distribution of wells upgradient and within the treatment area is specified by the project context and site conditions.
- ☐ Groundwater monitoring wells should not be used for measuring parameters such as dissolved oxygen or tracer gases, because results can be affected by well screens that extend above the water table (Leeson et al., 2001).

4.3.3.2 Multilevel Monitoring Points

Monitoring points are used for groundwater and soil vapor measurements and are a very important component of an air sparging system. Figure 4-8 is a diagram of a typical multilevel groundwater and soil vapor monitoring point. Proper construction of monitoring points is essential for monitoring groundwater and soil vapor concentrations.

Each monitoring point should be screened at a minimum of two depths. The deepest sampling screen or port should be located in the saturated zone within the target treatment area. The sampling ports should be placed in the aquifer at depths within which most of the dissolved contamination is located as determined by site characterization (sampling and lithology) and permeability test data. Because air distribution and contaminant migration are very sensitive to site-specific conditions, sampling port placement must be determined on a site-specific basis. The objective of the location is to be situated in the target treatment area and to facilitate tracking of the performance of the air sparging system in situ.

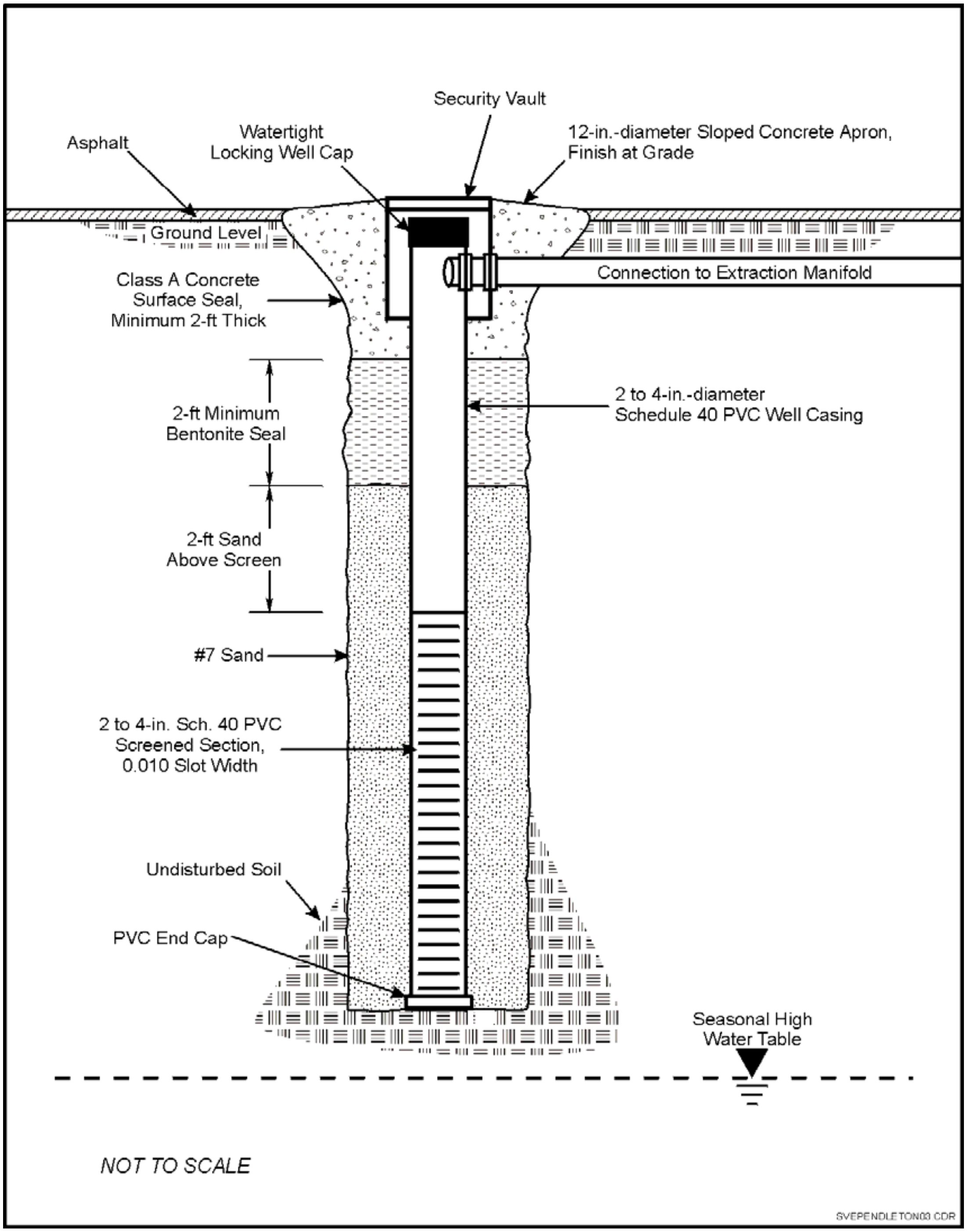


FIGURE 4-7. Typical SVE Well Construction

Depth intervals may be determined from historical site data or a preliminary groundwater survey. At least one sampling port should be located in the vadose zone 1 to 2 ft above the water table to monitor contaminant vapor concentrations. In some cases, it may be desirable to add additional screened depths to more fully monitor the contaminated interval, to monitor differing stratigraphic intervals, or to adequately monitor deeper sites.

Soil vapor monitoring point construction will vary depending on the drilling depth and technique. If traditional auger drilling is being used, a simple construction technique is to use small-diameter (1/4 inch) tubes extending to the specified depth in the vadose zone,

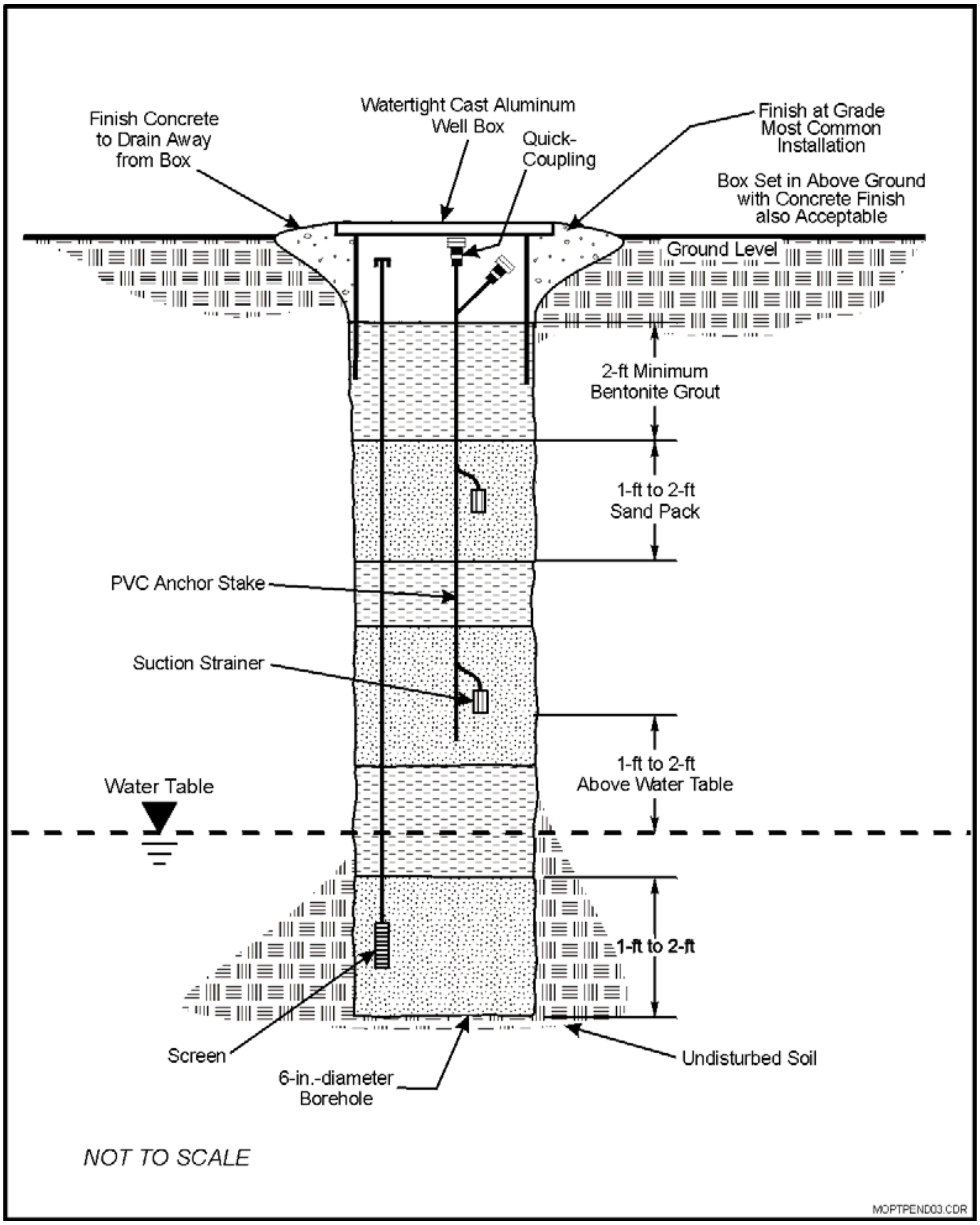


FIGURE 4-8. **Typical Soil-Vapor/Groundwater Monitoring Point Construction**

with a screen approximately 6 inches long and 1 inch in diameter attached to the end. In shallow open-hole installations, rigid tubing terminating in the center of a gravel or sand pack may be adequate. The gravel or sand pack normally should extend for an interval of 1 to 2 ft, with the screen centered. In low-permeability soils, a larger gravel pack may be desirable. In wet soils, a longer gravel pack with the screen near the top may be desirable. A bentonite seal at least 2 ft thick normally is required above and below the gravel pack. The following issues should be considered regarding multilevel monitoring points:

☐ Monitoring points should be distributed throughout a site to adequately measure contaminant concentrations.

☐ A sufficient number of monitoring points should be installed to ensure representative sampling. The actual number installed is site-specific and is driven primarily by plume size, the cost of installing and monitoring additional monitoring points, the scope of the project, and regulatory considerations.

- ☐ Monitoring points must be located between the injection well and any buildings that may be at risk to ensure that the structures are not impacted by vapor-phase contaminants.

- ☐ Monitoring points typically are used to collect groundwater and soil vapor for measurement of oxygen and contaminants. The tubing material must have sufficient strength and be nonreactive. Appropriate materials include nylon and Tygon™. Sorption and gas interaction with the tubing materials have not been significant problems for this application. If a monitoring point will be used to monitor specific organics in the low-ppm or low-ppb range, Teflon™ or stainless steel tubing may be appropriate.

5.0 SYSTEM OPERATION, MONITORING, AND OPTIMIZATION

Operation, monitoring, and optimization efforts must be focused on specific remedial objectives. Generally, these objectives include maximizing mass removal efficiency with respect to both time and money, minimizing O&M costs, and achieving site closure. This section outlines system startup, operation, and monitoring recommendations that can be applied toward project-specific objectives. A troubleshooting guide for air sparging system operation is presented in Appendix H.

5.1 System Startup

The objectives of performing system startup checks are to ensure that the system was designed, installed, and assembled properly, that continued operation of the system will not result in safety hazards or equipment failures, and that preremediation conditions are well understood. Typical startup activities are as follows:

- ❑ A brief startup test must be conducted to ensure that all system components are operating properly. Components to be checked include the air compressor; in-line airflow meters and pressure gauges; groundwater and soil vapor monitoring points; groundwater analysis instrumentation; soil vapor analysis instrumentation; SVE system (if applicable); and any vapor treatment system components. A site-specific checklist should be used to document the system shakedown (see Table 5-1).
- ❑ If the air sparging system is coupled to an SVE system to collect vapors stripped from the groundwater, then the SVE system should be operated for a period of time prior to air sparging startup to (1) ensure that the SVE system is operating properly; (2) help dry the soil, increase vadose zone permeability, and maximize SVE capture efficiency; and (3) capture the initial high mass loading from air sparging. Note that if the SVE system is installed in an area having impacted unsaturated soil (such as near the source release or an area where the water table elevation fluctuates over a wide

TABLE 5-1. Air Sparging System Startup Checklist

System Component	Evaluation Criteria
Compressor shutoff switch	Ensure the proper function of this safety feature. This switch shuts off delivery to the reservoir at the target pressure. Follow manufacturers' instructions.
Compressor tank relief valve	Ensure the proper function of this safety feature. This valve exhausts air from the reservoir if the internal pressure exceeds safety limits (in the event the shutoff switch fails). Follow manufacturers' instructions.
Primary pressure regulator	Check to ensure that the pressure delivered from the reservoir can be adjusted within the range of intended operating pressures.
Primary flow valve	Check to ensure that the flow from the reservoir can be immediately terminated by closing this valve.
Manifold system (to split airflow to multiple sparging wells)	Check to ensure that there are no air leaks from the manifold and that connections to sparging well lines are secure.
In-line pressure gauge	Check to ensure that the pressure in each sparging line can be adjusted and that the air flowrate responds to changes in pressure within the safe range of operating pressures.
In-line flowmeter	Check to ensure that there is no debris or obstruction in the meter that would impede its proper function. Check that air flowrate changes with pressure adjustments within the safe range of operating pressures.
In-line check valve	Ensure that check valves are in place if cyclical operation of some or all sparging wells is expected. (Under some conditions check valves may not be necessary.)
In-line flow valve	Check to ensure that flow to each individual sparging well can be immediately terminated by closing each valve.
Air line hoses, fittings, connectors	Check to ensure general integrity and secure fittings and connections. Damaged hoses and fittings should be replaced immediately upon observation.
Sparging wellhead	Check to ensure that excessive pressure is not damaging the wellhead and surrounding seal. Ensure that access to wellhead fittings is maintained.

range), the mass removal rate achieved by volatilization from the vadose zone may dominate the additional mass removal rate added by starting air sparging and may not be noticeable using field instruments. For example, using typical sparging and extraction air flowrates and a generous estimate of in situ stripping efficiency, 1,000 μg/L of benzene in groundwater would result in an SVE off-gas concentration of about 25 ppmv (assuming the extraction flowrate is twice the injection flowrate). Initial SVE off-gas concentrations without air sparging can be greater than 10,000 ppmv, and may therefore mask any contribution from air sparging once that airflow stream is initiated.

- ☐ If an SVE system is not part of the air sparging system, then soil vapor concentrations (including contaminant and oxygen concentrations) should be measured. The initial baseline contaminant concentrations in the vadose zone should be measured and compared to the levels observed after startup. An increase in contaminant soil vapor concentrations can then be attributed to volatilization from the groundwater. Initial oxygen concentrations are useful for measuring bioactivity in the vadose zone. Field instruments, as opposed to more costly laboratory analysis, should be appropriate for this purpose.

- ☐ To initiate air sparging, the air flowrate should be increased slowly to the desired flowrate in order to ensure that the pressure does not exceed the maximum pressure and prevent damaging the well seal or fracturing the soil. As groundwater is temporarily displaced after the initiation of sparging, backpressures and flowrates are likely to fluctuate. This variable period is typically short-lived as air channels are formed allowing sparged air to reach the vadose zone.

5.2 System Operation

Air sparging systems can be operated in either a continuous or pulsed mode, but cycling air injection in each well intermittently is thought to achieve more extensive air distribution. Cyclical or pulsed operation of banks of two to five injection wells is recommended for the following reasons:

- ☐ Studies suggest that mass removal can be increased by 20% to 30% through pulsed operation (Bruce et al., 2001, Kirtland and Aelion, 2000).

- ☐ The difficulty of controlling a multiwell air injection system increases as the number of wells manifolded together increases.

- ☐ The total required system injection flow capacity is lower in pulsed mode, resulting in lower costs for air compressors.

- ☐ Pulsed operation may be necessary in sparge barrier applications to prevent groundwater bypassing due to water permeability reductions in the formation caused by air injection.

The most effective cycling frequency is site-specific and depends on the characteristics of site soils and the distribution of the dissolved contaminants. To date, there is little guidance on how to choose pulsing frequencies (defined by on and off times). SVE system data provide a direct measure of volatilization removal rates, and therefore can be used to assess how changes in pulsing conditions affect volatilization rates. Some practitioners believe that the minimum injection period (the on times) for air sparging should be consistent with transient pressure transducer response data identified during pilot testing. Air injection needs to last at least as long as the time necessary to reach the peak in transducer response, and preferably as long as the time required for pressures to return to near equilibrium or asymptotic values. This indicates that the injected air has emerged from the aquifer into the vadose zone, and near steady-state flow conditions have been achieved (Johnson et al., 2001).

5.3 System Performance Monitoring

The general objectives of system monitoring are to provide current information regarding progress toward remedial objectives. System monitoring provides the opportunity to maintain contaminant removal efficiency, improve operation strategies, track progress toward remedial goals, and stop operations when cost efficiency is lost or remedial goals are achieved. A monitoring plan containing data objectives, monitoring parameters, locations, and frequencies should be developed and agreed upon by the site managers and regulators to ensure that these goals are met. Appropriate quality assurance (QA) procedures should be followed in developing and implementing this plan to ensure that valid data are collected and analyzed.

Regardless of the air sparging system design, it is essential to include one or multiple wells for monitoring contaminants on the upgradient side of the air sparging system. Upgradient wells can provide an early warning of potential plume breakthrough if, over time, the plume develops in such a way that influent concentrations exceed those planned for in the design.

5.3.1 Operation Parameters

During continued operation, the following measurements should be made on a periodic basis (ranging from weekly to semiannually):

☐ Air sparging system injection flowrates (weekly)

☐ SVE system inlet and outlet concentrations (as required by the air discharge permit) and flowrate monitoring (weekly)

☐ System controls that regulate cycling (monthly)

☐ Groundwater quality monitoring of dissolved oxygen and contaminant concentrations (quarterly to semiannually as required by regulatory guidelines)

☐ Groundwater level measurements in wells unaffected by air injection (seasonal) to assess the position of the groundwater table relative to the injection and extraction wells' screened intervals

☐ Soil vapor VOCs, oxygen, and carbon dioxide (quarterly to semiannually).

RPMs should ensure that enough data is available to track the performance and cost trends of the air sparging system. The following recommended plots should be developed and incorporated into reports to track system performance of an air sparging system with SVE:

☐ Influent VOC concentration vs. time

☐ Cumulative mass recovered vs. time

☐ Cumulative treatment costs vs. cumulative VOCs recovered

☐ Average treatment cost per pound of VOC recovered vs. time.

5.3.2 Estimating Contaminant Removal

SVE off-gas concentrations should be monitored regularly for VOC levels and volumetric flowrate to estimate and track the mass of VOCs removed by the SVE system. The mass removal rate at the time of monitoring can be estimated using Equation 5-1:

$$m_{SVE} = C \cdot Q \left(\frac{1\,\text{kg}}{10^6\,\text{mg}} \right) \qquad (5\text{-}1)$$

where: m_{SVE} = mass removal rate in the SVE off-gas stream, kg/day
C = concentration of VOCs in SVE off-gas stream, mg/m^3
Q = volumetric flowrate in SVE off-gas stream, m^3/day.

The total VOC mass removed (m_{SVE}) in the SVE off-gas stream can be estimated using Equation 5-2:

$$M_{SVE} = \sum_{i=1}^{n} C \cdot Q \cdot t_i \cdot \left(\frac{1\,\text{kg}}{10^6\,\text{mg}} \right) \qquad (5\text{-}2)$$

where: C = concentration of VOCs in SVE off-gas stream, mg/m^3
Q = volumetric flowrate in SVE off-gas stream, m^3/day.
i = counting variable
n = total number of time periods summed
t_i = time intervals over which the concentration and flowrate data are taken to be representative, days.

To calculate the VOC concentration in mass per unit volume from parts per million by volume (as are common units in field instruments), Equation 5-3 can be used (at 25°C):

$$1\,\text{ppmv} = \frac{0.041 \frac{\text{mg}}{\text{m}^3}}{\text{unit MW}} \qquad (5\text{-}3)$$

For example, if the off-gas temperature is 25°C and the relative concentration weighted average molecular weight (MW) of VOCs in the off-gas stream is 80, then

1,000 ppmv would convert to 3,280 mg/m^3 in units of mass per unit volume by the following equation:

$$80\,(\mathrm{MW})\cdot 1{,}000\,(\mathrm{ppmv})\cdot 0.041\left(\frac{\frac{\mathrm{mg}}{\mathrm{m}^3}}{\mathrm{MW}\cdot\mathrm{ppmv}}\right) = 3{,}280\,\frac{\mathrm{mg}}{\mathrm{m}^3} \tag{5-4}$$

If no SVE system is employed, contaminant mass removal can be measured in situ or estimated based on a simple aerobic biodegradation equation (Leeson et al., 2001) as follows:

$$R_{gw} = V_{soil}\cdot n\cdot O\cdot \frac{10^3\,\mathrm{L}}{\mathrm{m}^3}\cdot\frac{10^{-6}\,\mathrm{kg}}{\mathrm{mg}}\cdot\frac{0.33\,\mathrm{kg\text{-}HC}}{\mathrm{kg\text{-}O_2}} \tag{5-5}$$

where: R_{gw} = aerobic biodegradation rate of contaminant in groundwater due to oxygen delivery to groundwater (kg/day)
V_{soil} = volume of treatment zone (m^3)
n = porosity of aquifer (L-pores/L-soil)
O = dissolved oxygen delivery rate to groundwater outside of air channels (mg-O_2/L-water/d).

5.3.3 Compliance Monitoring

Compliance monitoring for an air sparging system typically involves the collection and analysis of both groundwater and soil vapor samples. Compliance monitoring allows a practitioner to track the air sparging system performance and the progress made towards meeting cleanup goals and performance objectives.

5.3.3.1 Groundwater Monitoring

The frequency of compliance monitoring should be determined with the regulators prior to system startup. Discussions should focus on eliminating unnecessary data (type and quantity) that do not help meet specific data objectives. Quarterly monitoring typically is required during operations in order to minimize uncertainty related to impacts from seasonal hydrologic conditions. However, after the system has been shut down and rebound has been determined to be insignificant, less frequent monitoring (biannual or annual) can confirm that concentrations continue to decrease or are consistently below remedial objectives. Distinctions should be drawn between operational monitoring collected to provide information to help maintain efficient operations and data collected for regulatory compliance. The following suggestions apply to improving groundwater monitoring implementation:

- ☐ The chemical parameters that typically are measured in the monitoring wells include concentrations of contaminants and potentially toxic byproducts. Sampling and analytical techniques for monitoring wells located in the aquifer are similar to those for site characterization. Groundwater sampling can generally be done with an appropriate length of Teflon™ tubing and a peristaltic pump. At deeper sites (>30 ft [9 m]) a submersible pump or a bailer may be required to lift water to the surface. The methods used to collect and analyze groundwater should be clearly defined in the monitoring plan. Guidance documents are available to help practitioners develop technically sound and cost-effective monitoring plans including NFESC's *Guide to Optimal Groundwater Monitoring* (NFESC, 2000a).

- ☐ Because monitoring costs constitute a major annual operating cost of the air sparging system for several years after construction, site managers should optimize both the number of monitoring wells sampled and the information gained. Data objectives must be clearly identified in the monitoring plan and agreed upon among the project team (project manager, contractor, and regulator). Adequate site characterization in the vicinity of the proposed air sparging system, as well as hydrologic modeling, can assist both project managers and regulators in determining the appropriate number and locations of monitoring wells to install at a given site.

- ☐ Cost minimization is most effectively achieved by focusing on the monitoring data objectives. It is very common to collect data in greater quantity, at a greater frequency, and at more locations than are actually used to interpret plume behavior. Collecting excess data should be avoided if at all possible.

- ☐ Minimizing levels of investigation-derived waste (IDW) is another way to reduce costs. Applicable regulations and guidance documents should be reviewed to determine if alternative well purging techniques are permissible at the site. For example, micropurging techniques (Kearl et al., 1992) and diffusion samplers (Vroblesky and Campbell, 2000) are becoming more generally accepted and can reduce both IDW and the cost of handling, treatment, and disposal.

5.3.3.2 Soil Vapor Monitoring

It is common for air sparging systems to be regulated under an air discharge permit to protect against harmful vapor discharges to the atmosphere, even if the system is not coupled with an SVE system. In an air-sparging-only system, periodic monitoring of shallow soil vapor or ambient air just above ground surface may be required to ensure against excessive discharges of VOCs. Typically, air injection will result in only minimal emissions to the surface (U.S. EPA, 1992). Soil vapor monitoring options include sampling from shallow soil vapor monitoring points into Tedlar™ bags or evacuated polished metal canisters, or the use of vapor-phase diffusion samplers. Typically, laboratory analysis of vapor samples is required because the quantitation limits achieved by field meters cannot satisfy data objectives for regulatory compliance. However, hand-held, direct reading instruments are useful for operational monitoring.

5.4 System Optimization

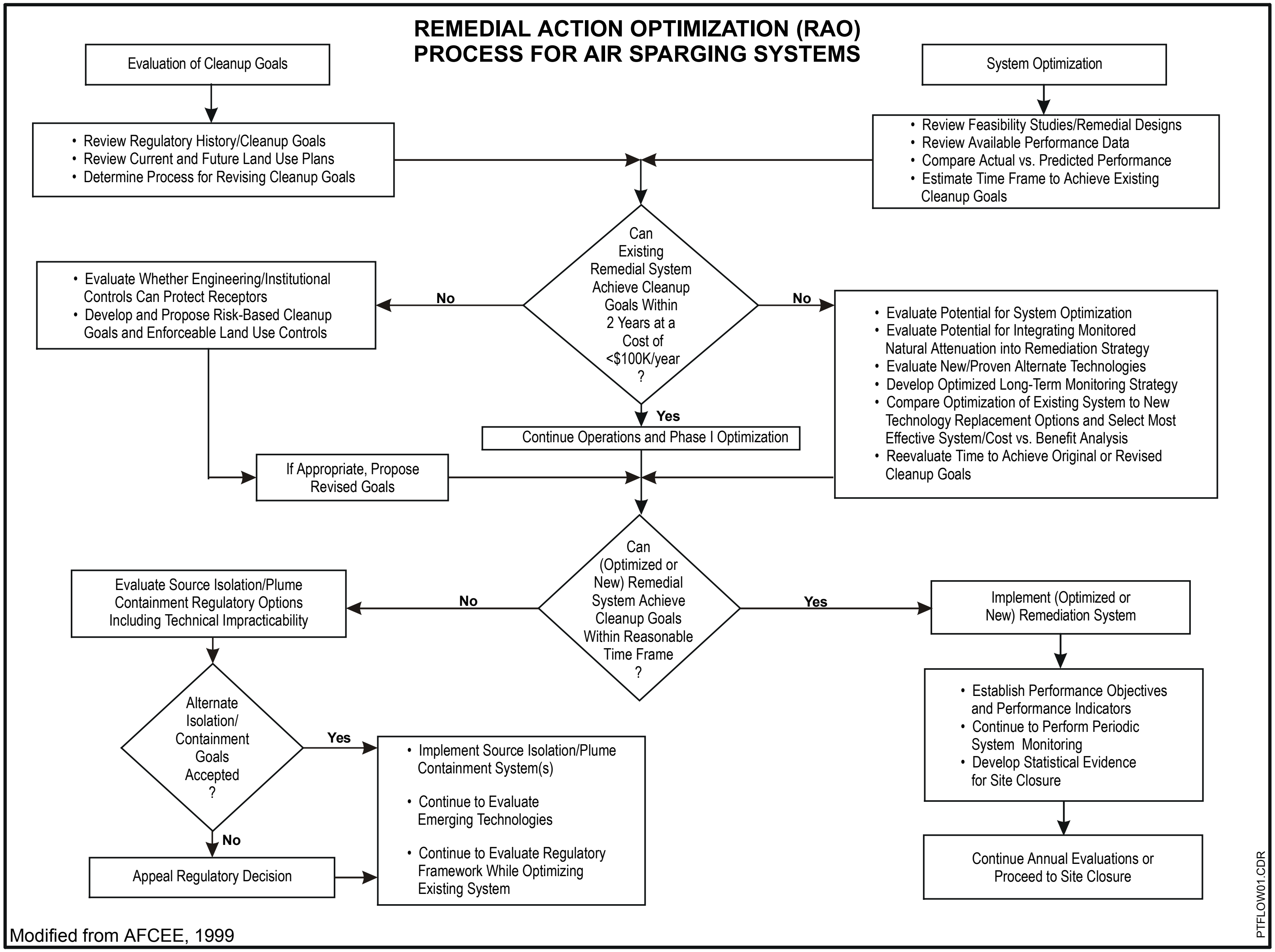
The objective of system optimization is to achieve remedial goals with a minimum investment of time and money. Understanding the likely or typical behavior of these systems can provide opportunities to reduce costs in the initial design phase, and throughout the life of the project. The practitioner should review current monitoring data and look for opportunities to improve removal efficiency such as optimizing air flowrates and sparge well placement. Figure 5-1 is a flowchart showing a remedial action optimization process for air sparging.

The experience of the environmental remediation industry, case histories of previously installed and operated air sparging systems, and knowledge of pertinent mass transfer mechanisms all can be incorporated into the design, installation, operation, optimization, management, and exit strategies for an air sparging project. It is expected that after a variable plateau period of maximum mass removal rates (possibly ranging from nonexistent to several weeks), the mass removal rate will rapidly decline over time as mass reaching the air/water interface comes from sites farther away from the injection wells and air channels. Literature has shown that significant mass removal for BTEX compounds (96-98%) can be achieved in less than six months (Bass et al, 2000). Figure 5-2 shows an idealized plot of cumulative mass removed over time. Note that the majority of the mass is removed in the initial stages of operation and that every equivalent time interval thereafter produces greatly diminishing removal rates. This behavior results in a remediation system that is achieving a mass removal rate substantially less than that for which it was designed, typically the maximum rate observed soon after system startup. The following issues should be addressed during the design or optimization phase in order to ease transition of the system to final shutdown:

- ☐ Focus strategic sparging well placement on localized areas with elevated contaminant concentrations or the plume centerline. This approach can greatly reduce the cost of installation (compared to complete plume coverage) without substantially increasing operating time.
- ☐ Reduce the design capacity of air supply, vapor extraction, and vapor treatment units. This approach will reduce the maximum mass removal capacity of the system, but will result in a system that operates near its optimum design capacity (60 to 80% of maximum capacity) for a longer duration. (Note that the trade-off of lower capital equipment expenses could extend the time required to achieve active remediation goals and should be evaluated accordingly. Reducing maximum removal capacity does not necessarily extend the required time of remediation, but it may.)
- ☐ Consider constructing air supply, vapor extraction, and vapor treatment units on mobile trailers. This approach has been used at many installations to reduce the fixed costs of equipment and enable the equipment to be reused at other sites on an installation. Furthermore, the air supply and extraction equipment can be employed for multiple uses (beyond air sparging and soil vapor extraction). Typically these equipment items can be considered to have service lives of approximately five years, depending on their size, quality, and rate of use.

5.4.1 Evaluation of Cleanup Goals and Performance Objectives

Cleanup goals and performance objectives should be evaluated periodically to review the regulatory history, review the current and future land use plans, and evaluate the need to revise goals.



Modified from AFCEE, 1999

FIGURE 5-1. Remedial Optimization for Air Sparging Systems

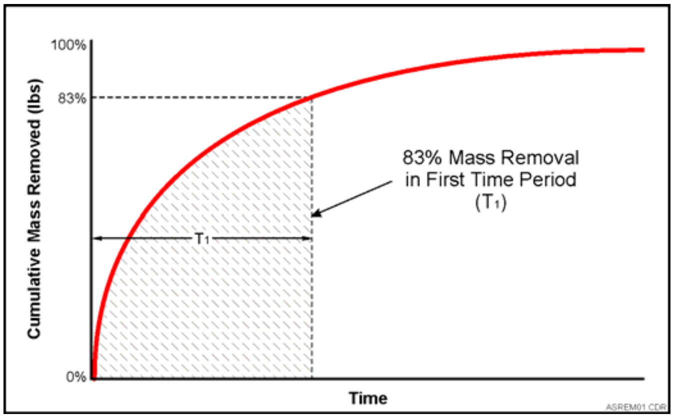


FIGURE 5-2. Typical Behavior of an Air Sparging System

5.4.2 Optimizing Airflow

The objective of optimizing airflow is to maximize mass removal. Typically, mass removal is maximized in homogeneous deposits by an approximately uniform distribution within the treatment area matching the likely distribution of contaminants. In heterogeneous deposits, contaminant distribution is more likely to be concentrated in zones of greater permeability. Focusing sparging activities in these areas of greater permeability is likely to be an efficient way to maximize removal.

Once the desired flowrate is achieved in a single injection well, a practitioner then can begin balancing the flow to all injection wells operating within the well bank. It can be difficult to achieve the same flowrate in all injection wells within the same well bank. Adjusting flowrates to ±2 cfm from the desired flowrate is reasonable. Balancing of flows will have to be repeated for each well bank. Flowrates should be checked and minor adjustments made through several air injection cycles. In general, checking flowrates frequently during the first two weeks of operation should be sufficient to ensure stable flowrates.

In heterogeneous deposits, contaminant distribution and achievable air flowrates will be determined by the relative permeability of the deposits in the target treatment area. For example, the most significant migration of dissolved contaminants will occur in preferential pathways, or zones of greater permeability connected to the source zones. Mass removal is likely to be most effective in these same zones; therefore, air sparging activity should focus on these areas, if they can be identified. In the absence of an SVE system, monitoring the relative concentration of VOCs in soil vapor may provide insight regarding which sparging wells are most effectively stripping contaminants from zones of higher concentration. In addition, these preferential pathways also result in greater flowrates at lower injection pressure due to less frictional headloss in the formation itself. Elevated VOC concentrations in soil vapor indicate that the subject air sparging well(s) is in a good location for effective removal.

5.4.3 Optimizing Well Placements

Although adequate site characterization data should be collected prior to the design of a site-specific air sparging system, inevitably more information regarding the extent and distribution of contaminants is gained as system operation and monitoring proceed. This information can be used to improve mass removal efficiency by adjusting the system design in accordance with the new information. For example, groundwater monitoring and soil vapor data can be used to identify areas between sparging wells (or outside their area of influence) where reservoirs of contaminant mass are only minimally affected by the sparging activity. Placing a few additional sparging wells in these areas can substantially accelerate removal and decrease the time to system shutdown. Figure 5-3 illustrates how focused well placements can improve VOC recovery rates. Helium tracer tests also can be used to identify dead zones between sparging locations; if dead zones are identified, additional sparging wells should be installed. Additional site characterization such as soil borings, groundwater wells, or other activities may reveal new sources or areas with elevated contaminant concentrations, and additional sparging wells can be added to increase airflow to these areas. Also, operators should continuously explore opportunities to shut off airflow and possibly abandon inefficient sparging wells located in areas of low concentration or tight deposits.

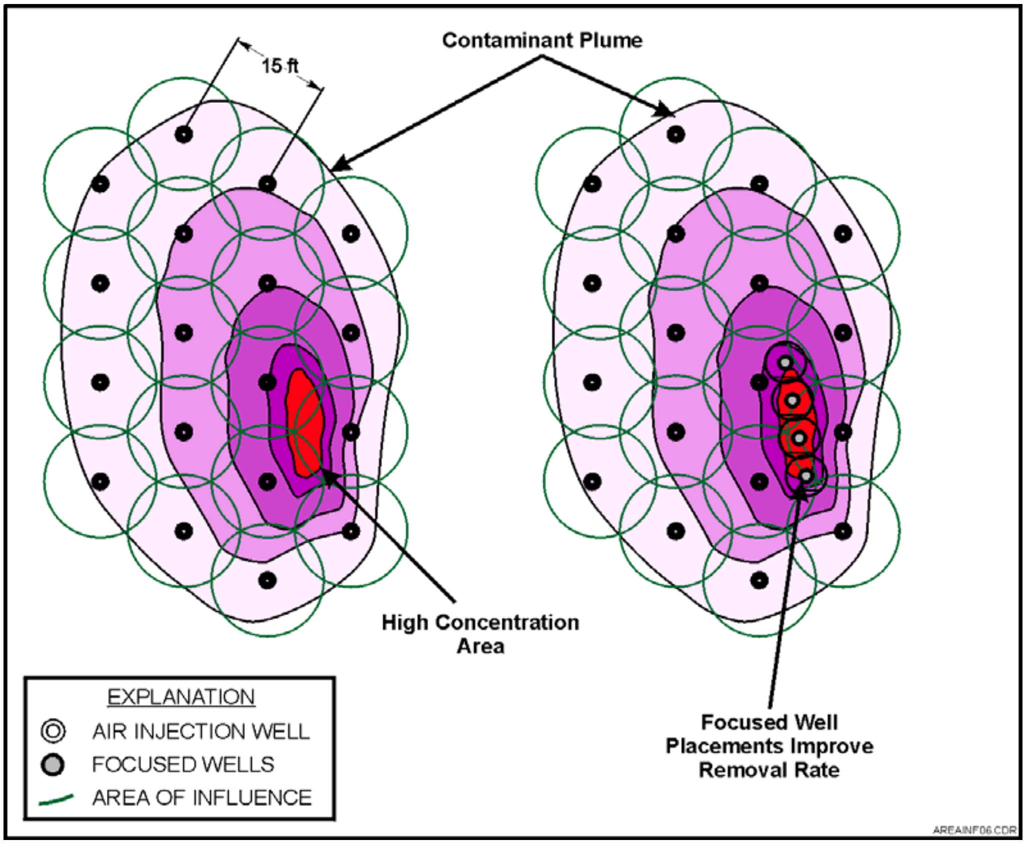


FIGURE 5-3. **Optimized Well Placement in High Concentration Areas**

6.0 SYSTEM SHUTDOWN, LONG-TERM MONITORING, AND SITE CLOSURE

When cleanup goals have been attained or when continued operation of the air sparging system is no longer cost-effective, it is appropriate to terminate system operation. System shutdown should generally be accomplished after 6 to 18 months of full-scale operation (Bass et al., 2000). Following system shutdown, it will likely be necessary to perform postremedial long-term monitoring to evaluate contaminant rebound and plume stability prior to obtaining site closure.

6.1 System Shutdown

At some sites the air sparging system will reduce contaminant concentrations sufficiently to meet the cleanup goals. However, at other sites the air sparging system will reach an asymptotic level of mass removal prior to achieving the cleanup goals. In these cases, alternative approaches, such as monitored natural attenuation, should be considered to attain final cleanup requirements. The political and regulatory context must be considered in making the decision to shut down the system and switch remedial strategies, but incorporation of this expected outcome from the early stages of the project can facilitate the change when it is appropriate. In addition, a cost-effective remedy is commonly mandated by regulation, and the system operation data may be presented as evidence that active remediation is no longer cost-effective. Incorporating the expected behavior of the remediation system into the project management and system design will reduce project costs and time.

For example, exit strategies at recent Navy air sparging sites in Southern California have included provisions to transition to monitored natural attenuation after reaching asymptotic removal of contaminants based on results from quarterly groundwater monitoring. At one site, system shutdown was granted after greater than 80% mass removal of BTEX and MTBE was achieved and asymptotic removal had been reached (NFESC, 2000b). Shutdown was granted even though cleanup goals for benzene and MTBE had not been achieved in all monitoring locations. Furthermore, the recommendation for system shutdown was supported by the 100-fold increase in monthly treatment costs per pound of contaminant removed.

As part of the exit strategy, the air sparging system should remain in place for at least one year after system shutdown in case contaminant rebound requires additional operation. Poor performance at air sparging sites can often be attributed to a rebound in VOC concentrations occurring six months to a year after the system has been shut down. Bass et al. (2000) determined that rebound was found to be particularly prevalent at petroleum hydrocarbon sites where a LNAPL smear zone was present and the seasonal fluctuation of the water table exposed the groundwater to new sources of contamination.

6.2 Long-Term Monitoring

After active remediation, a rational strategy for reducing the coverage and frequency of groundwater monitoring should be included in a site closure plan. The objectives of long-term monitoring should be to confirm that the groundwater plume is shrinking or remains stable, that natural processes continue to reduce concentrations over the long term (seasonal variations should be considered as having much less interpretive value than consistent interseason trends), and that site closure objectives will be achieved within a time frame that will maintain protection of human health and the environment. There are several good guidance documents regarding long-term monitoring strategies including NFESC's *Guide to Optimal Groundwater Monitoring* (2000a).

A suggested approach for reducing the cost of the overall long-term monitoring program is to establish decision criteria or project milestones that, when achieved, will cause another phase of the monitoring plan to begin. Each successive phase will consist of less frequent monitoring of fewer wells. As uncertainty regarding the long-term behavior of the plume is reduced, the need for monitoring is correspondingly reduced. The reduction in monitoring should accompany reduced uncertainties in the spatial and temporal behavior of the plume. In addition, monitoring plans initially cover a broad range of constituents typically due to uncertainties and complexities in thoroughly describing the source of the plume. As knowledge is gained by periodic monitoring, compounds can be safely and responsibly dropped from the list.

Decision criteria for executing these changes to the monitoring plan should be clearly described and approved by regulatory authorities. Monitoring data should not be collected, tabulated, plotted, and documented without further action. The objective of monitoring data is to aid in the management of the project and the risk associated with the groundwater contaminants; therefore, data analysis should support a management decision. For example, the monitoring plan may include a requirement to review data gaps and monitoring needs annually, with the agreement that additional data will be collected only to meet defined objectives.

6.3 Site Closure

Finally, project management should petition for site closure when monitoring objectives are achieved, plume concentrations have been reduced to cleanup objectives, or concentrations are consistently decreasing toward cleanup objectives. With appropriate interaction, regulatory authorities should expect the petition for site closure.

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APPENDIX A

FOCUSED LITERATURE REVIEW

A literature review was performed to analyze the lessons learned from recent field-scale air sparging remediation projects and to highlight improvements in conventional techniques for design, operation, and monitoring of in situ air sparging systems. This review does not focus on the results of laboratory or modeling research efforts. For a more complete summary of recent advances in air sparging research, the literature review by Johnson et al. (2001) should be consulted. The issues covered in this review should help remedial project managers anticipate and correct common performance problems and improve the rate of success for implementation of air sparging remediation projects.

A.1 Site Background Review

All of the field-scale air sparging projects reviewed involved the cleanup of groundwater impacted by chlorinated solvents and/or petroleum hydrocarbons. Of the articles chosen for review, eight dealt with chlorinated solvents, ten dealt with petroleum hydrocarbons, and two dealt with both types of compounds. The case studies involved a variety of soil and aquifer conditions and a variety of air sparging systems, from pilot studies with one sparging well to full-scale systems with as many as 134 injection wells. Table A-1 presents some pertinent data from several selected sites. This table should provide the reader with an idea of the scope and size of some recent air sparging projects. The reader is referred to Bass et al. (2000) for a detailed review of a database of 49 air-sparging projects completed by a single environmental consulting firm for both chlorinated solvent and petroleum hydrocarbon contaminated sites.

Mass recovery rates drop off dramatically over the lifetime of the air sparging project. For example, during the Glass (2000) project, volatile organic compound (VOC) mass recovery rates dropped by a factor of 20 over an eight-month period. In general, pilot study results yield mass removal rates much higher than those experienced during full system operation and therefore provide limited information for the prediction of mass recovery rates over the lifetime of a project. A DOE (1995) pilot test of horizontal air sparging found that soil vapor extraction (SVE) alone removed an estimated 109 lb/day, while the use of air sparging enhanced removal by an additional 20 lb/day. This suggests that under some circumstances VOC recovery from the residual contamination in the vadose zone may be significantly greater than recovery induced by air sparging at the water table. Remedial project managers should

TABLE A-1. Summary of Site Parameters for Selected Air Sparging Remediation Projects

Compound(s)	Description of Geologic Material	Depth to Ground-water	Project Size	Duration of Operation	VOC Mass Removal Rate	Number of Sparge Wells	Air Flowrate per Well	Reference
DCA, DCE, TCE, VC	Fine-grained sand	6 ft bgs	Not listed	8 months	22 to 1 lb/day	3	10 to 15 cfm	Glass, 2000
DCE, PCE, TCE, VC	Sandy gravel	15 to 25 ft bgs	Not listed	1 year	0.35 to 0.13 lb/day	5	30 to 110 cfm	USACE, 1998
DCE, PCE, TCA, TCE, methylene chloride	Medium to coarse sand and gravelly sand	0.5 to 9 ft bgs	1.7 acres	450 days	12 to 2.4 lb/day	134	Not listed	Gordon, 1998
TCA, TCE, PCE	Sand with thin lenses of clay	120 ft bgs	1 acre	139 days	140 to 100 lb/day	1 (horizontal)	65 to 270 cfm	DOE, 1995
BTEX	Silty sands	20 ft bgs	3,000 ft^2	72 hours	0.06 lb/day	1	1 to 3 cfm	Murray et al., 2000
BTEX	Sandy clay to sandy clay loam	20 to 25 ft bgs	1,200 ft^2	44 days	32 lb/day	6	0.5 to 5 cfm	Kirtland and Aelion, 2000

consider the initial contaminant distribution and the remedial action goals in deciding when the extra cost of installing an air sparging system is warranted.

Bass et al. (2000) found that almost half of the air sparging sites reviewed in their study achieved a 95% average permanent reduction in groundwater VOC concentrations. The percent reductions in groundwater VOC concentrations ranged from 27% to almost 100% for all 49 sites reviewed. However, at several of these sites, permanent reductions in groundwater VOC concentrations greater than 90% were still insufficient to meet stringent cleanup standards. Table A-2 shows a sample of percent reductions in target compounds from several selected sites, along with a comparison to the respective remedial action objectives. A number of sites did not achieve closure levels despite high mass removal via air sparging. It is clear that remedial project managers need to develop a long-term closure strategy for each site because air sparging alone may not achieve cleanup standards. One possibility is the use of a site-specific risk assessment to negotiate with local or state regulators to set more appropriate and feasible remediation goals. Another possibility is to transition to monitored natural attenuation once the air sparging system reaches asymptotic levels of VOC recovery.

A.2 Design Issues Review

Several issues were addressed in the literature regarding the successful design of full-scale air sparging systems. The following discussion contains suggestions on improving the design of conventional air sparging systems, as well as suggestions for the implementation of innovative air sparging projects at sites with less than optimal geologic characteristics.

☐ The study by Bass et al. (2000) showed that the most successful air sparging systems consisted of those with wells spaced an average of 28.6 ft apart. For petroleum sites where a smear zone is present, Bass et al. suggest a more aggressive approach to sparge well spacing of 15 to 20 ft or an assumed radius of influence of 7 to 10 ft.

☐ Although most studies involved spatially varied monitoring points and monitoring wells, at least one (Murray et al., 2000) had vapor monitoring points that were lined up along one axis because of site access problems. Vapor monitoring points should be spatially varied and placed at several different angles from the sparge well because preferential flow and channeling make the air distribution pattern unpredictable. A straight line of monitoring points might provide inadequate or nonrepresentative data (Bruce et al., 2001).

☐ Several of the full-scale project sites reviewed contained networks of wells ranging 3 to 134 wells (Glass, 2000, Gordon et al., 1998, Hartley et al., 1999, Klemm et al., 1997, Kraus et al., 1997, Maheux and McKee, 1997). The full-scale system

TABLE A-2. Example Percent Contaminant Reductions after Air Sparging Application at Selected Sites

Compound(s)	Initial Groundwater Concentrations	Final Groundwater Concentrations	Remedial Action Objective	Percent Reduction for Each Contaminant	Duration of Operation	Reference
DCE, PCE, TCE, VC	DCE at 7 µg/L TCE at 79 µg/L VC at 7.8 µg/L	DCE at ND TCE at 6.4 µg/L VC at ND	TCE < 5 µg/L VC < 1 µg/L	DCE 100% TCE 92% VC 100%	12 months	USACE, 1998
DCE, PCE, TCE	DCE at 26,400 µg/L PCE at 6,670 µg/L TCE at 9,870 µg/L	DCE at 24,000 µg/L PCE at 1,200 µg/L TCE at <500 µg/L	PCE < 5 µg/L TCE < 5 µg/L	DCE 9% PCE 82% TCE 95%	9 months	Hughes and Dacyk, 1998
DCA, DCE, TCE, VC	TCE at 978,000 µg/L	TCE at 845 µg/L	TCE <1,000 µg/L	TCE 99.9%	8 months	Glass, 2000
BTEX	BTEX at 15,000 µg/L	BTEX at 1 µg/L	BTEX < 2 µg/L	BTEX 99.9%	15 months	Hartley et al., 1999
Ethylbenzene and xylenes	E at 20,000 µg/L X at 100,000 µg/L	E at 410 µg/L X at 660 µg/L	E < 680 µg/L X <1,750 µg/L(a)	E 98% X 99%	10 months	Kraus et al., 1997

(a) Remedial action objectives not provided for this site, so drinking water MCLs were added for comparison.
ND = not detected.

should be designed to allow flexibility in delivering airflow to individual wells and groups of wells. The sparging wells should be clustered in groups of two to five wells and each well should have its own pressure regulator and airflow meter to ensure that adequate airflow distribution is occurring within the network of wells (Johnson et al., 2001).

- The Bass et al. study noted that air sparging is generally more efficient at high flowrates typically ranging from 6 to 20 cfm.

- When selecting air sparging as an option for site remediation, there are generally two modes of technology application based on the primary removal mechanism that the design objective maximizes.

  1. Biosparging, which involves the injection of air into the subsurface to promote aerobic biodegradation of the contaminant, and
  2. Air sparging, which relies on the partitioning of volatile organic compounds from the dissolved or free phase to the vapor phase (air stripping).

- Through the development of a simplified conceptual model, Johnson (1998) noted that if aerobic biodegradation occurs at a site, it will only enhance air sparging performance at initial VOC concentrations less than 1 mg/L in groundwater. At contaminant concentrations greater than 1 mg/L, the volatilization process will be the dominant driving force for mass removal from groundwater. Stripped vapors that reach the vadose zone can then be biodegraded if adequate oxygen is present in the vapor stream. For aerobically biodegradable contaminants, the biodegradation capacity of the vadose zone can be determined by performing site-specific tests in which the injection flowrate is increased until acceptable atmospheric emissions are observed, at which point the biodegradation capacity of the vadose zone has been exceeded. These tests should be performed by experienced practitioners. When volatile contaminant concentrations are significantly greater than 1 mg/L at a site and the site geology allows high injection flowrates, air sparging should be considered the preferred application and steps should be taken to manage and monitor soil vapor migration. If the air sparging injection rate is observed to be below the biodegradation capacity of the vadose zone, in situ biodegradation may be a viable alternative for vapor management. This situation would be equivalent to an aggressively designed and operated biosparging application. A brief review of the literature shows that initial concentrations at biosparging sites ranged from 0.69 mg/L to the presence of free product (see Table A-3). None of the selected projects employed soil vapor extraction; however, one system (Klemm et al., 1997) used biorespiration monitoring to track contaminant biodegradation rates and estimate hydrocarbon emissions to the surface.

TABLE A-3. Initial Contaminant Concentrations for Selected Sites where Biosparging is the Stated Remediation Objective

Compound(s)	Initial Groundwater Concentration	Reference
VC	0.69 mg/L	Cannata et al., 2000
BTEX	0.157 to 11 mg/L	Muehlberger et al., 1997
BTEX	10 to 20 mg/L	Payne et al., 1997
BTEX	15 mg/L	Hartley et al., 1999
TPH, BTEX	Free product	Klemm et al., 1997

- Although air sparging is a widely used technology, several common conditions at sites can impede successful implementation. According to Sittler and Peacock (1997), less than 25% of remediation sites nationwide are amenable to conventional air sparging due to variable geologic and hydrogeologic conditions. However, the literature review suggests that air sparging may still be a viable option at sites with low permeability formations and at sites with high water tables.

- According to Kirtland and Aelion (2000), it is widely accepted that air sparging and soil vapor extraction is best suited to homogenous, sandy formations with hydraulic conductivities on the order of 10^{-3} cm/s. Kirtland and Aelion suggest, however, that low flowrates and pulsing might still be effective for the implementation of air sparing at low permeability sites. At a site with hydraulic conductivities ranging from 6×10^{-7} to 3×10^{-4}, 10 pulsed air sparging tests removed approximately 78 kg of petroleum hydrocarbons over a 23-day period. For the remediation of chlorinated solvents in low permeability soils, Marley (1996) suggests that the best technologies are modifications to in situ air sparging including recirculatory sparging systems, sparging/biosparging trenches, and induced fracturing techniques.

- Air sparging projects should generally not be implemented in areas with high water tables (depth to groundwater < 5 ft bgs) because the use of soil vapor extraction wells will be impractical. If necessary, some innovative modifications such as horizontal SVE wells, horizontal SVE trenches, or multiphase vapor-liquid pumps may be useful in effecting soil vapor control at these sites (Gordon, 1998).

- The use of horizontal wells in environmental projects is increasing because of recent innovations in drilling techniques and declining installation costs. By 1995, the Department of Energy had documented the installation of over 100 horizontal environmental wells, with 25% for groundwater extraction, 25% for soil vapor extraction, and 50% for other purposes including air injection, bioventing, and petroleum recovery (DOE, 1995). Several articles are available for review regarding the use of horizontal wells in air sparging projects (DOE, 1995; Kershner and Theoret, 1997; Roth et al., 1998; and Wade et al., 1996). Roth et al. (1998) discusses a case study at an airport in New York where 27 horizontal air sparging wells and 15 horizontal soil vapor extraction wells were used to clean up a jet fuel spill. The air sparging wells were 680 ft in length and installed at a depth of 12 ft bgs, while the soil vapor extraction wells were 660 ft in length and installed at a depth of 3.5 to 5 ft bgs. The system removed approximately 47,000 lb of VOCs over an 18-month period of operation. Horizontal wells were the preferred technology at this site because of the large area of coverage needed and the restricted access to the runways and terminal area. Wade et al. (1996) discusses the use of a 200-ft horizontal well as a barrier to the migration of a chlorinated solvent plume. Horizontal technology was selected initially because it was believed that a line of vertical sparge wells would not create a uniform curtain of air and that groundwater would follow the path of least resistance moving preferentially through areas with gaps in coverage. During the monitoring phase of the project, however, it was determined that the areal extent of the sparging zone was approximately half as wide at the far end compared to the near end of the horizontal well during low flow conditions. At high flow conditions (320 scfm at 11 psi), the areal extent of the sparge zone was more uniform.

A.3 Operational Issues Review

Several system performance problems can be overcome by changing the operation of the air sparging system from a continuous mode to cycling and/or pulsing of air injection. Several articles recommend the use of cycling and pulsing over the use of continuous air injection (Gordon, 1998; Johnson et al., 2001; and Kirtland and Aelion, 2000). For this discussion, cycling is defined as turning the system on/off over a period of weeks or months, while pulsing is defined as turning the system on/off over a period of hours.

- Although pulsing is widely encouraged, Bass et al. (2000) has found that continuous mode systems can still be effective. The fact that continuous mode systems represented 61% of the most successful air sparging projects in their review suggests that continuous mode systems are still viable. Bass et al. (2000), however, states that pulsing does improve sparging performance by increasing mixing and the sparged zone of influence. Pulsing also has economic benefits because it allows for a reduction in the size of the compressor needed to run a network of sparge wells and also decreases energy usage. Case studies from petroleum hydrocarbon sites suggest that a 20% to 30% increase in mass removal rates can be achieved by pulsing the injected air (Bruce et al., 2001; Kirtland and Aelion, 2000). Kirtland and Aelion demonstrated that in a low permeability formation, BTEX and TPH mass removal rates increased from 14.3 kg/day under continuous operation to 17.6 kg/day under 8-hour pulsing of air injections.

- Based on the Bass et al. (2000) database, the projects that implemented pulsing had pulse times ranging from 0.5 to 24 hours, with an average pulse time of 10 hours. Only limited guidance is available in the literature on how to select the pulse time. It has been suggested in the literature that pulse times be determined via the time required for hydraulic gradients (local groundwater mounding) to dissipate after the onset or termination of an interval of air sparging (Wade et al., 1996).

- ☐ For source zone air sparging wells, pulsing over periods of hours can minimize the effects of hydraulic mounding and contaminant migration. Hydraulic mounding can be mitigated by setting up a network of sparge wells, and sparging the downgradient wells first (Gordon, 1998).

- ☐ Frequently, after the startup of a sparging system in the source zone, residual product will be liberated and may temporarily increase groundwater concentrations in the vicinity of the sparge well. Any free product identified should be removed by hand bailing or other methods (Gordon, 1998).

- ☐ For downgradient air sparging wells, used as a contaminant migration barrier, the system operator should avoid increasing the air saturation to the point that a reduction in hydraulic conductivity causes bypassing of groundwater around the well network. Again, pulsing at the proper time intervals can minimize this effect (Gordon, 1998).

- ☐ As air sparging in the subsurface continues, VOC recovery will drop off dramatically over time because the most readily available contaminants volatilize first. As shown in Glass (2000), VOC mass recovery rates dropped by a factor of 20 after eight months of air sparging operation. At this point, the VOC mass recovery rate becomes limited by the rate of diffusion from the residual or free product to the groundwater. Cycling over a period of weeks allows for the slow process of diffusion-limited mass transfer to take place during extended system shutdowns. Projects that implement cycling will also have less of a rebound effect six months to a year after the end of active operation (Gordon, 1998). Poor performance at sparging sites can often be attributed to a rebound in VOC concentrations after the system has been shut down. Bass et al. (2000) found that rebound at the least successful sites averaged 0.68 or two orders of magnitude of rebound for every three orders of magnitude of initial reduction in groundwater VOC concentrations. Rebound is particularly prevalent at petroleum hydrocarbon sites where a light NAPL smear zone is present and the seasonal fluctuation of the water table exposes the groundwater to new sources of contamination (Bass et al., 2000). Cycling can also allow substantial savings in vapor treatment costs. After a temporary system shutdown on the order of weeks or months, the higher VOC vapor concentrations may require less supplemental fuel to combust in a thermal or catalytic oxidizer.

- ☐ Testing of startup modes for air sparging systems has indicated that a gradual system startup is better than a sudden burst of flow. The subsurface appears to exhibit a “memory” of the air channel structures between pulses, and the initial formation of the channel structure is important for future operations (Gordon, 1998).

A.4 Monitoring Issues Review

At most field sites, monitoring efforts are minimized to weekly or monthly system checks. During operation of an air sparging system, several parameters are monitored including in situ soil vapor concentrations, SVE off-gas concentrations, dissolved oxygen levels, and water level measurements. Most air sparging projects also require initial baseline and final site characterization studies, which include soil and groundwater sampling efforts. Several new techniques for system monitoring and site characterization have been suggested by Johnson et al. (2001) to improve air sparging system performance at larger, more complicated sites which demand a site-specific approach.

- ☐ In order to better characterize a site, it is suggested that one continuous core from the top of the injection well screen to the water table be obtained and photographed for future reference at or near each sparge well location.

- ☐ Johnson suggests the use of helium (He) and sulfur hexafluoride (SF_6) tracer studies to enhance understanding of the sparging zone of influence. The distribution of the helium or SF_6 in vapor monitoring points provides an idea of the location of preferential paths and/or channels and allows a quantitative assessment of the air distribution pattern around the sparge well. This data can be used to identify treatment dead zones and help in planning modifications to the number of sparge wells or the flowrate of the sparge wells in a large network. Tracer tests can also be used to estimate the capture efficiency of the soil vapor extraction system.

- ☐ The use of transient water-level pressure transducers in nearby groundwater monitoring wells is recommended for pilot test activities. The pressure transducers provide data that indicate the effect of air sparging on water table mounding and on the time it takes for the air injected into the subsurface to find an outlet or vent to the vadose zone. For aquifers with silt and clay lenses or stratified layers, the pressure may continue to build for hours or days before a release occurs. This data can be used to determine if a site is suitable for air sparging, and it can also be used to estimate appropriate shutdown times for pulsed operation (Johnson et al., 2001).

- ☐ The use of multitracer push-pull tests is recommended during the pilot test phase. The data from these tests can be used to calculate the volatilization rates and oxygen utilization rates in the subsurface. The reader should consult Amerson-Treat et al. (2001) for more information on this type of performance test.

- ☐ Wardwell (1999) describes the use of groundwater velocity probes (manufactured by HydroTechnics, Inc.) at a petroleum hydrocarbon, air sparging remediation project in Port Hueneme, California. These sensors allowed in situ measurement of three-dimensional groundwater flow. The study indicated that the effects of groundwater mounding dissipated within 24 hours of the start of air sparging at the site and that hydraulic mounding likely had little impact on the distribution or spreading of hydrocarbon contaminants. The study also indicated that at airflow injection rates greater than 10 cfm, the groundwater flow direction was diverted away from the sparge area.

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APPENDIX B

COMPENDIUM OF COMPETING REMEDIAL TECHNOLOGIES

This appendix describes the remedial technologies that may be competitive with the application of in situ air sparging for groundwater remediation. The various technologies are as follows:

Pump and Treat
In Situ Chemical Oxidation
Enhanced In Situ Aerobic Bioremediation
In-Well Air Stripping/Groundwater Circulating Wells
Monitored Natural Attenuation
Phytoremediation
Reactive Barriers
Surfactant-Enhanced Aquifer Remediation
In Situ Thermal Treatment
Two-Phase (Dual-Phase) Extraction

SUMMARY SHEET

Air Sparging vs. Pump and Treat

Technology Description – Pump and Treat

Pump and treat consists of one or more wells from which contaminated groundwater is pumped to the surface for treatment. The aboveground treatment system consists of a sequence of physical, chemical, or biological units designed to perform operations such as phase separation, precipitation, and activated sludge treatment. After treatment, the groundwater commonly is discharged to a sewage treatment plant. Site-specific conditions may allow discharge to local surface water or reinjection of treated groundwater. Figure 1 shows a conceptual diagram of a pump and treat system.

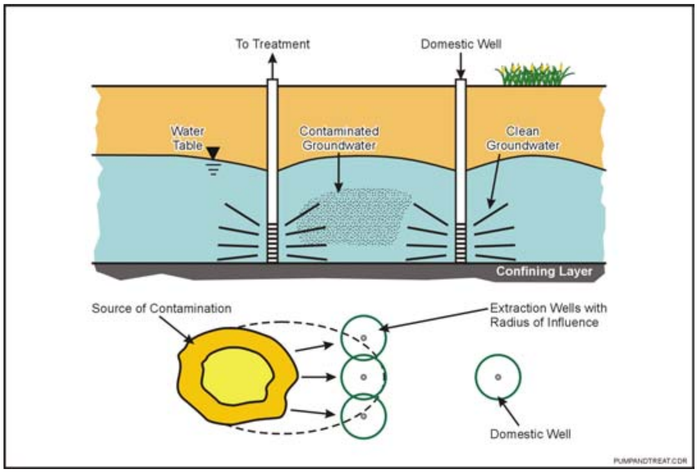

FIGURE 1. CONCEPTUAL DIAGRAM OF TYPICAL PUMP AND TREAT SYSTEM

Advantages and Limitations Relative to Air Sparging

The pump and treat approach is a mature technology with well-established design standards and an established track record. System design is more straightforward than with air sparging because groundwater extraction well positions and flowrates needed to capture the plume typically can be determined accurately with groundwater modeling methods.

Water treatment required for a pump and treat system typically is more complex than the off-gas treatment system that may be needed for the air sparging system.

Initial equipment costs for installation are low to moderate (typically similar to that of an air sparging system), but the materials and operating labor needed for the water treatment system results in higher operating costs for a pump and treat system compared to an air sparging system.

The mass removal rate in the dissolved phase by a pump and treat system is very low due to low solubility of organic contaminants and slow release of sorbed contaminants. As a result, the operating time typically is longer than that of an air sparging system, resulting in higher project costs, except when contaminants with very low sorption rates, like MTBE, are considered.

For a well-defined plume, a pump and treat system can be effective as a first line of defense in preventing further migration and in removing the bulk of free product, but typically is not cost-effective for remediation of an entire plume.

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SUMMARY SHEET

Air Sparging vs. In Situ Chemical Oxidation

Technology Description – In Situ Chemical Oxidation

In situ chemical oxidation treatment involves injecting a solution of oxidizing agent into groundwater to destroy dissolved contaminants. The technology is implemented by drilling wells so that the oxidizing solution can be injected into the contaminated zone. Hydrogen peroxide (H_2O_2), hydrogen peroxide with ozone (H_2O_2/O_3), Fenton's Reagent (iron-catalyzed hydrogen peroxide), and potassium permanganate ($KMnO_4$) are the most commonly used oxidants used for treating organic contaminants in groundwater. Figure 1 shows a conceptual diagram of a chemical oxidation injection point.

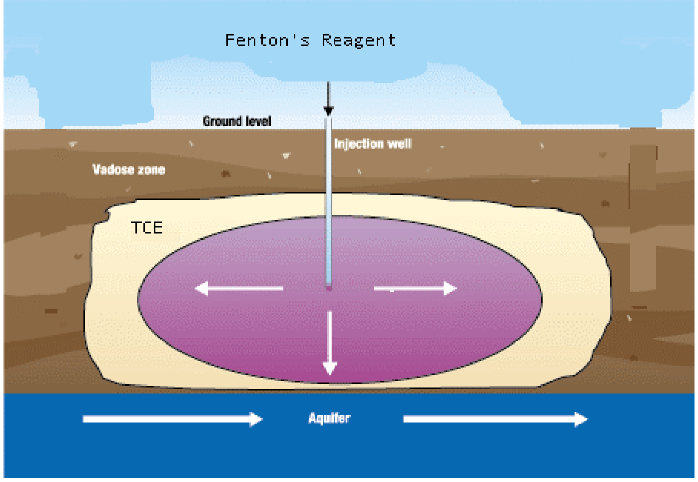

FIGURE 1. CONCEPTUAL DIAGRAM OF CHEMICAL OXIDATION INJECTION POINT

Advantages and Limitations Relative to Air Sparging

In situ chemical oxidation is an innovative technology that allows in situ destruction of contaminants. Chemical oxidation has a 50-year history of commercial-scale use for ex situ water treatment to reduce organic pollutant concentrations, biological oxygen demand (BOD), chemical oxygen demand (COD), and/or odor and color, and currently is being extended to in situ remediation of groundwater.

Successful application of in situ chemical oxidation is very sensitive to site conditions such as natural organic matter content and hydrogeology. The range of applicable sites for in situ chemical oxidation is more limited than for air sparging. It may be difficult to achieve good mixing between the groundwater and the oxidant solution. The injected solution tends to displace the affected groundwater and then react with natural organic matter before it reacts with affected groundwater. Oxidant solution injection has the potential to displace the plume and increase chemical migration.

Injection of a chemical oxidation solution will be regulated under UIC regulations.

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SUMMARY SHEET

Air Sparging vs. Other Oxygen Delivery Options for Enhanced In Situ Aerobic Biodegradation

Technology Description

In order to enhance in situ aerobic biodegradation, the limited supply of oxygen in the subsurface should be overcome by an engineered oxygen delivery system. This typically results in enhanced aerobic biodegradation rates that are adequate for site remediation. Although other limiting factors can exist, such as the supply of nutrients, they typically are of secondary importance to oxygen levels.

Oxygen delivery systems may be either active or passive. Active delivery, as used for air sparging, is the forced injection of oxygen or air into the saturated zone. Pure oxygen sources can be used, but have rarely been demonstrated to be economical. Passive delivery is the introduction of oxygen in some form such as solid peroxide, which is placed in the aquifer to aerate groundwater as it flows under a natural gradient. Aquifer oxygenation with oxygen release compounds (ORCs) involves placing ORC in porous bags in conventional drilled wells or by injecting a slurry of ORC into push-well points. Liquid delivery consists of dissolving oxygen into water and then using the water as the carrier to deliver oxygen. In the case of hydrogen peroxide (H_2O_2) the H_2O_2 is dissolved into water and oxygen is produced by decomposition.

Advantages and Limitations Relative to Air Sparging

Active oxygen delivery options are primarily limited by the solubility of oxygen in water, and are strongly influenced by aquifer permeability and flow characteristics. Passive alternatives are limited by the diffusion rate of oxygen in water, and distribution problems caused by heterogeneities in the aquifer material. There are numerous other limitations to the various oxygen delivery options which are specific to the approach. For example, it has proven very difficult to control the rate of hydrogen peroxide decomposition when using H_2O_2, which has resulted in poor oxygen distribution. During air sparging, consideration must be given to the fate of the air injected and an off-gas collection and treatment system may be required. Similarly, in the case of solid peroxides, pH increase may become a problem. These technology and site-specific limitations must be considered on a site and case specific basis.

With reasonable estimates of oxygen demand at contaminated sites ranging from thousands to (conceivably) millions of pounds, the cost of oxygen becomes a critical factor in remedy selection and system design. Table 1 lists achievable concentrations from various commercially available oxygen sources and provides an order-of-magnitude estimate of the cost of oxygen for each source.

TABLE 1. OXYGEN CONCENTRATION IN WATER ACHIEVED BY VARIOUS SOURCES

Oxygen Source	Achievable Oxygen Concentration Range, mg/L	Estimated Cost of Oxygen, $/Pound
Air	8 to 10	0.01
Pure Liquid Oxygen (LOX)	40 to 50	0.1
Pure Oxygen (generated)	40 to 50	1
Liquid H_2O_2	25 to 50	10
Solid Peroxide	25 to 50	100

In many applications the decision driver will be the cost of oxygen because of the magnitude of typical oxygen demands. At some sites other considerations are appropriate. For example, the least expensive form of oxygen (air) has operation and maintenance costs associated with the equipment (compressors and blowers) necessary to deliver the oxygen. The effectiveness of oxygen distribution can be a very specific consideration, and is typically a site- and case-specific consideration. At sites with high oxygen demand such as petroleum hydrocarbon source areas it may not be economically feasible to deliver sufficient oxygen in a dissolved form no mater what the source.

Because of its low cost, air sparging is a commonly selected alternative for remediating hydrocarbons in the saturated zone. Solid peroxides such as Oxygen Release Compound (ORC®) are widely used at sites with low operation and maintenance requirements.

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SUMMARY SHEET

Air Sparging vs. Nutrient Addition for Enhanced In Situ Aerobic Bioremediation

Technology Description – Enhanced In Situ Aerobic Bioremediation

Enhanced in situ aerobic bioremediation processes often involve the delivery of oxygen to the aquifer to stimulate natural biodegradation of contaminants in soil or groundwater and the addition of other nutrients and/or cometabolites. A water solution of amendments usually is injected into upgradient wells or trenches and circulated through the contaminated zone by removing groundwater from downgradient wells. This circulation of the amendment solution through the contaminated zone provides mixing and contact between the oxygen, nutrients, contaminants, added cometabolics, and microorganisms.

Some chlorinated organics (e.g., TCE, chlorobenzene, and PCB-Aroclor 1242) can be treated by cometabolic techniques that involve adding a primary substrate to support the growth of the microorganisms that fortuitously or coincidentally promote contaminant degradation. Figure 1 shows a conceptual diagram of a typical enhanced aerobic bioremediation system.

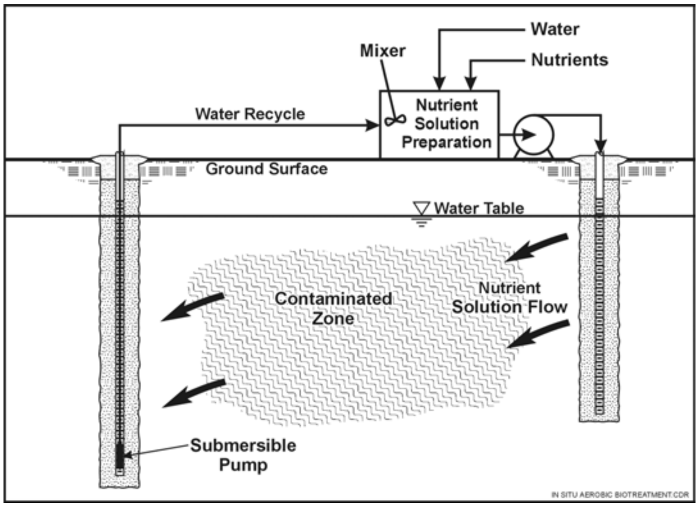

FIGURE 1. CONCEPTUAL DIAGRAM OF TYPICAL ENHANCED AEROBIC BIOREMEDIATION SYSTEM

Advantages and Limitations Relative to Air Sparging

Enhanced in situ aerobic bioremediation is an innovative technology with a limited history of full-scale application. The technology promotes in situ removal or detoxification of contaminants using natural low intensity biological transformation processes. Some inorganic contaminants may be immobilized by soil oxidation.

Achieving controlled flow and uniform oxygen delivery in the aquifer can be difficult. Amendment solution flow must be controlled to avoid contaminant escape from zones of active biodegradation. Low-permeability soils are difficult to treat. Subsurface heterogeneity can make it difficult to deliver amendments throughout the different zones of contamination, resulting in rapid remediation in the higher permeable zones and insignificant to slow remediation in the tighter zones where oxygen/ nutrient diffusion rates limit effectiveness. Concentrations of hydrogen peroxide greater than 100 to 200 mg/L in groundwater inhibit the activity of microorganisms. Furthermore, rapid breakdown of hydrogen peroxide by soil microbe enzymes and minerals can limit its effectiveness. Iron precipitation and/or other changes in groundwater chemistry can cause permeability reductions through fouling and result in reduced ability to deliver amendments.

The added oxygen can be consumed by biotic and abiotic mechanisms near the injection well, which creates two significant problems: (1) biological growth can be limited to the region near the injection well, limiting the treatment zone area and (2) biofouling of wells can retard the input of recirculated groundwater or injected gases.

Most in situ bioremediation approaches use commercially available materials and conventional methods. As a result, the initial capital cost to install the system is low to moderate (typically similar to that of an air sparging system), but remediation is slow, typically requiring several years to decades to reach cleanup levels. The long operating time contributes to high monitoring, operation and maintenance costs. Both biotic and abiotic sinks for oxygen can prolong treatment duration, resulting in higher operation, monitoring, and maintenance costs. As a result, the operating time typically is longer than that of an air sparging system, resulting in higher project costs.

Sources for Further Information

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SUMMARY SHEET

Air Sparging vs. In-Well Air Stripping/Groundwater Circulating Wells

Technology Description – In-Well Air Stripping/Groundwater Circulating Wells

In-well air stripping involves using air stripping wells to physically remove VOCs from the groundwater. Limited aerobic biodegradation may also occur within the aquifer due to aeration of the water around the stripping well. The simplest implementation of in-well air stripping is to inject air under pressure at the bottom of a well. The well acts as a small stripping column where contaminants in the groundwater partition into the stripping air. The well is maintained under vacuum to collect the stripped contaminants.

In-well air stripping is usually combined with groundwater circulating wells (GCWs) to increase the radius of influence of the well. Air injected into the well provides stripping action to volatilize contaminants and air lift pumping to circulate water around the well. The GCW has two screens, one at the bottom and the other near the water table, to generate a hydraulically driven groundwater circulation cell. GCW systems theoretically create a three-dimensional circulation pattern in the aquifer by drawing groundwater into the well, pumping it up the well, and then releasing it into the aquifer without pumping it above ground. GCW circulation patterns are highly dependent on well configuration and hydrogeological conditions at a site. A typical GCW is shown in Figure 1.

Advantages and Limitations Relative to Air Sparging

In-well air stripping removes VOCs without requiring groundwater extraction and treatment above ground. This eliminates the need for water discharge permitting. The use of GCWs may also result in energy cost savings especially at sites with deep water tables.

Application of GCW is more sensitive to in situ geology than is application of air sparging. GCW systems have been tested at more than 100 locations within the United States and Europe with documented successes at a few sites; however, the technology is generally not chosen for groundwater cleanup. This is due to a general lack of knowledge concerning GCWs and also from mixed results from past applications. It is generally believed that the technology does not work well at most sites due to the horizontal (K_h) to vertical (K_v) hydraulic conductivity ratio (anisotropy) being outside the technology's applicable range. The applicable range considered to promote an effective recirculation zone is 3 to 10 K_h/K_v. Because sites with high anisotropies (>10 K_h/K_v) are quite common, this technology appears to have limited application potential. Impermeable soils will generally result in slow and confining recirculation, where highly permeable soils may cause short-circuiting. Impermeable layers between the upper and lower well screens may also prevent the formation of the recirculation zone.

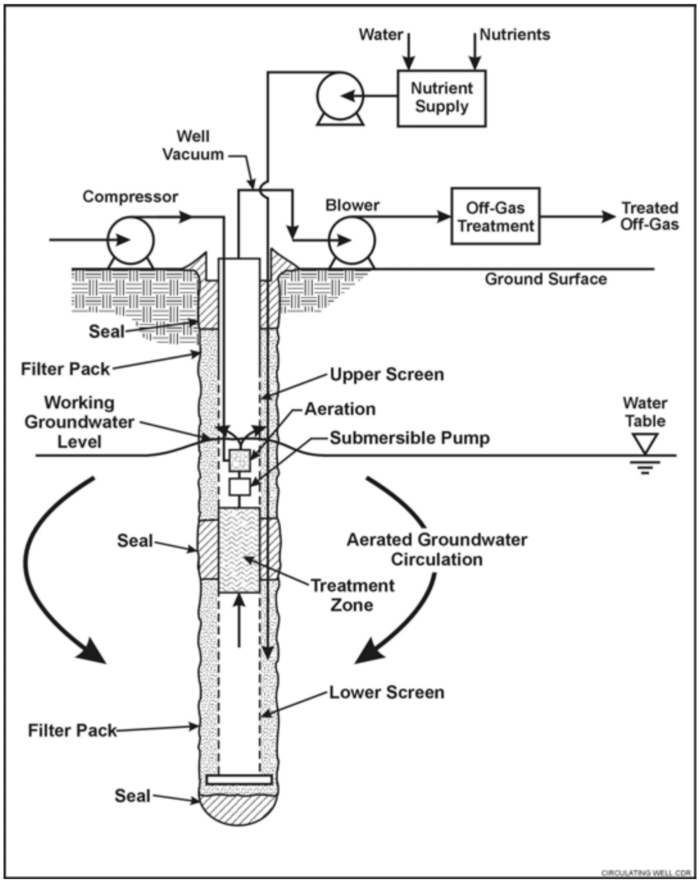

FIGURE 1. DIAGRAM OF GCW

The submergence (ratio of the well depth below the water table to the total depth below the ground surface) of a GCW must be high enough to ensure a cost-effective groundwater circulation zone. For generation of an effective circulation zone, GCW groundwater flowrates must overcome regional groundwater flows. The effective radius of a well will be severely limited by a thin heterogeneous aquifer. Seasonal variation of the water table will greatly influence the recirculating flow and in some cases stop flow completely. Improperly placed upper and lower well screens could lead to little or no recirculating flow. Locating upper and lower screens to provide circulation year-round can be difficult in cases with seasonal variations.

Off-gas collected from the stripping well typically requires treatment.

Sources for Further Information

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SUMMARY SHEET

Air Sparging vs. Monitored Natural Attenuation

Technology Description – Monitored Natural Attenuation

Monitored natural attenuation (MNA) is an in situ remediation technology that relies on naturally occurring processes to reduce contaminant concentrations in soil and groundwater. In order to implement MNA, it must be determined that natural remedial processes will be protective of human health and the environment and achieve remedial goals within a reasonable time frame.

For MNA, natural subsurface processes such as dilution, volatilization, biodegradation, adsorption, and chemical reactions with subsurface materials reduce contaminant concentrations to acceptable levels. Consideration of this option often requires modeling and evaluation of contaminant degradation rates and pathways. The primary objective of site modeling is to demonstrate that natural processes of contaminant degradation will reduce contaminant concentrations below regulatory standards before potential exposure pathways are completed. In addition, a strict site monitoring plan must be followed to confirm that contaminant degradation is proceeding at rates and following pathways that meet cleanup objectives. A typical MNA scenario is shown in Figure 1.

Advantages and Limitations Relative to Air Sparging

MNA is not the same as “no action,” although it often is perceived as such. Natural attenuation is considered in the Superfund program on a case-by-case basis, and guidance on its use is still evolving. It has been selected at Superfund sites where, for example, polychlorinated biphenyls (PCBs) are strongly sorbed to deep subsurface soils and are not migrating; where removal of DNAPLs has been determined to be technically impracticable (Superfund is developing technical impracticability [TI] guidance); and where it has been determined that active remedial measures would be unable to significantly speed remediation time frames. Where contaminants are expected to remain in place over long periods of time, TI waivers must be obtained. In all cases, extensive site characterization is required.

Unlike air sparging, which requires installation of wells and compressors, MNA allows site remediation with almost no disturbance of the environment. Short-term risks to workers and the surrounding population are reduced in comparison to active remediation. MNA avoids transfer of contaminants to new media, which can result in new contaminant exposure pathways.

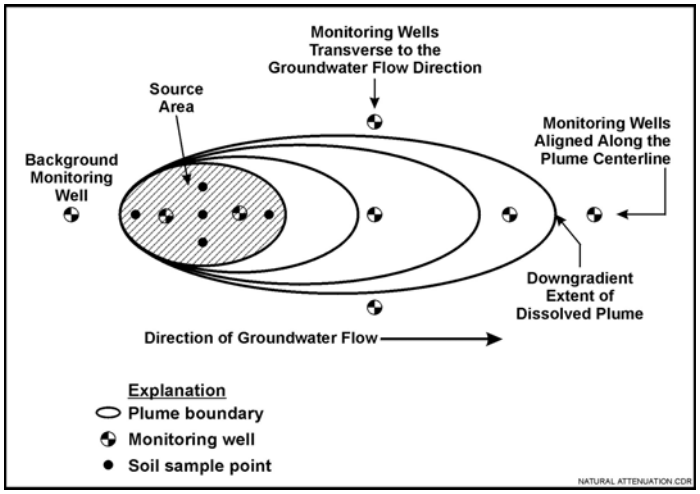

FIGURE 1. DIAGRAM OF SUBSURFACE NATURAL ATTENUATION OF A CONTAMINANT PLUME

MNA typically is a lower cost option compared to active remediation methods such as air sparging. However, MNA may not be applicable when an expanding plume is predicted to intercept potential receptors. Remediation by natural processes can be slow, typically requiring several years to decades, to reach cleanup levels. Land use controls may be required during implementation of MNA and data must be collected and analyzed to determine plume behavior, such as seasonal plume variability, dilution, and site stratification. It also is possible that intermediate degradation products produced by natural degradation may be more mobile or more toxic than the original contaminant.

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Wiedemeier, T.H., J.T. Wilson, D.H. Kampbell, R.N. Miller, and J.E. Hansen. 1995. Technical Protocol for Implementing Intrinsic Remediation with Long-Term Monitoring for Natural Attenuation of Fuel Contamination Dissolved in Groundwater. U.S. Air Force Center for Environmental Excellence, San Antonio, TX.

SUMMARY SHEET

Air Sparging vs. Phytoremediation

Technology Description – Phytoremediation

Phytoremediation is a soil and groundwater treatment technology that uses vegetation and its associated microbiota, soil amendments, and agronomic techniques to remove, contain, or reduce the toxicity of environmental contaminants. It is generally used as an in situ technology, but can be used ex situ. Phytoremediation is implemented by establishing a plant or community of plants that have been selected to provide the required remediation mechanisms. The technology exploits the natural hydraulic and metabolic processes of plants, and thus is passive and solar driven. The technology can be used in combination with mechanical treatment methods or as a "standalone" treatment method. Figure 1 shows a conceptual diagram of a phytoremediation system.

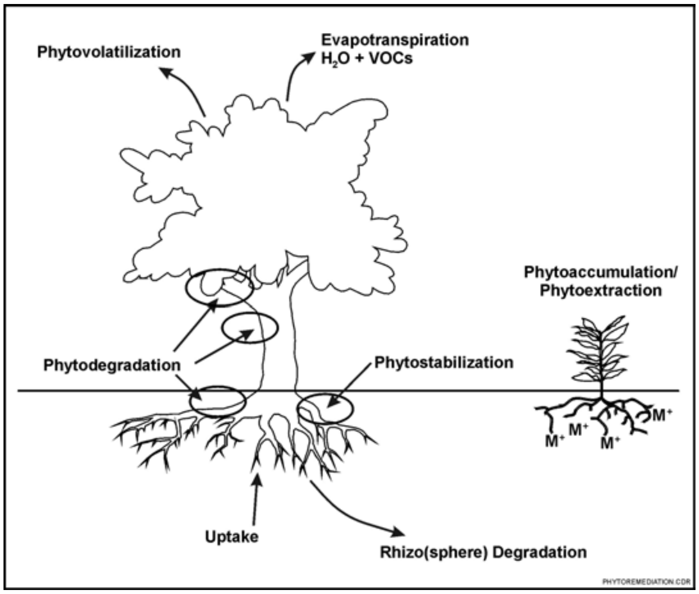

FIGURE 1. CONCEPTUAL DIAGRAM OF PHYTOREMEDIATION SYSTEM

Advantages and Limitations Relative to Air Sparging

Phytoremediation is an innovative technology with a limited history of full-scale application. The ability of plantings to remove water and provide hydraulic control has been demonstrated in pilot-scale tests, but the ability to immobilize or degrade contaminants is not as well tested. Some volatile organics typically are released with the transpired water vapor.

Implementing and maintaining the phytoremediation plantings involves very little disturbance of the site and improves site aesthetics.

The cleanup time for phytoremediation is longer than that for air sparging. A growth period of several seasons is needed for plants to become established and provide full remedial performance. The rate of remediation is limited by the plant growth rate. Plantings must be monitored and managed to ensure that contaminants are not spread off site by falling leaves or ingested by herbivores.

The depth that can be remediated with phytoremediation is limited in comparison to the depth that can be treated with air sparging. Phytoremediation depth is limited to the root zone (e.g., a few feet for grasses and about 20 ft for trees). Roots enter the capillary fringe and create a zone of groundwater depression, but do not extend into the saturated zone, so it can be difficult to treat fast flowing and/or thick aquifers.

For sites where it is applicable, phytoremediation is expected to be less costly than air sparging.

Sources for Further Information

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Schnoor, J.L. 1997. *Phytoremediation*. TE-80-01. Ground-Water Remediation Technologies Analysis Center, Pittsburgh PA.

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SUMMARY SHEET

Air Sparging vs. Reactive Barriers

Technology Description – Reactive Barriers

Reactive barrier technology is an in situ groundwater treatment method that involves installing a vertical barrier containing a reactive media to intercept and remediate a contaminant plume. In its simplest form, a treatment barrier consists of a trench placed in the path of a dissolved contaminant plume. This trench is filled with a reactive material, such as granular iron to reduce Cr(VI) or to dechlorinate halogenated organics, chelators to sequester selected metals, or other treatment media. As the groundwater passes through the treatment barrier, the contaminants react with the media. For example, chlorinated organics that come in contact with elemental iron in a barrier are degraded to potentially nontoxic dehalogenated organic compounds and inorganic chloride. Although a variety of reactive media could be used to treat groundwater contaminants, the most commonly used media are zero-valent metals, particularly granular iron. Figure 1 shows a conceptual diagram of a reactive barrier.

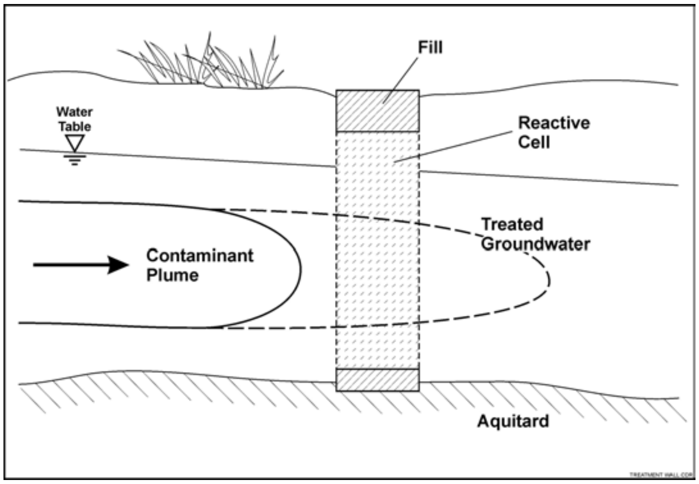

FIGURE 1. CONCEPTUAL DIAGRAM OF A REACTIVE BARRIER

Advantages and Limitations Relative to Air Sparging

Reactive barriers are an innovative technology that have seen extensive application to treatment of chlorinated hydrocarbon contaminants in groundwater. The main advantage of this system is that no pumping or aboveground treatment is required. Treatment occurs entirely in situ as the contaminated groundwater passively moves through the barrier. Because there are no aboveground installed structures, the affected property can be put to productive use while subsurface groundwater is being cleaned up.

Unlike air sparging, which allows considerable flexibility in well placement to accommodate site features, installing a reactive barrier requires placing a trench that intercepts the leading edge of the plume. Geotechnical features, such as underground utility lines, rocks, or consolidated sediments, can increase the difficulty of installing a barrier. Construction of the barrier requires site disruption while the trench is being prepared to receive the reactive media.

The cost to implement a reactive barrier depends greatly on the size of the plume, because large plumes are difficult and expensive to contain. Also, costs of barrier construction increases with increasing plume width or depth. The cost to install a treatment wall increases significantly at depths greater than 80 ft.

The capital cost to install a reactive barrier typically is higher than the cost to install an air sparging system. This higher initial cost may be offset by lower operating costs; however, site conditions and remedial objectives will determine if reactive barrier treatment is more cost effective than air sparging. For example, reactive barriers may be selected instead of air sparging if the concentrations of the contaminant plume are too low for efficient treatment by air sparging.

It can be difficult to install an effective barrier if the plume is close to site boundaries or receptors.

Sources for Further Information

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SUMMARY SHEET

Air Sparging vs. Surfactant-Enhanced Aquifer Remediation (SEAR)

Technology Description – Surfactant-Enhanced Aquifer Remediation (SEAR)

Surfactant-enhanced recovery is an in situ treatment process used to increase the aqueous solubility of contaminants in an aquifer for greater pump-and-treat recovery. The surfactant-enhanced recovery process typically is coupled with conventional pump-and-treat systems to expedite subsurface remediation. Typical examples of contaminants requiring the addition of surfactants for pump-and-treat remediation include dense, nonaqueous-phase liquids (DNAPLs), which have low aqueous solubilities and may otherwise require hundreds of years to remediate using conventional pump-and-treat methods. Increasing DNAPL aqueous solubility by using surfactants potentially can reduce remediation time. Recovery of light, nonaqueous-phase liquid (LNAPL) also can be increased by the surfactant-enhanced recovery process. Figure 1 shows a conceptual diagram of a surfactant-enhanced recovery system.

Surfactant-enhanced recovery requires the injection of surfactants into a contaminated aquifer. Typical systems utilize a pump to extract groundwater at some distance away from the injection point. The extracted groundwater is treated ex situ to separate the injected surfactants from the contaminants and groundwater. Once the surfactants have separated from the groundwater they can be reinjected into the subsurface. Surfactants are expensive, making recycle of the flushing solution essential for maximum cost-effectiveness. Contaminants must be separated from the groundwater and treated prior to discharge of the extracted groundwater.

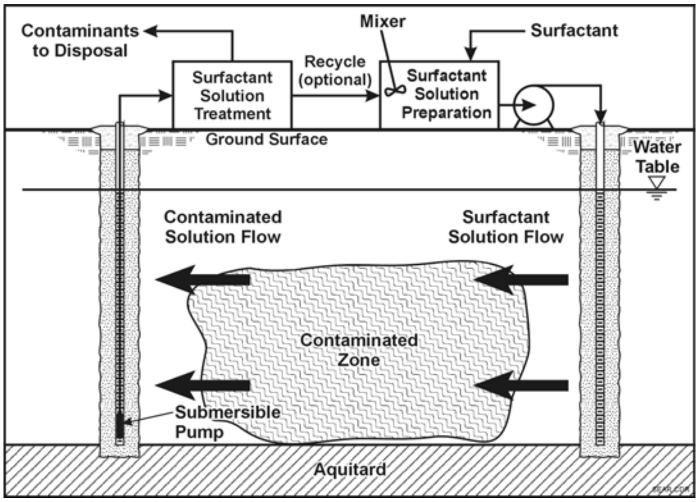

FIGURE 1. CONCEPTUAL DIAGRAM OF SEAR IMPLEMENTATION

Advantages and Limitations Relative to Air Sparging

Surfactant-enhanced recovery is an innovative technology that does not have a well-established history of full-scale application. The technology does not provide in situ treatment, but enhances the effectiveness of contaminant removal to speed remediation. The use of surfactants can increase the concentration of contaminants in the extracted fluid by a factor of 10 or more compared to natural groundwater. The higher concentration reduces the time needed to clean the site somewhat in comparison to air sparging. Site cleanup typically is accomplished in 4 to 8 months.

Effective application of surfactant-enhanced recovery depends on the ability to control in situ flows. Complex, heterogeneous geology increases the difficulty of applying surfactants. Difficulties will also be encountered with low-permeability soils.

Application of surfactant flushing requires more sophisticated site data collection and pilot-scale testing than does application of air sparging. Development of an effective surfactant solution requires sophisticated bench- and pilot-scale testing at each application site. Regulatory limitations on groundwater injection can limit options available for additives to increase contaminant solubility (i.e., food-grade surfactants may be required).

Although data from full-scale surfactant applications is sparse, initial data suggests that surfactant flushing is expensive to implement compared to alternative remedial technologies. It is unlikely that surfactant-enhanced recovery would be competitive with air sparging unless rapid remediation of the site is required and the contaminants are too deep or the aquifer too permeable to allow treatment by thermal methods.

Regulatory limitations on groundwater injection can limit the ability to recycle the flushing solution.

Sources for Further Information

Lowe, D.F., C.L. Oubre, and C.H. Ward. 1998. *Surfactants and Cosolvents for NAPL Remediation – A Technology Practices Manual*. Lewis Publishers, Boca Raton, FL.

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SUMMARY SHEET

Air Sparging vs. In Situ Thermal Treatment

Technology Description – In Situ Thermal Treatment

In situ thermal treatment options include thermal wells, six-phase soil heating, and in situ steam injection/extraction. These technologies involve using elevated temperature caused by conductive heating to vaporize VOCs and SVOCs in contaminated groundwater. Vaporized contaminants and groundwater are collected by vacuum extraction for treatment on site. Figure 1 shows a conceptual diagram of a typical in situ thermal treatment system.

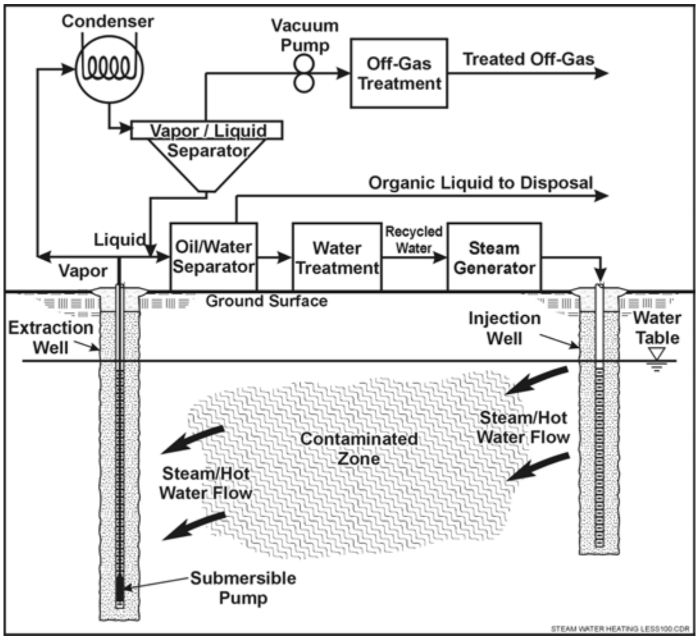

FIGURE 1. DIAGRAM OF IN SITU THERMAL TREATMENT OF A CONTAMINANT PLUME

Thermal well treatment involves using heating elements in blankets and wells operating at temperatures up to 1,000ºC to input thermal energy into the soil by conduction. Vaporized contaminants and groundwater migrate to the surface and are collected by a blower for treatment by incineration.

The six-phase soil heating option involves using elevated temperature caused by internal resistive heating to vaporize VOCs in contaminated groundwater. Vaporized contaminants and groundwater are collected by vacuum extraction for treatment above ground.

The steam injection option involves using elevated temperature caused by flow of a heated fluid to vaporize VOCs in contaminated groundwater and mobilize contaminants and groundwater for extraction. Vaporized contaminants and groundwater are collected by vacuum extraction and liquid groundwater is collected by pumping for treatment above ground.

Advantages and Limitations Relative to Air Sparging

In situ thermal treatment is an innovative technology with a limited history of full-scale application. All of the approaches to in situ thermal treatment are more intensive than air sparging, typically resulting in a cleanup duration in the range of 8 to 12 weeks. The initial cost to mobilize and set up equipment for in situ thermal treatment typically is greater than that for air sparging and, even with the shorter operating duration, the overall cost of heating technologies typically are higher than the cost for air sparging. In situ thermal treatment typically would be selected in favor of air sparging only in cases where rapid remediation is essential or there is significant quantity of free-phase DNAPL distributed as ganglia throughout the saturated zone.

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Steam Injection:

Balshaw-Biddle, K. 1998. “Heating Technologies and SVE in Hydraulic Fractures to Remove Hydrocarbon Fuels.” *Tech Trends*. www.clu-in.org/products/newsltrs/ttrend/tt0298.htm.

Cook, K. 1996. “In Situ Steam Extraction Treatment.” In J.R. Boulding (Ed.), *EPA Engineering Sourcebook*. pp 133-141. Ann Arbor Press, Inc., Chelsea, MI.

SUMMARY SHEET

Air Sparging vs. Two-Phase (Dual-Phase) Extraction

Technology Description – Two-Phase (Dual-Phase) Extraction

Two-Phase Extraction (TPE) (also known as dual-phase extraction or vacuum-enhanced extraction) is an in situ technology that applies a high-vacuum system to simultaneously remove liquid and gas from low permeability or heterogeneous formations.

Two-phase extraction is used primarily to treat halogenated and nonhalogenated VOCs and nonhalogenated semivolatile organic compounds (SVOCs). Two-phase vacuum extraction enhances airflow to remediate contaminants in unsaturated soil and, at the same time, collects groundwater for aboveground treatment.

Two-phase extraction provides airflow through the unsaturated zone to remediate volatile organic compounds (VOCs) and fuel contaminants by vapor extraction and/or bioventing. The airflow also extracts groundwater for treatment above ground. The screen in the two-phase extraction well is positioned in both the unsaturated and saturated zones. A vacuum applied to the well, using a drop tube near the water table, extracts soil vapor. The vapor movement entrains groundwater and carries it up the tube to the surface. Once above grade, the extracted vapors and groundwater are separated and treated. The drop tube is located below the static water level, so the water-table elevation is lowered, exposing more contaminated soil to remediation by the airflow. A conceptual diagram of a typical two-phase system is shown in Figure 1.

Advantages and Limitations Relative to Air Sparging

TPE is an innovative technology with a well-established history of full-scale application. Simultaneous extraction of groundwater and soil gas allows vapor extraction without the disadvantage of the upwelling of the groundwater level around the extraction well that can occur in conventional soil vapor extraction. LNAPL extraction typically is inefficient in heterogeneous or low permeability formations and relies on fortuitous well placement under these conditions. Subsurface heterogeneity can also interfere with uniform collection of contaminated groundwater and aeration of contaminated soil. Combination with complementary technologies (e.g., pump-and-treat) may be required to recover groundwater from high-yielding aquifers. When containment of vapors/liquids is necessary, the results are better than those obtained through air sparging. However, two-phase extraction requires both water treatment and vapor treatment that is not necessarily included with air sparging.

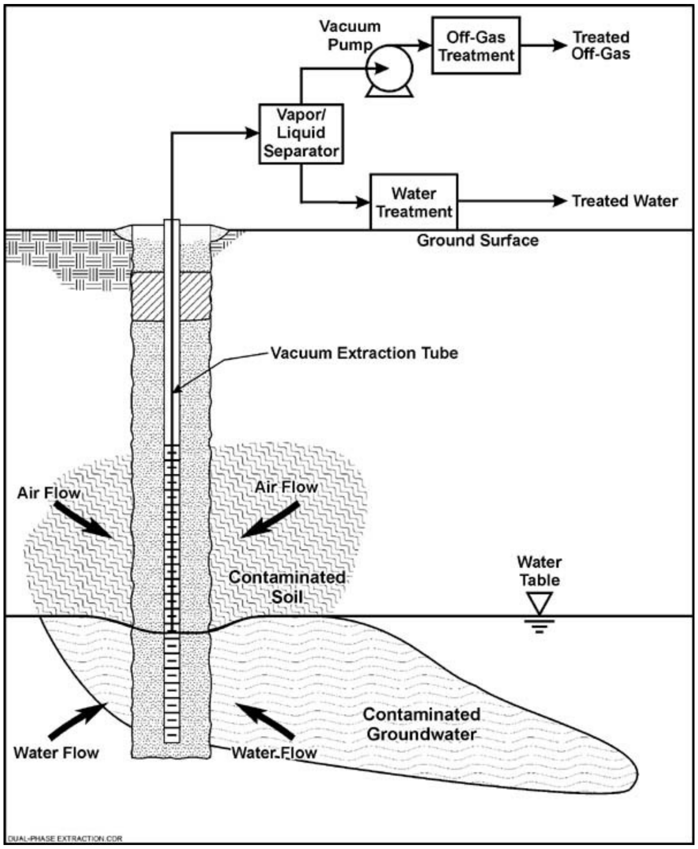


FIGURE 1. CONCEPTUAL EXAMPLE OF TWO-PHASE RECOVERY SYSTEM

Capital costs and operating duration for TPE are expected to be similar to those for air sparging. The overall cost for TPE could be considerably higher than air sparging if it requires a complex aboveground treatment for the extracted groundwater or vapor treatment. TPE can reduce the cost of groundwater treatment compared to conventional pumping and treatment due to the air stripping action that occurs in the drop tube. In the single-pump configuration, separating the liquid and vapor streams for treatment can be difficult, particularly if LNAPL is present and the groundwater chemistry promotes formation of stable emulsions.

Source for Further Information

U.S. EPA. 2000. *Dual-Phase Extraction*. www.epa.gov/OUST/cat/dualphas.htm.

APPENDIX C

PROPERTIES OF SELECTED VOCs

This appendix includes a summary of physical-chemical properties that impact the fate and transport of volatile organic compounds in the subsurface.

Table C-1 includes physical-chemical properties for several VOCs. These properties are useful for general calculations or simple modeling exercises to estimate equilibrium partitioning of contaminants from soil and/or groundwater to the soil vapor phase. These parameters include the molecular weight, organic carbon partition coefficient, diffusivity terms, water solubility, physical state at ambient conditions, Henry's law constants, and vapor pressure and are defined as follows:

☐ The organic carbon partition coefficient (K_{oc}, cm^3/g) provides a measure of how readily a contaminant will adsorb to organic matter in soil.

☐ The diffusivity in air (D_a, cm^2/s) is a mass transfer parameter related to the rate of contaminant molecular diffusion in air.

☐ The diffusivity in water (D_w, cm^2/s) is a mass transfer parameter related to the rate of contaminant molecular diffusion in water.

☐ The water solubility is the maximum concentration at which a pure phase contaminant will dissolve into water at a given temperature to form a saturated solution.

☐ Henry's law coefficient is a measure of how readily a contaminant will partition from a dilute aqueous phase to a vapor phase. It can be used to estimate equilibrium partitioning of a contaminant from groundwater to soil vapor or vice versa. The law states that the partial pressure of the compound in the gas phase (P_x) is proportional to the concentration of a compound in solution (C_x). Henry's law coefficient can be approximated as the ratio of a compound's vapor pressure to its aqueous solubility. Henry's law is as follows:

$$P_x = K_H \cdot C_x \tag{C-1}$$

The units for Henry's constant are K_H, atm-m^3/mol-K.

☐ Vapor pressure is the pressure exerted by a vapor in equilibrium with its pure liquid phase at a given temperature. It is a measure of the maximum concentration that a given contaminant will volatilize into air to form a saturated vapor. The vapor pressure, along with the component mole fraction, can be used to estimate the equilibrium partitioning of a contaminant from the NAPL phase to soil vapor. The equation is as follows:

$$C_i = \frac{x_i \cdot P_i^v \cdot MW_i}{R \cdot T} \tag{C-2}$$

where: C_i = estimate of contaminant vapor concentration (mg/L)
x_i = mole fraction of contaminant i in liquid phase (unitless)
P_i^v = pure component vapor pressure at a given phase (atm)
MW_i = molecular weight of contaminant i (mg/mol)
R = universal gas constant = 0.0821 L-atm/mol-K
T = absolute temperature (K).

Figures C-1 and C-2 show vapor pressure versus water solubility and provide an illustration of how these physical-chemical properties impact the fate and transport of a given compound. As water solubility increases, there is an increasing tendency for the compound to dissolve into and move with groundwater. As the vapor pressure increases, there is an increasing tendency for volatilization to be the primary means of contaminant transport.

Figure C-3 is a graph relating a given contaminant's vapor pressure to its aerobic half-life. Aerobic half-life is the time for 50% of the initial compound concentration to biodegrade under aerobic or oxygenated conditions. The general trend shows that as contaminant vapor pressure increases, the aerobic half-life decreases. A contaminant with a high vapor pressure is generally more bioavailable and therefore is degraded more readily.

TABLE C-1. Physical-Chemical Constants for Selected Volatile Organic Compounds(a)

Compound	Molecular Weight	Organic Carbon Partition Coefficient, K_{oc} (cm^3/g)	Diffusivity in Air, D_a (cm^2/s)	Diffusivity in Water, D_w (cm^2/s)	Pure Component Water Solubility, S (mg/L)	Physical State(c)(d)		Henry's Law Constant H (atm-m^3/mol)	Henry's Law Constant H′ (unitless)	Pure Component Vapor Pressure (mm Hg)
Acetone	58	5.75E-01	1.24E-01	1.14E-05	1.00E+06	V	L	3.88E-05	1.59E-03	180
Benzene(b)	78	6.20E+01	8.80E-02	9.80E-06	1.80E+03	V	L	5.63E-03	2.34E-01	75
Bromodichloromethane	164	1.00E+02	2.98E-02	1.06E-05	6.74E+03	V	L	1.60E-03	6.56E-02	NA
Bromoform	253	1.10E+02	-	-	3.20E+03	NV	L	5.32E-04	2.18E-02	5
Bromomethane	95	9.00E+00	7.30E-02	1.20E-05	1.50E+04	V	G	6.20E-03	2.54E-01	1,444
Carbon tetrachloride(b)	154	1.50E+02	7.80E-02	8.80E-06	7.93E+02	V	L	2.98E-02	1.24E00	91
Chlorobenzene(b)	113	2.20E+02	7.30E-02	8.70E-06	4.72E+02	V	L	3.88E-03	1.61E-01	9
Chloroethane	65	1.50E+01	1.00E-01	1.00E-05	5.70E+03	V	L	1.10E-02	4.51E-01	1,000
Chloroform(b)	119	5.30E+01	1.04E-01	1.00E-05	7.92E+03	V	L	4.24E-03	1.76E-01	160
Chloromethane	51	3.50E+01	1.10E-01	6.50E-06	8.20E+03	V	G	2.40E-02	9.84E-01	3,800
Dibromochloromethane(b)	199	4.70E+02	9.60E-02	1.00E-05	4.00E+03	V	L	1.16E-03	4.83E-02	NA
Dibromoethane, 1,2-	188	2.80E+01	7.30E-02	8.10E-06	3.40E+03	V	L	3.20E-04	1.31E-02	12
Dichlorobenzene, 1,2-(b)	147	3.80E+02	6.90E-02	7.90E-06	1.56E+02	V	L	1.86E-03	7.72E-02	1
Dichlorobenzene, 1,3-(b)	147	3.80E+02	6.90E-02	7.90E-06	1.60E+02	V	L	3.29E-03	1.37E-01	NA
Dichlorobenzene, 1,4-(b)	147	6.20E+02	6.90E-02	7.90E-06	7.38E+01	V	S	3.18E-03	1.32E-01	1.3
Dichloroethane, 1,1(b)	99	5.30E+01	7.42E-02	1.05E-05	5.06E+03	V	L	6.49E-03	2.70E-01	182
Dichloroethane 1,2(b)	99	3.80E+01	1.04E-01	9.90E-06	8.52E+03	V	L	1.54E-03	6.39E-02	64
Dichloroethylene, 1,1(b)	97	6.50E+01	9.00E-02	1.04E-05	2.25E+03	V	L	2.66E-02	1.10E00	500
Dichloroethylene, *cis* 1,2	97	3.60E+01	7.36E-02	1.13E-05	3.50E+03	V	L	4.07E-03	1.67E-01	180-265
Dichloroethylene, *trans* 1,2-	97	3.80E+01	7.07E-02	1.19E-05	6.30E+03	V	L	9.39E-03	3.85E-01	180-265
Dichloropropane, 1,2-(b)	113	4.70E+01	7.82E-02	8.73E-06	2.80E+03	V	L	2.61E-03	1.09E-01	40
Dichloropropene, 1,3	111	2.70E+01	6.26E-02	1.00E-05	2.80E+03	V	L	1.77E-02	7.26E-01	28
Ethylbenzene(b)	106	2.00E+02	7.50E-02	7.80E-06	1.69E+02	V	L	8.52E-3	3.54E-01	7
Methylene chloride(b)	85	1.00E+01	1.01E-01	1.17E-05	1.30E+04	V	L	2.93E-03	1.22E-01	350
Methyl-*tert*-butyl ether	85	1.17E+01	8.10E-02	9.41E-05	4.80E+04	V	L	5.87E-04	2.41E-02	NA
Naphthalene (b)	128	1.20E+03	5.90E-02	7.50E-06	3.10E+01	V	S	7.80E-04	3.24E-02	0.08
Styrene	104	9.10E+02	7.10E-02	8.00E-06	3.10E+02	V	L	2.80E-03	1.15E-01	5
Tetrachloroethane, 1,1,1,2-	168	7.90E+01	7.10E-02	7.90E-06	2.97E+03	V	L	3.50E-04	1.44E-02	14
Tetrachloroethane, 1,1,2,2-(b)	168	7.90E+01	7.10E-02	7.90E-06	2.97E+03	V	L	4.53E-04	1.45E-02	5
Tetrachloroethylene(b)	166	2.70E+02	7.20E-02	8.20E-06	2.00E+02	V	L	1.82E-02	7.58E-01	14
Toluene	92	1.40E+02	8.70E-02	8.60E-06	5.26E+02	V	L	6.60E-03	2.71E-01	21
Trichlorobenzene, 1,2,4(b)	180	1.70E+03	3.00E-02	8.23E-06	3.00E+02	V	L	2.14E-03	8.88E-02	1
Trichloroethane, 1,1,1(b)	133	1.40E+02	7.80E-02	8.80E-06	1.33E+03	V	L	1.74E-02	7.25E-01	100
Trichloroethane, 1,1,2-(b)	133	7.50E+01	7.80E-02	8.80E-06	4.42E+03	V	L	1.16E-03	4.28E-01	19
Trichloroethylene	131	9.40E+01	7.90E-02	9.10E-06	1.10E+03	V	L	1.03E-02	4.22E-01	58
Vinyl chloride(b)	63	1.90E+01	1.06E-01	1.23E-06	2.76E+03	V	G/L	1.77E-02	7.34E-01	2,508
Xylenes(b)	106	2.00E+02	7.00E-02	7.80E-06	1.61E+02	V	L	7.349E-3	3.05E-01	7-9

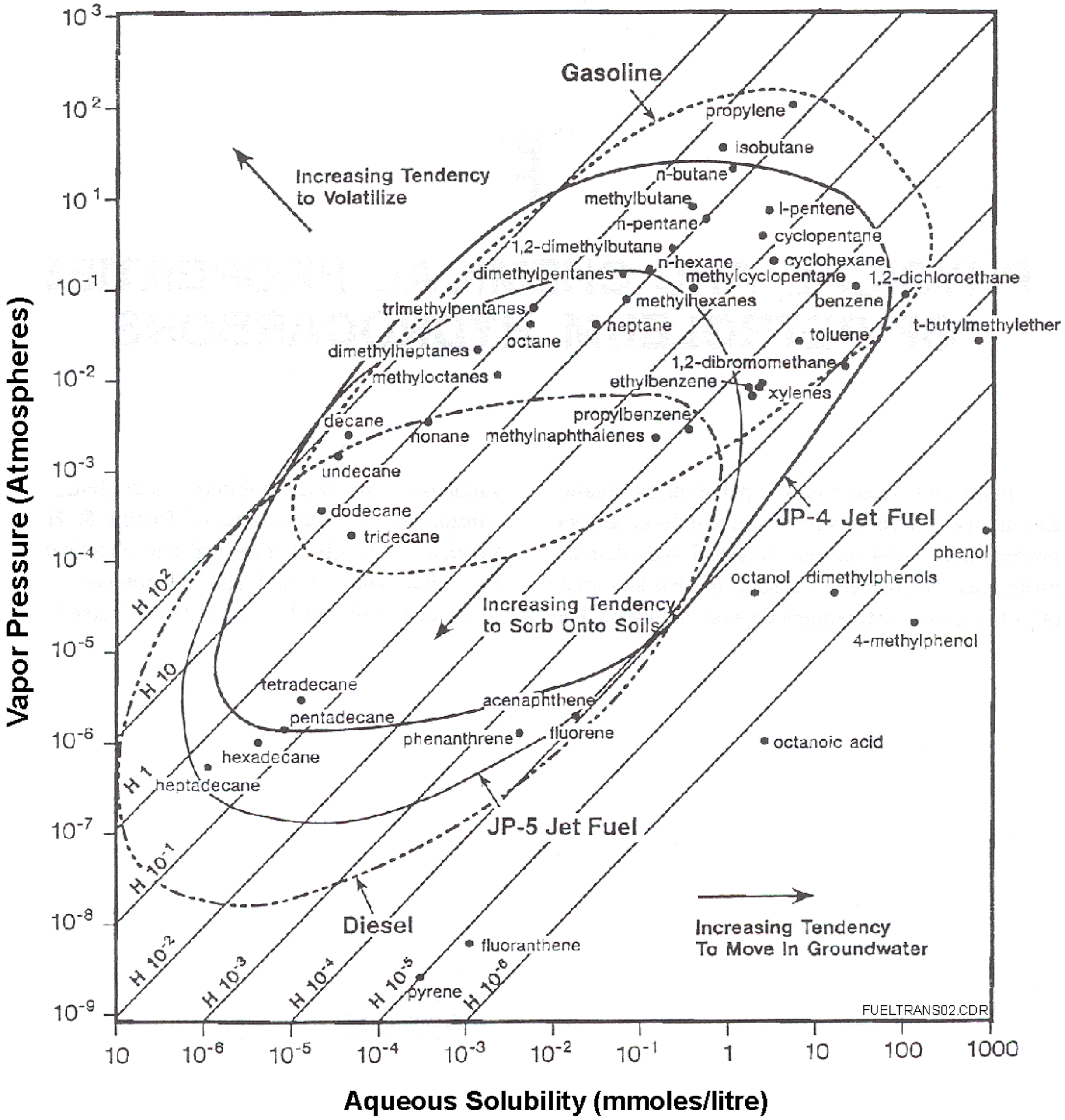
(a) Source: The San Francisco Bay Regional Water Quality Control Board (RWQCB) publication "Application of Risk-Based Screening Levels and Decision Making to Sites with Impacted Soil and Groundwater" (Interim Final, August 2000).

(b) Henry's law coefficient for these compounds are from the Equilibrium Partitioning in Closed Systems (EPICs) Model.

(c) Vapor pressures at 68°F from *NIOSH Handbook*.

(d) Physical state of chemical at ambient conditions (V - volatile, NV - nonvolatile, S - solid, L - liquid, G - gas).

NA= Not available.



H = Henry's Law Coefficient (atm • m^3/mole)

FIGURE C-1. Effect of Properties of Fuel Compounds on In Situ Transport

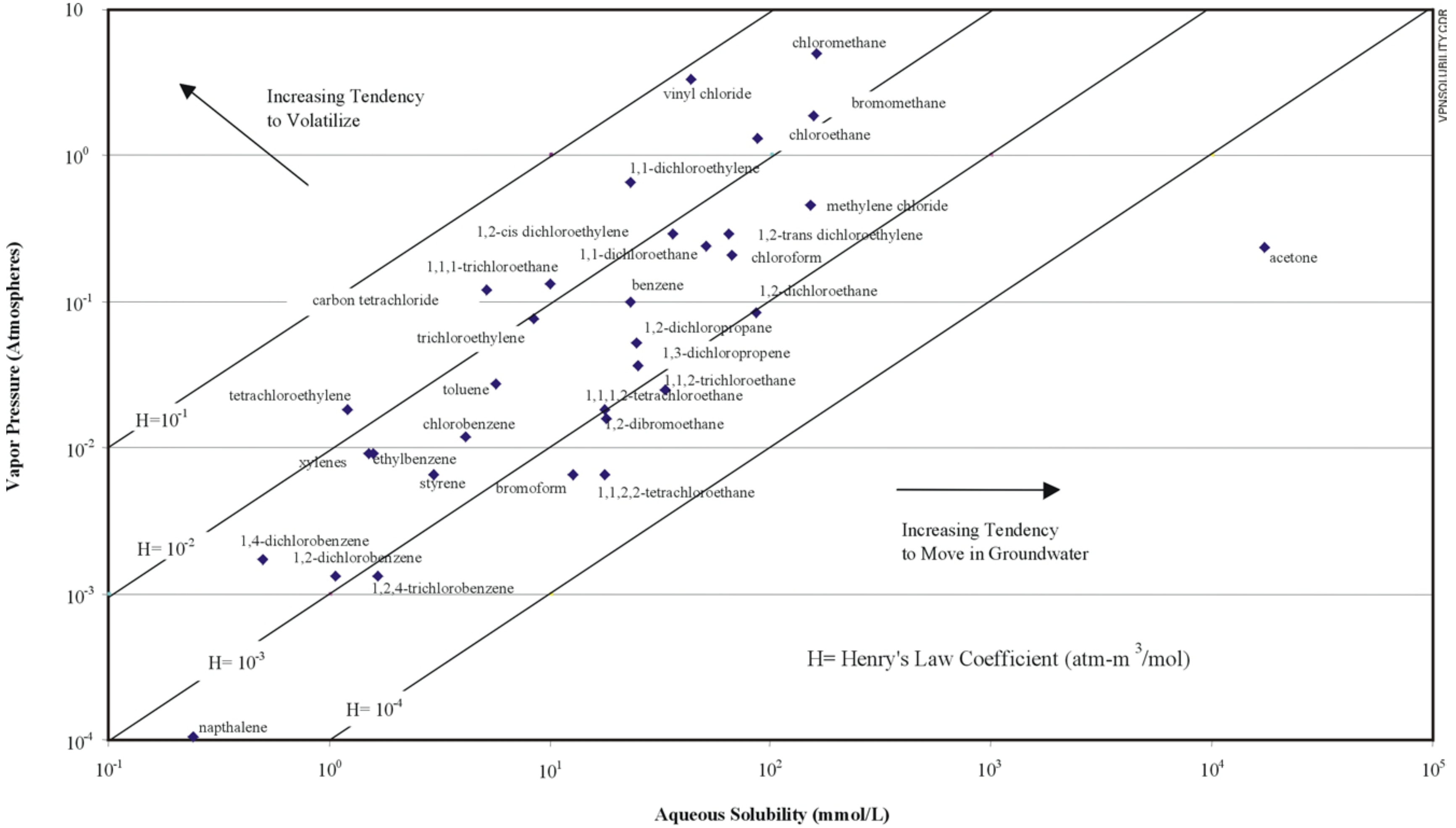


FIGURE C-2. **Vapor Pressure vs. Aqueous Solubility for Selected VOCs**

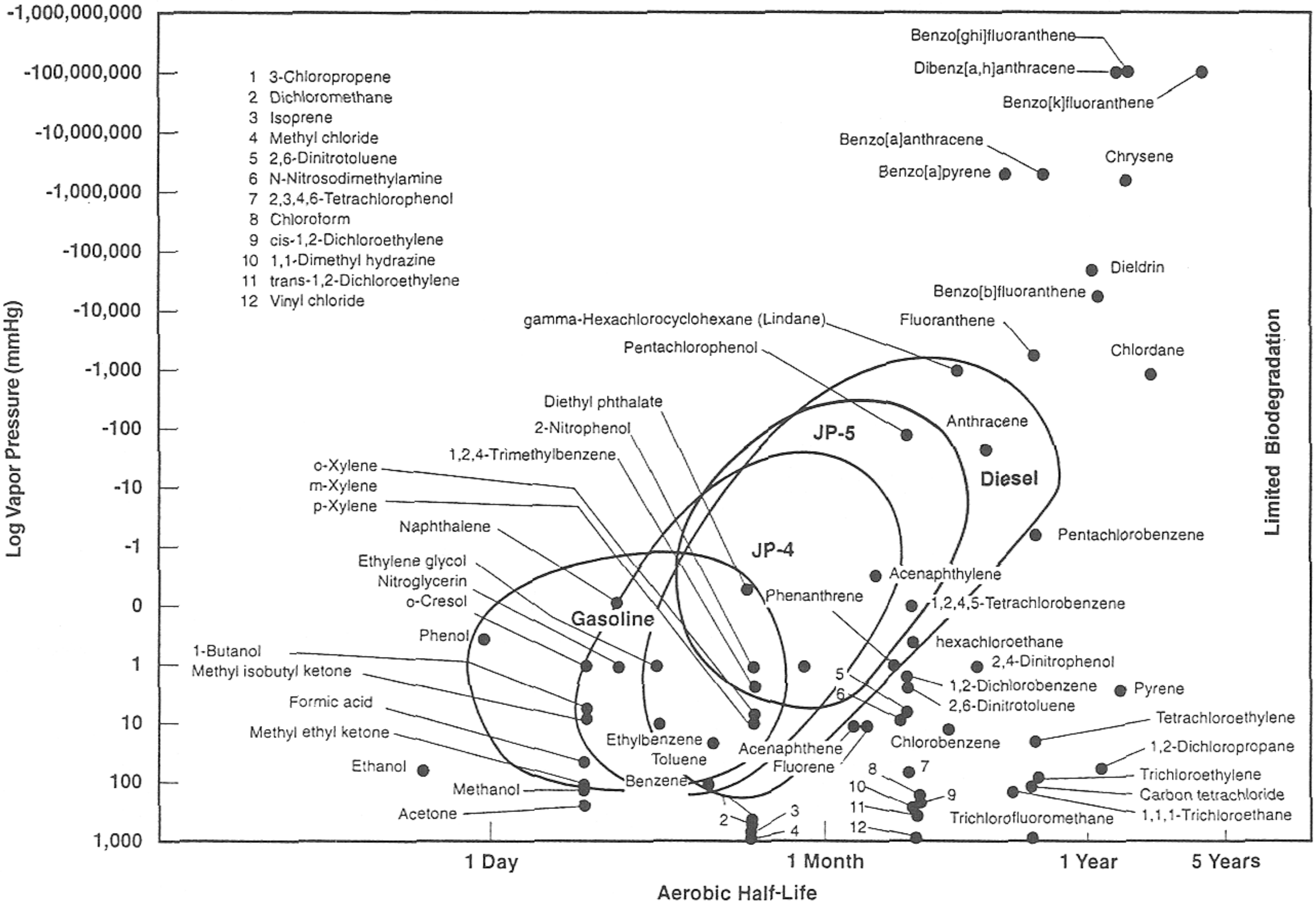


FIGURE C-3. Relationship Between Contaminant Vapor Pressure and Aerobic Biodegradability

References

Engineering and Services Center Tyndall Air Force Base, *Equilibrium Partitioning in Closed Systems (EPICs) Model from Evaluation and Prediction of Henry's Law Constants and Aqueous Solubilities for Solvents and Hydrocarbon Fuel Components, Volume 1: Technical Discussion*, Florida, September 1987.

San Francisco Bay Regional Water Quality Control Board (RWQCB) publication "Application of Risk-Based Screening Levels and Decision Making to Sites with Impacted Soil and Groundwater" (Interim Final, August 2000).

U.S. Department of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health*, NIOSH Pocket Guide to Chemical Hazards. June 1997.*

APPENDIX D

SOIL PROPERTIES

This appendix includes typical soil properties that impact the fate and transport of contaminants in the subsurface.

Table D-1 shows typical values for soil characteristics that govern the transport of contaminants in the vadose or unsaturated zone. These parameters are generally used as input parameters in soil vapor modeling programs that estimate contaminant mass transfer from the soil or groundwater to the vapor phase. This table can also be used to check field measurements to see if they fall within reasonable expected ranges. The parameters are described as follows:

- The soil total porosity, n, provides a measure of how much void space is available between soil particles.
- The soil water-filled porosity, q_w, provides a measure of how much of the void space is filled by water in the unsaturated zone.
- The soil vapor permeability, k_v, is a measure of the ability of air to flow through a given soil formation. The higher the soil vapor permeability, the less resistance there is to airflow.
- The soil organic carbon fraction, f_{oc}, is a measure of the amount of organic matter present in a given soil for contaminant adsorption.

Table D-2 shows typical contaminant distributions for a light hydrocarbon in varying soil types. This table illustrates the fact that a large percentage of contaminant mass can be found in the smear zone (up to 99.8%). Air sparging is an effective means of targeting the smear zone because the injected air moves vertically up through this region.

Figure D-1 illustrates the U.S. Soil Conservation Service classification system for several soil types. It can be used to classify a given soil based on the percentage of sand, silt, or clay present in the material.

Figure D-2 provides typical hydraulic conductivity and permeability values for a variety of soil types.

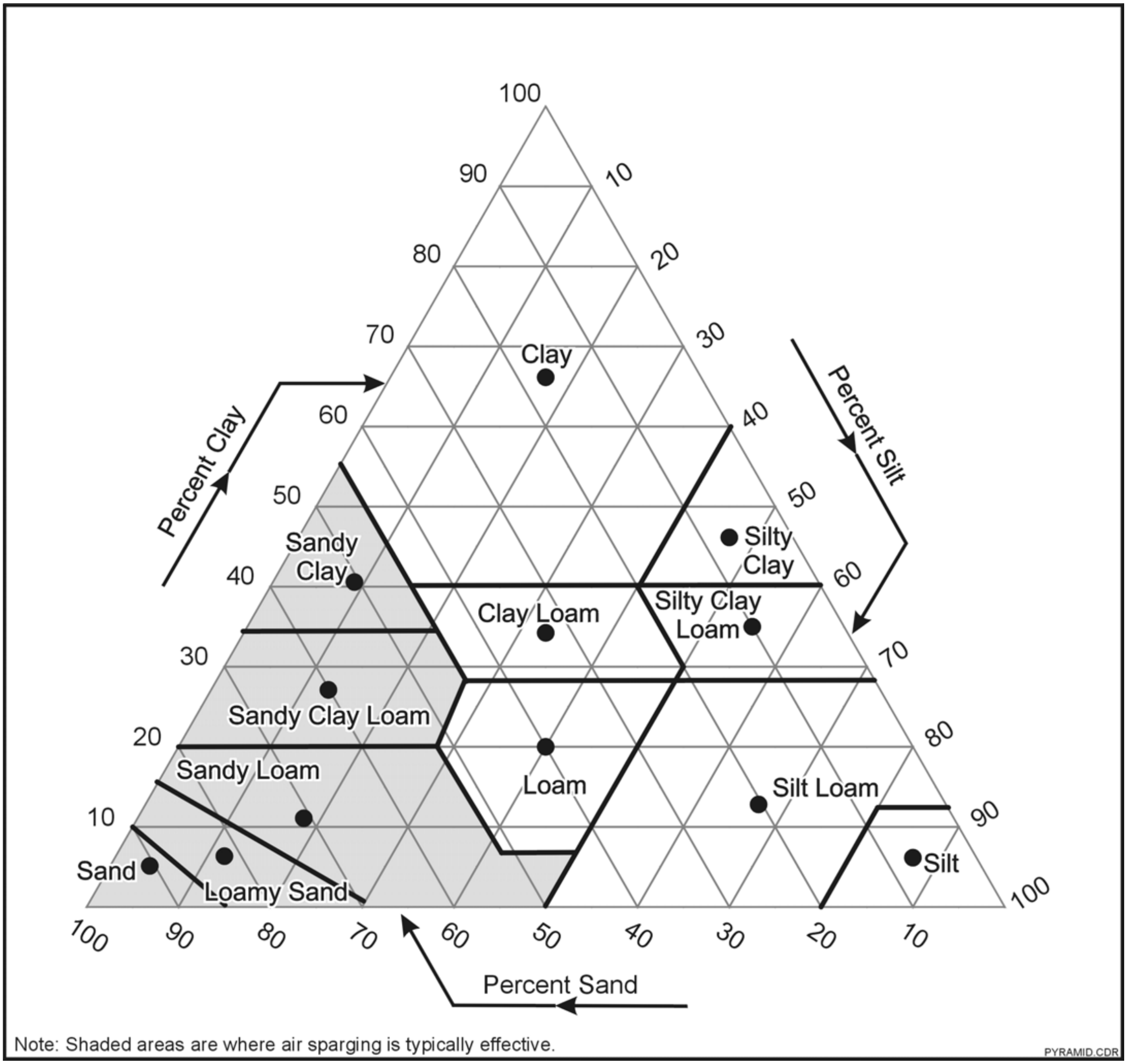
TABLE D-1. Range of Selected Soil Properties Relevant to Air Sparging Applications[(a)]

Description	Symbol	Practical Range of Values
Soil total porosity	n	0.34 to 0.53 cm^3/cm^3
Soil water-filled porosity	q_w	0.02 to 0.43 cm^3/cm^3
Soil vapor permeability	k_v	10^{-6} to 10^{-12} cm^2
Soil organic carbon fraction	f_{oc}	0.001 to 0.006
Soil bulk density	r_b	1.25 to 1.75 g/cm^3

(a) Soil property values excerpted from U.S. EPA (2001).

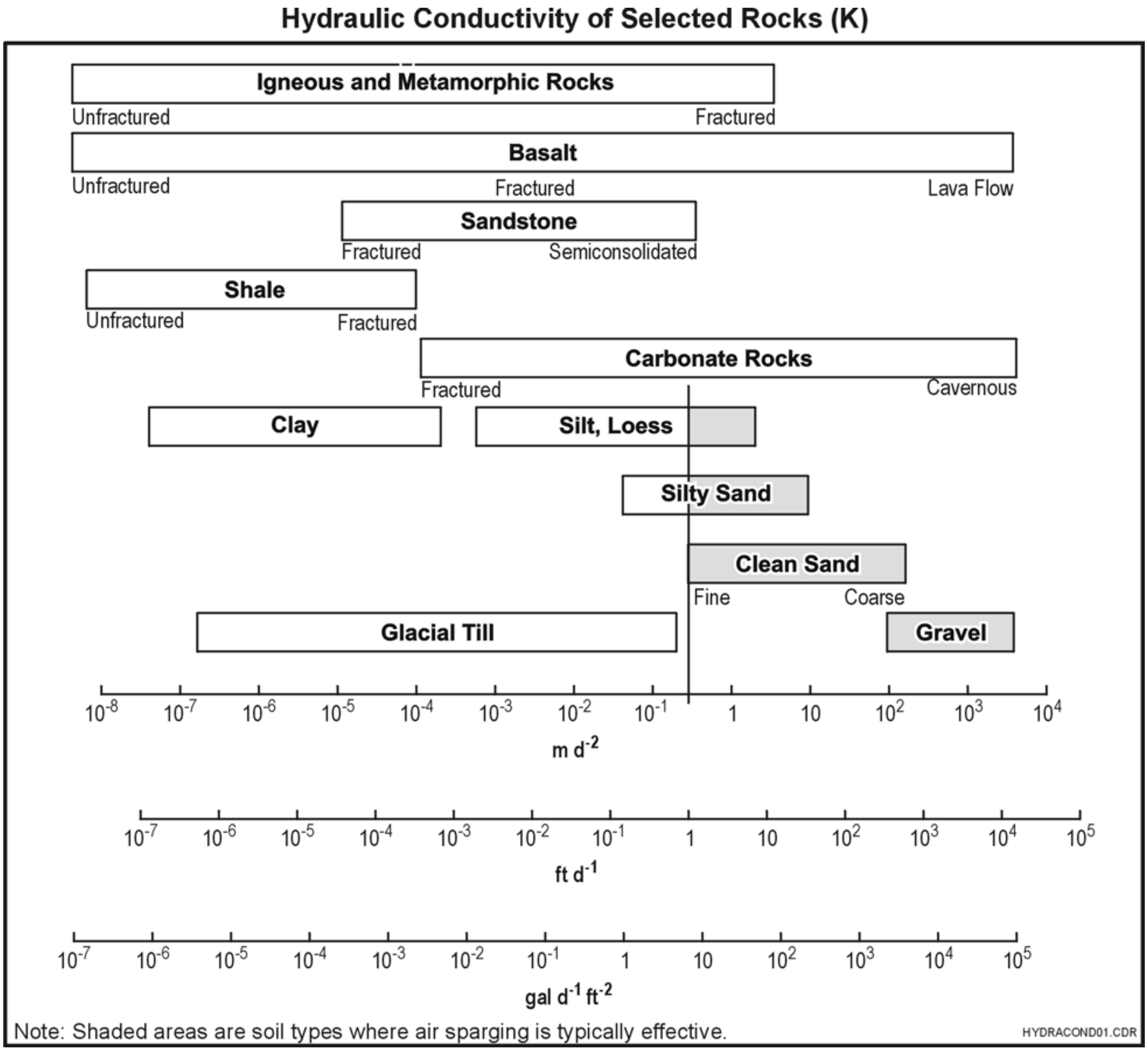
TABLE D-2. Mass/Volume Distribution of Spilled Hydrocarbon (Gasoline) at Six Active Service Stations

Phase	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Dissolved	0.2%	0.3%	0.002%	0.1%	0.02%	0.1%
Residual	38%	72%	48%	0.02%	36%	11%
Free Product	0%	3%	50%	0%	0%	51%
Smear Zone	61%	24%	2%	99.8%	64%	38%
Soil Type	Sandy	Clayey	Sandy	Clayey	Clayey	Sandy
Spill Age	Old	Old	New	Old	Old	New



Note: Shaded areas are where air sparging is typically effective.

FIGURE D-1. U.S. Soil Conservation Service Classification Chart Showing Centroid Compositions (solid circles)


Hydraulic Conductivity of Selected Rocks (K)

Note: Shaded areas are soil types where air sparging is typically effective.

FIGURE D-2. **Range of Values for Hydraulic Conductivity and Permeability**

References

Boelsma, F., E.C.L. Marnette, C.G.J.M. Pijls, C.C.D.F. van Ree, K. Vreeken. 1999. *In Situ Air Sparging, A Technical Guide.* Geodelft Environmental. Stieltjesweg 2, Delft, The Netherlands.

United States Environmental Protection Agency. 2001. "User's Guide for the Johnson and Ettinger (1991) Model for Subsurface Vapor Intrusion into Buildings." Located at http://www.epa.gov/oerrpage/superfund/programs/risk/airmodel/ guide.pdf.

U.S. EPA, see United States Environmental Protection Agency.

APPENDIX E

AIR SPARGING ECONOMICS AND COST ESTIMATING WORKSHEET

The two main categories of costs for any technology are initial investment and operation and maintenance (O&M). Initial investment costs include expenditures like additional site characterization, pilot-scale testing, design, and system construction, while O&M costs can include monitoring, vapor treatment, and site decommissioning costs. These two categories of costs with respect to air sparging are discussed in detail in this appendix. Key variables that affect these costs are depth of groundwater, depth to base of contamination, area of groundwater contamination, geology, type of contamination, and treatment duration. Additional design information that affects costs include the spacing of the air injection and soil vapor extraction wells, air injection flowrate, air extraction flowrate, and regulatory requirements (e.g., monitoring, permitting, etc.).

The cost evaluation described in this section can be applied to varying degrees of precision at two stages in the design of an air sparging system. First, a preliminary cost evaluation may be conducted during preparation of the corrective action plan or feasibility study to determine the suitability of a site for an air sparging application. This evaluation would compare the cost of an air sparging application at the site to the cost of using a competing technology (see Appendix A for the competing technologies matrix). Although a detailed cost evaluation may not be possible at this stage, rough estimates for initial and O&M costs can be developed. This early process of cost evaluation also helps to identify the most cost-effective air sparging construction technique for a given hydraulic conductivity, contaminant depth, and other site features involved. NFESC currently is working on an Internet-based program called the Remediation Technology Evaluation Tool (ETET), which will provide useful features for technology evaluation and preliminary cost estimating. If the preliminary cost evaluation turns out to be favorable for air sparging, site managers could proceed to pilot testing, engineering design, and construction, as described in Section 4.0 of the main document. Once the draft design is ready, contractors can be contacted to obtain detailed cost estimates, and a detailed cost analysis then can be conducted.

E.1 Initial Investment

Initial investment in a technology refers to the funds required to cover the initial nonrecurring cost involved in acquiring and installing the technology to the point where it is ready for its intended use. The initial investment for installing an air sparging system includes the following major items:

- ☐ Site characterization costs
- ☐ Pilot-scale testing costs
- ☐ Design costs
- ☐ System construction costs.

E.1.1 Site Characterization Costs

Site characterization costs include collecting and analyzing soil and groundwater samples, as well as evaluating site geology, hydrogeology, and hydrology. These activities can be a substantial component of remediation costs, whether for air sparging or any other alternative. Given the fact that the effective radius of air injection wells is strongly influenced by site conditions, adequate site characterization is all the more important for understanding the local contaminant and groundwater conditions of the site on the scale of the planned air sparging system. The degree of site characterization required at a site may vary depending on the extent of contamination, complexity of the subsurface environment, and on the amount of existing information available from previous site assessment activities or remedial investigations/feasibility studies (RI/FS).

E.1.2 Pilot-Scale Testing Costs

Because of the uncertainty inherent with any in situ treatment technology, a pilot test is needed to evaluate air sparging feasibility and to collect design basis information prior to detailed design of the full-scale system. Pilot-scale testing is used to determine site-specific design parameters such as optimal air injection pressure and flowrate, air extraction vacuum and flowrate, off-gas concentrations, the effective sparging radius, the effective vapor extraction radius, and vadose zone biodegradation capacity. The sparging and vapor extraction radii control the spacing of the air injection and extraction wells and thus the number of wells needed to effectively remediate the area. Off-gas concentrations are needed to determine the most cost-effective vapor treatment approach, and biodegradation capacity is important if the soil vapor extraction will not be implemented.

Costs for pilot testing include labor, materials and equipment to install test wells and monitoring points, conduct testing protocols, and collect/analyze samples. Pilot testing usually requires 1 to 2 weeks of fieldwork.

E.1.3 System Design Costs

System design and subsequent regulatory review are important activities that will require some effort and labor costs. Design generally includes the analyses conducted to interpret site assessment and pilot test data to determine the location, orientation, configuration, and dimensions of the air sparging system.

Regulatory requirements can significantly influence the system design. Meeting stringent treatment criteria will require closer well spacing or increased operating time, both of which increase the cost. Also, in jurisdictions with stringent requirements on air releases, it may be necessary to install a soil vapor extraction system to collect sparged air and an off-gas treatment system to treat contaminants collected by the SVE system.

E.1.4 System Construction Costs

System construction costs include labor, materials, and equipment necessary to install a full-scale air sparging system. Major components of system construction costs include well installation (i.e., air sparging, soil vapor extraction, and monitoring wells), sampling and analysis, compressor(s) to deliver air to the subsurface, vapor extraction and treatment equipment, support facilities, utility connections, construction materials (e.g., piping, fittings, etc.), and labor. Depending on the size and complexity of the system, construction duration typically ranges from as short as two weeks to as long as two months.

E.2 Operating and Maintenance Costs

The O&M costs of a technology are the recurring or periodic costs incurred during the operating life of the system. The O&M costs of an air sparging system include the following major items:

- ☐ Contaminant monitoring costs
- ☐ Performance monitoring costs
- ☐ Equipment rental and maintenance costs
- ☐ Site decommissioning costs.

E.2.1 Contaminant Monitoring Costs

These costs may vary from site to site depending on regulatory requirements, number of monitoring wells, and frequency of sampling. These costs include sampling, laboratory analysis, reporting, and labor. Typically, contaminant monitoring is conducted quarterly during air sparging operation.

E.2.2 Performance Monitoring Costs

If additional monitoring is desired by site managers to achieve other performance monitoring objectives (see Section 5.3 of the main document), additional monitoring costs may be incurred. These costs will vary depending on the objectives of site managers at a given site. For example, if vapor extraction and treatment is required at the site, periodic off-gas contaminant concentration measurements may be required.

E.2.3 Equipment Rental and Maintenance Costs

The air sparging system is mechanically simple, consisting of wells, piping, and compressors, so the annual O&M cost requirements are relatively low. The addition of a vapor collection and treatment system will significantly increase operating complexity and costs. Rental costs may be incurred for the vapor treatment system (e.g., catalytic oxidation, activated carbon, etc.), meters, compressors, etc. Maintenance costs for an air sparging system include labor and equipment necessary to service equipment, such as compressors, blowers, and other treatment equipment. Also, utility costs for operating the air sparging system are included in this cost category.

E.2.4 Site Decommissioning Costs

Upon completion of the air sparging at a site, site closeout activities will result in identifiable costs. These activities include system removal and equipment demobilization, well abandonment, labor, and reporting.

E.3 Air Sparging Cost Estimate Worksheet

A worksheet for preparing a preliminary cost estimate for an air sparging project is provided in this appendix. This worksheet does not address site characterization costs because it is assumed that these data will be required for any remediation technology and are not specific to air sparging. The air sparging cost model is based on cost driving parameters such as the depth to groundwater, the size of the target treatment area, the required air sparging and SVE well spacing, along with other site-specific factors. These basic parameters are then used to estimate the costs for pilot scale testing, construction, operation and maintenance, and site decommissioning. The Air Sparging Cost Estimate Worksheet is based on the assumptions provided in Table E-1. This table provides a step-by-step guide to the assumptions for each cost model item. The assumptions include information about air sparging system design, unit material and labor costs, labor hours, and other important cost considerations.

TABLE E-1. Assumptions Associated with the Air Sparging Cost Estimate Worksheet

Item No.	Parameter	Associated Assumptions
	Cost Driving Parameters	
(a)	Depth to Groundwater, ft	Site-Specific Parameter
(b)	Area of Groundwater Plume, acres	Site-Specific Parameter
(c)	Air Sparging Well Spacing (R_w), ft If unknown, assume: R_w= 15 ft	Site-Specific Parameter. Assumptions are provided for different soil types.
(d)	Number of Air Sparging Wells [Assume 17,900 × (b) ÷ $(c)^2$]	Number of wells is a function of area of contamination and the standard well spacing. The following equation is used: Number of Sparge Wells = $\frac{1.3\,A}{\pi R_w^2}$ where A = Area of Contamination (ft^2) R = Standard Well Spacing (ft) 17,900 = 1.3 × 43,560 ÷ π
(e)	Installation Depth of Sparge Wells, ft bgs [Assume (a) + 10 ft]	Site-Specific Parameter. Wells should be installed below the lowest depth of contamination. The assumption adds 10 ft to the depth to groundwater.
(f)	SVE Radius of Influence (R), ft If unknown, assume based on soil type: Gravel/Coarse Sand: R = 30 ft Sand: R = 25 ft Sandy Silt/Clay: R = 20 ft	Site-Specific Parameter. Assumptions are provided for different soil types.
(g)	Number of SVE Wells [If remediating VOCs, assume 17,900 × (b) ÷ $(f)^2$. Otherwise Assume 0]	Number of wells is a function of area of contamination, SVE ROI, and whether or not an SVE system is necessary. The following equation is used: Number of SVE Wells = $\frac{1.3\,A}{\pi R^2}$ where A = Area of Contamination (ft^2) R = SVE ROI 17,900 = 1.3 × 43,560 ÷ π
(h)	Installation Depth of SVE Wells, ft bgs [Assume = (a)]	Site-Specific Parameter. Wells are typically installed to the top of the water table. The assumption is the depth to groundwater.
(i)	Number of Monitoring Wells [Assume 10 × (b)]	Site-Specific Parameter. Number of monitoring wells may be subject to regulatory requirements. The assumption provides 10 wells per acre.
(j)	Installation Depth of Monitoring Wells, ft bgs [Assume (a) + 10]	Site-Specific Parameter. The assumption is that monitoring wells will extend 10 ft below groundwater surface.

TABLE E-1. Assumptions Associated with the Air Sparging Cost Estimate Worksheet (continued)

Item No.	Parameter	Associated Assumptions
(k)	Air Injection Flowrate, cfm [Assume 10 × (d)]	Assumed to be 10 cfm per air sparging well.
(l)	SVE Extraction Flowrate [If remediating VOCs, assume 3 × (k). Otherwise Assume 0]	If SVE is necessary, the extraction flowrate is assumed to be 3 times the air injection flowrate.
(m)	Operation and Maintenance Duration, years (Assume 1.5 years)	Typical operation and maintenance durations for air sparging systems range between 1 and 2 years.
	Cost Estimating	
Pilot-Scale Testing		
(n)	Sparging, SVE, and Monitoring Point Installations [$] = 1,250 + 28 × [(e)+(g)] + 60 × (a)	• 1 Sparge well, 1 SVE Well, if necessary, and 3 monitoring points • $1,250 mobilization cost • $28 per foot for Sparge and SVE Wells • $20 per foot for monitoring points • Includes disposal of drill cuttings
(o)	Equipment, Materials, Sampling, and Analytical Services = $12,000	• $8,000 for piping, sampling materials, etc. • $2,000 for air sampling (5 samples at $400 each) • $2,000 for soil sampling (10 samples at $200 each)
(p)	Labor = $23,000	• Field Labor: 100 hours each for technician and project engineer/geologist • Reporting/Management: 20 hours for Project Superintendent, 80 hours for Project Engineer, 40 hours for Staff Engineer, 20 hours for QA/support
Construction Costs		
(q)	Air Sparging Well Installation [$] = 1,250 + 28 × (d) × (e)	• $1,250 mobilization cost • $28 per foot for well installation • Includes disposal of drill cuttings
(r)	SVE Well Installation [$] = 28 × (g) × (h)	• $28 per foot for well installation • Includes disposal of drill cuttings
(s)	Monitoring Well Installation [$] = 35 × (i) × (j)	• $35 per foot for well installation • Includes disposal of drill cuttings
(t)	Sampling and Analysis [$] = 400 × (d)	• 2 soil samples per sparge well at $200 each
(u)	Equipment and Materials [$] = 2,000 + 10,000 × (b)	• $2,000 fixed materials costs • $10,000 per acre of site
(v)	Air Compressor(s) [$] = 200 × (k)	• $25,000 per 125 cfm of total injection flowrate
(w)	Off-Gas Treatment System Mobilization and Setup [$] = 5 × (l)	• If SVE is necessary, $2,500 per 500 cfm extraction flowrate
(x)	Support Facility(ies) [$] = 5,000 + 40 × (k)	• $5,000 fixed costs • $5,000 per 125 cfm of total inject flowrate
(y)	Electrical/Power Connections = $15,000	• $15,000 to make electrical/power connections (typically 3-phase 460 volt service)
(z)	Field Labor [$] = 1,800 × (d)	• Labor markup (multiplier) = 2.75 • 10 hours/Sparge well each for two technicians and one project engineer/geologist
(aa)	Reporting and Project Management Labor = $10,000	• Reporting/Management: 20 hours for Project Superintendent, 80 hours for Project Engineer, 40 hours for Staff Engineer, 20 hours for QA/support
Operating and Maintenance Cost		
(bb)	Off-Gas Treatment [$] = (54 + 10 × [(m) × 12 – 3]) × (l)	• Catalytic Oxidizer for 3 months at $9,000 per month per 500 cfm total extraction flowrate (9,000 × 3 ÷ 500 = 54) • Granular Activated Carbon for remainder of project duration at $5,000 per month per 500 cfm total extraction flowrate (5,000 ÷ 500 = 10)
(cc)	Sampling and Analysis [$] = 9,600 × (m)	• 2 air samples per month at $400 each (2 × 12 × 400 = 9,600)

TABLE E-1. Assumptions Associated with the Air Sparging Cost Estimate Worksheet (continued)

Item No.	Parameter	Associated Assumptions
(dd)	Electric [$] = 500 × (m) × ((k) ÷ 3,125 + (l) ÷ 5,000)	• $0.08/kW-h (0.08 × 24 × 350 × 0.7475 = 500) • System operating 24 hours a day, 350 days per year • 25 hp per 125 cfm total air injection flowrate (25 × 125 = 3,125) • 10 hp per 500 cfm total air extraction flowrate (10 × 500 = 5,000)
(ee)	Maintenance [$] = 6,000 × (m)	• $6,000/year
(ff)	Groundwater Monitoring [$] = 10,000 × (i) × (m)	• Quarterly sampling during system operation • $2,500/monitoring well per sampling event (4 × 2,500 = 10,000)
(gg)	Field Labor [$] = 22,900 × (m)	• Labor markup (multiplier) = 2.75 • 8 hours/week for one technician
(hh)	Reporting and Project Management Labor [$] = 27,350 × (m)	• Labor markup (multiplier) = 2.75 • 4 hours/month for Project Superintendent, 16 hours/month for Project Engineer, 8 hours/month for Staff Engineer, 8 hours/month Clerical
System Closeout Costs		
(ii)	System Removal/Demobilization [$] = 5,000 + 5,000 × (b)	• $5,000 fixed cost • $5,000 per acre
(jj)	Well Abandonment [$] = 1,250 + 20 × [(d) × (e) + (g) × (h) + (i) × (j)]	• $1,250 mobilization cost • $20/foot
(kk)	Field Labor [$] = 18,000 × (b)	• Labor markup (multiplier) = 2.75 • 100 hours/acre each for two technicians and one project engineer/geologist
(ll)	Reporting and Management Labor = $20,000	• Labor markup (multiplier) = 2.75 • 20 hours for Project Superintendent, 80 hours for Project Engineer, 40 hours for Staff Engineer, 20 hours for QA/support

Air Sparging Cost Estimate Worksheet

This worksheet provides a method for estimating the capital and O&M costs for a typical air sparging project. Table E-1 can be consulted for more background information on the assumptions that went into developing the equations used in this basic cost model.

Cost Driving Parameters

(a)	Depth to Groundwater		feet bgs
(b)	Area of Groundwater Plume		acre(s)
(c)	Air Sparging Well Spacing (R_w) If unknown, assume based on soil type: Gravel/Coarse Sand: R_w = 20 feet Sand: R_w = 15 feet Sandy Silt/Clay: R_w = 7.5 feet		feet
(d)	Number of Sparge Wells [Assume $17{,}900 \times (b) \div (c)^2$]		
(e)	Installation Depth of Sparge Wells [Assume (a) + 10]		feet bgs
(f)	SVE Radius of Influence (R) If unknown, assume based on soil type: Gravel/Coarse Sand: R = 30 feet Sand: R = 25 feet Sandy Silt/Clay: R = 20 feet		feet
(g)	Number of SVE Wells [If remediating VOCs, assume $17{,}900 \times (b) \div (6)^2$. Otherwise Assume 0]		
(h)	Installation Depth of SVE Wells [Assume = (a)]		feet bgs
(i)	Number of Monitoring Wells [Assume 10 × (b)]		
(j)	Installation Depth of Monitoring Wells [Assume (a) + 10]		feet bgs
(k)	Air Injection Flowrate [Assume 10 × (d)]		cfm
(l)	SVE Extraction Flowrate [If remediating VOCs, assume 3 × (k). Otherwise assume 0]		cfm
(m)	Operation and Maintenance Duration (Assume 1.5 years)		years

Cost Estimating

Pilot-Scale Testing Costs

(n)	Sparge, SVE, and Monitoring Point Installations = 1,250 + 28 × [(e)+(g)] + 60 × (a)	
(o)	Equipment, Materials, Sampling, and Analytical Services = $12,000	
(p)	Labor = $23,000	

Installation/Construction Costs

(q)	Air Sparging Well Installation = 1,250 + 28 × (d) × (e)	
(r)	SVE Well Installation = 28 × (g) × (h)	
(s)	Monitoring Well Installation = 35 × (i) × (j)	
(t)	Sampling and Analysis = 370 × (d)	
(u)	Equipment and Materials = 2,000 + 10,000 × (b)	
(v)	Air Compressor(s) = 200 × (k)	
(w)	Off-Gas Treatment System Mobilization and Setup = 5 × (l)	

(x) Support Facility(ies) = 5,000 + 40 × (k)
(y) Electrical/Power Connections = $15,000
(z) Field Labor = 1,800 × (d)
(aa) Reporting and Project Management Labor = $10,000

Operation and Maintenance Costs

(bb) Off-Gas Treatment = (54 + 10 × [(m) × 12 – 3]) × (l)
(cc) Sampling and Analysis = 9,600 × (13)
(dd) Electric = 500 × (m) × ((k) ÷ 3125 + (l) ÷ 5,000)
(ee) Maintenance = 6,000 × (m)
(ff) Groundwater Monitoring = 10,000 × (i) × (m)
(gg) Field Labor = 22,900 × (m)
(hh) Reporting and Project Management Labor = 27,350 × (m)

System Closeout Costs

(ii) System Removal/Demobilization = 5,000 + 5,000 × (b)
(jj) Well Abandonment = 1,250 + 20 × [(d) × (e) + (g) × (h) + (i) × (j)]
(kk) Field Labor = 18,000 × (b)
(ll) Reporting and Management Labor = 20,000

Cost Totals

(mm) Total – Pilot-Scale Testing = Sum of (n) through (p)
(nn) Total – Installation/Construction = Sum of (q) through (aa)
(oo) Total – Operation and Maintenance = Sum of (bb) through (hh)
(pp) Total – System Closeout = Sum of (ii) through (ll)
(qq) System Design = 0.10 × [(mm) + (nn)]
(rr) Travel = 0.05 × [(mm) + (nn) + (oo) + (pp)]
Grand Total = (mm) + (nn) + (oo) + (pp) + (qq) + (rr)

APPENDIX F

OVERVIEW OF APPLICABLE FEDERAL ENVIRONMENTAL REGULATIONS

F.1 Introduction

The following sections provide brief descriptions of the federal regulations relevant to the implementation of air sparging remediation projects as well as a summary of the potential responsibilities generated by each act. It should be noted that administration of these federal laws often has been delegated to the individual states. In some cases, state laws may exist that are more stringent than the corresponding federal laws. Please refer to Section 3.0 for a discussion of relevant state/local regulations.

F.1.1 Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA)

CERCLA, also known as the Superfund Act, provides for the identification and remediation of abandoned or uncontrolled hazardous waste sites. CERCLA regulations apply only to those sites listed on the National Priorities List (NPL). Remediation of a Superfund site is carried out by the Environmental Protection Agency in accordance with the procedures and standards outlined in the National Oil and Hazardous Substances Pollution Contingency Plan (NCP). Current or former owners and operators of the affected sites are liable for the cleanup costs. At federally owned sites, the federal agency in charge of that facility is responsible for oversight and implementation of the remediation project. The requirements of CERCLA are extensive and a complete discussion of the regulatory implications is beyond the scope of this manual. The CERCLA regulations covering environmental remediation are included in 40 CFR Parts 300-311, 355, and 373. CERCLA was amended in 1986 through the Superfund Amendments and Reauthorization Act (SARA). SARA streamlined the Superfund process by simplifying various aspects of the CERCLA regulation. SARA also contained provisions for community right-to-know laws, which are discussed in Section F.1.2. The following steps generally are followed during the Superfund process:

(1) Preliminary site assessment
(2) Site investigation
(3) Listing on the NPL
(4) Remedial investigation and feasibility study
(5) Record of decision
(6) Remedial design
(7) Remedial action
(8) Long-term operation and maintenance.

The following is a list of potential responsibilities generated by CERCLA requirements:

- ☐ Conduct remedial investigation and feasibility study.
- ☐ Propose remedial action and provide opportunities for public comment.
- ☐ Implement remedial action.
- ☐ Perform system operation and maintenance.
- ☐ Maintain institutional controls, such as zoning restrictions, water use restrictions, and well drilling prohibitions.

F.1.2 Emergency Planning and Community Right-to-Know Act (EPCRA)

The goal of EPCRA is to promote emergency planning for chemical releases and to provide citizens with information about chemical hazards in their community. Under EPCRA rules, the U.S. EPA is required to establish a publicly available toxic chemical release inventory (TRI) which tracks chemical releases and waste management information from major facilities. The EPCRA regulations are included in 40 CFR Parts 302, 355, 370, and 372.

The following is a potential responsibility generated by EPCRA requirements:

- ☐ Track wastes generated during the investigation and remediation phase and include in facility's toxic chemical release inventory (EPCRA Reporting Form R or Form A).

F.1.3 Resource Conservation and Recovery Act (RCRA)

The goal of RCRA is to regulate hazardous waste management activities. If a remediation project generates hazardous waste, then certain waste management provisions of RCRA should be followed. Hazardous waste is defined as materials that contain the constituents listed in RCRA Subtitle C or materials that exhibit hazardous characteristics, including ignitability, corrosivity, reactivity, and toxicity. At facilities permitted to manage or dispose of hazardous wastes, certain RCRA provisions will require corrective action when point-of-compliance wells at solid waste management units are above the permitted groundwater protection standards. The corrective action requirements of RCRA are extensive and a complete discussion of the regulatory implications is beyond the scope of this manual. The RCRA regulations are included in 40 CFR Parts 240-282.

The following is a list of potential responsibilities generated by RCRA requirements:

☐ Perform corrective action at out-of-compliance solid waste management units.

☐ Identify, characterize, and label hazardous waste.

☐ Manifest hazardous waste for off-site disposal.

☐ Maintain required records and documentation.

☐ Ensure that land disposal restrictions are followed.

☐ Ship wastes within mandated time limits.

F.1.4 Clean Water Act (CWA)

The CWA sets surface water quality standards and permit requirements for the treatment and discharge of wastewater and stormwater. The CWA will have limited applicability to air sparging remediation projects, except for those projects where liquid wastes are disposed of via a sewer hookup to a publicly owned treatment works (POTW). Liquid wastes generated at air sparging sites can include recovered groundwater, monitoring well purge water, and knockout tank condensate. The CWA regulations are included in 40 CFR Parts 100-136, 140, 230-233, 401-471, and 501-503.

The following is a list of potential responsibilities generated by CWA requirements:

☐ Follow all federal, state, and local pretreatment standards for POTW discharges.

☐ Apply for 40 CFR Part 404 dredge and fill permits for construction projects at wetland sites.

F.1.5 Safe Drinking Water Act (SDWA)

The SDWA sets standards for the permissible level of contaminants in drinking water and establishes treatment standards for drinking water supply systems. If the affected groundwater at an air sparging site is a current or potential drinking water source, then the project may have to meet maximum contaminant levels (MCLs) or maximum contaminant level goals (MCLGs) for protection of the groundwater source. The SDWA regulations are included in 40 CFR Parts 141-149.

The following is a potential responsibility generated by SDWA requirements:

☐ Meet MCLs or MCLGs to protect groundwater source and achieve site closure.

F.1.6 Clean Air Act (CAA)

The CAA regulates point source and mobile source emissions and sets ambient air quality standards. For air sparging and soil vapor extraction projects, off-gas treatment is usually required and will involve the control of volatile organic carbon emissions via thermal oxidation, catalytic oxidation, carbon adsorption, or other technologies. The CAA requirements will be relevant to the operation of these air pollution control devices. The permits to operate air pollution control equipment are issued at the state or local level and the typical components of these permits will be discussed in the section on state and local regulations. However, the state or local agencies authorized to issue permits must make sure that the permits comply with certain CAA provisions. Only Title I and Title III of CAA are likely to directly impact air sparging remediation projects. Title I of the Act requires states to identify areas that have not achieved National Ambient Air Quality Standards (NAAQS) for certain critical air pollutants. If the project is in a nonattainment area, it may be subject to additional emission control standards as outlined in the State Implementation Plan (SIP). Title III of the Act specifies point source standards for hazardous air pollutants. For all sources that emit HAPs, the EPA sets Maximum Achievable Control Technology (MACT) standards.

The CAA regulations are included in 40 CFR Parts 50-99.

The following is a list of potential responsibilities generated by CAA requirements:

☐ Obtain the necessary permits for air pollution control equipment.

☐ Maintain emissions within permitted levels.

☐ Comply with SIP requirements.

☐ Maintain all required records and documentation.

F.1.7 Occupational Safety and Health Administration Rules (OSHA)

OSHA requires that all work performed on a hazardous waste site be in compliance with a site-specific health and safety plan (HASP) as described in 29 CFR 1910.120. If a site-specific HASP has not yet been prepared, it should be and should address all hazards associated with the site and activities thereon. If a site-specific HASP has already been developed but does not address hazards associated with air sparging, an amendment should be made to the HASP (typically regarded as a "living" document) to include those hazards. One safety concern particular to air sparging is the migration of vapors into subsurface structures or occupied surface structures. If these types of structures are within the zone of influence of an air sparging system, then an air extraction or injection system can be used to conduct vapors away from sensitive areas and prevent the accumulation of explosive or toxic vapors in these structures. Another safety issue related to air sparging is the possible use of a compressor that stores pressurized air. Catastrophic or unintended sudden release of pressurized air can result in severe injury and hearing damage or loss. Adequate safeguards must be taken and protective devices (hearing protection and hard hat) must be worn around high-pressure equipment.

F.2 Other Selected Federal Environmental Laws and Executive Orders

Several other federal regulations and executive orders may have an impact on the management of air sparging remediation projects. The following summarizes some federal regulations and executive orders that could apply to air sparging remediation projects under certain limited conditions.

F.2.1 Endangered Species Act (ESA)

The ESA includes provisions to conserve endangered or threatened species. Remediation projects must not destroy or adversely modify critical habitat areas. The U.S. Fish and Wildlife Service or National Marine Fisheries Service must be contacted when proposed activities may affect listed species. The ESA regulations are included in 40 CFR Parts 200 and 402.

F.2.2 Executive Order Number 11988, Floodplain Management

Federal agencies are required to avoid the adverse effects associated with construction or development in a floodplain. An Environmental Impact Statement (EIS) should be prepared and mitigation may be necessary to restore and preserve natural resources such as wetlands.

F.2.3 Executive Order Number 11990, Protection of Wetlands

The remediation project must minimize the loss, destruction, or degradation of wetlands.

F.2.4 Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA)

The goal of FIFRA is to control the sale and use of pesticides. The FIFRA regulations are included in 40 CFR Parts 150-189. Air sparging projects at sites with pesticide contamination must follow certain provisions for the disposal of pesticide-containing wastes. At sites with pesticide contamination, the remedial project manager should investigate whether or not the pesticide residues in the subsurface will have an adverse impact on biodegradation, especially if biosparging is the chosen application.

F.2.5 National Environmental Policy Act (NEPA)

The goal of NEPA is to ensure that projects conducted by the federal government involve a review and analysis of anticipated environmental impacts. NEPA requires an environmental impact statement (EIS) for all projects that will significantly affect the environment. The NEPA regulations are included in 40 CFR Parts 1500-1508.

The following is a list of potential responsibilities generated by NEPA requirements:

☐ If applicable, perform environmental assessment and prepare an environmental impact statement.

☐ Address the EIS findings and propose project alternatives and mitigation measures.

☐ Submit plans to state and/or local agencies and ensure public participation.

F.2.6 National Historic Preservation Act (NHPA)

NHPA requires a determination of whether or not the project would impact any district, site, building, structure, or object listed or eligible to be listed on the National Register of Historic Places. The NHPA regulations are included in 36 CFR Part 800. Other related regulations include the Archaeological Resources Protection Act (36 CFR Part 65) and the Native American Graves Protection and Repatriation Act (43 CFR Part 10).

F.2.7 Toxic Substances Control Act (TSCA)

TSCA sets testing requirements and establishes restrictions on the use of certain hazardous chemicals, including polychlorinated biphenyls (PCBs), lead, and asbestos. TSCA contains four titles: Title I – Control of Toxic Substances; Title II – Asbestos Hazard Emergency Response; Title III – Indoor Radon Abatement; and Title IV – Lead Exposure Reduction. The TSCA regulations are included in 40 CFR Parts 700-799.

The following is a list of potential responsibilities generated by TSCA requirements:

☐ Proper handling, transport, and disposal of PCBs and PCB-containing material.

☐ Use of properly trained and certified contractors for lead abatement projects.

☐ Proper handling, transport, and disposal of asbestos-containing materials.

APPENDIX G

AIR SPARGING PILOT-SCALE TESTING ACTIVITY MATRIX

This appendix provides a table summarizing key pilot test activities that should be completed in order to confirm air sparging feasibility and obtain the information necessary to successfully design a full-scale air sparging system (Leeson et al., 2001). The table is organized by activity (i.e., baseline sampling) and briefly describes the method for data collection and the objective or questions that will be answered by interpretation of the data.

TABLE G-1. Summary of Pilot Test Activities

Activity	Question(s) Answered	Standard Pilot Test Approach	Site-Specific Pilot Test Approach	Comments
Baseline sampling	What are aquifer conditions prior to air sparging startup?	X	X	• It is important to establish baseline measurements for several key parameters in order to measure the effectiveness of the air sparging system. • Methods for collecting dissolved oxygen measurements; pressure transducer measurements; and VOC, and carbon dioxide measurements are described in Appendix B of the Design Paradigm (Leeson et al., 2001).
	Dissolved oxygen	X	X	• Conduct baseline dissolved oxygen measurements.
	Pressure transducer data	X	X	• Pressure data should be collected for a long enough period to assess diurnal changes in water level (e.g., tidal fluctuations) if they are believed to be significant.
	VOCs, O_2, and CO_2 concentrations	X	X	• Soil vapor concentrations (including VOCs, O_2, and CO_2 concentrations) should be measured prior to air sparging startup. This provides initial contaminant mass estimates and a measure of microbial activity in the vadose zone.
	Initial SVE off-gas contaminant concentrations	X	X	• If SVE will be utilized during pilot testing, conduct off-gas sampling and analysis; The SVE system should be operated prior to air sparging startup. This (1) verifies proper system operation and (2) establishes VOC volatilization rates from the vadose zone versus the saturated zone.
	Geophysical measurements		X	• Collect baseline geophysical measurements, if geophysical tools will be utilized during pilot testing.
Injection pressure and flowrate test	Is it possible to achieve desired flowrate at reasonable pressures?	X	X	• Injection pressures should be recorded at three flowrates: 5, 10, and 20 cfm. The air injection pressure is recorded at the onset of flow as well as every 5 to 10 minutes until the pressure and flow stabilize. If a flowrate of at least 5 cfm cannot be achieved without exceeding a safe pressure, air sparging is not feasible at this site. • The operating pressure is determined by the depth of the air sparging well below the water table and the permeability of the aquifer. • The pressure at which fracturing of the aquifer may occur can be estimated by: $P_{fracture}$ [psig] = 0.73 * D_{soil} where: D [ft] = depth below ground surface to the top of the air injection well screened interval. • Pressures in excess of $P_{fracture}$ can cause fracturing of the formation; however, as the pressure drops off rapidly away from an injection point, the extent of fracturing in most cases is expected to be limited to the area immediately surrounding the well.

TABLE G-1. Summary of Pilot Test Activities (page 2 of 4)

Activity	Question(s) Answered	Standard Pilot Test Approach	Site-Specific Pilot Test Approach	Comments
Groundwater pressure-response test	What are the general characteristics of the air distribution? a) Semiconical air distribution in a homogenous setting OR b) Irregular shape due to significant stratification.	X	X	• The primary objective of this test is to assess the time required for airflow distribution to come to steady state. • Typically, as long as the volume of air below the water table is increasing, the groundwater pressure will remain above pre-air sparging levels. As a result, the time required for groundwater pressure to return to pre-air sparging values is a good measure of the time required for the macro-scale air distribution to come to steady state. • For homogeneous media (e.g., uniform sands), the time required for air sparging pressures to return to pre-air sparging values will generally be measured in tens of minutes to a few hours. If the site is stratified with lower-permeability layers, then the groundwater pressure may remain elevated for tens of hours to days. • Generally, at sites where groundwater pressures remain elevated by more than a few tens of centimeters for more than 8 hours, it can be assumed that the air distribution is controlled to a high degree by the structure of the aquifer. It will be important to determine if the air is being delivered to the treatment area in an effective manner.
Helium tracer test	What is the lateral extent of the air distribution? Are there indications of preferential flowpaths?	X	X	• Helium can be used in two primary ways as a tracer for air sparging systems (Leeson et al., 2001). In both tests, a rechargeable helium leak detector is used to detect helium at concentrations from 0.01 to 100 percent. • To characterize the injected air distribution pattern in the subsurface, helium is added to the sparge air at a known rate to achieve a steady helium concentration of about 2 to 10% by volume. Immediately after helium injection, until 20 minutes have lapsed, all of the vadose zone monitoring points and groundwater monitoring wells are monitored for helium. The helium measurements show which portion of the saturated zone is coming into contact with the injected air. • To assess the effectiveness of the SVE system in capturing the injected air, helium is added into the sparge air at a known rate and the SVE off-gas is monitored for the appearance of helium. Injection should continue until a stable helium concentration is achieved. The fraction of helium recovered by the SVE system is calculated. • Helium recovery data tends to fall into two ranges. The sparge air either makes it to the vadose zone and is collected by the SVE system with a high (e.g., >70%) recovery, or the air is stratigraphically trapped, pushing it beyond the SVE system or out monitoring wells, in which case recovery is low (e.g., <20%).

TABLE G-1. Summary of Pilot Test Activities (page 3 of 4)

Activity	Question(s) Answered	Standard Pilot Test Approach	Site-Specific Pilot Test Approach	Comments
Soil-gas sampling/off-gas sampling	What is the volatilization rate? Are there any obvious safety hazards?	X	X	• For systems without an SVE system, over the period of the pilot test, soil-gas samples should be collected with a field handheld instrument appropriate for the contaminants of concern. The observed values should be compared to the pre-air sparging concentrations to determine if a significant mass of contaminant is being stripped out of the groundwater. • With an SVE system, increases in contaminant concentrations in the SVE off-gas, and the SVE extraction flowrate can be used to estimate the mass removal rate. • Measurements made during the short duration of a pilot test are not indicative of long-term performance. However, it can generally be assumed that the pilot test data represent the maximum removal rate from the system (pre-optimization). In that context, if mass removal rates during the pilot test are very low, then there should be significant concern about the viability of air sparging at the site.
Dissolved oxygen (DO) measurements	What is the approximate lateral extent of the air distribution? Are there indications of preferred directions?	X	X	• If the preliminary measurements show low DO concentrations (e.g., less than 2 mg/L), it may be possible to identify areas where air sparging has resulted in increases in DO. To determine this, dissolved oxygen should be measured in all groundwater monitoring points immediately following the pilot test. • At many sites where active biodegradation is ongoing, there may be significant quantities of reduced species (e.g., Fe(2+)) which act as rapid sinks for oxygen and masks the delivery of oxygen to that region. • Microbial consumption of oxygen can be very high, resulting in oxygen being consumed as rapidly as it reaches an area, and therefore cannot be detected with instrumentation. • Care must be taken to avoid artifacts caused by air entry into monitoring wells and preferential aeration within the well (Johnson et al., 1997).
Other observations	Are there any odors, noise, or other factors present that make system operation less acceptable?	X	X	• It is important to note any qualitative indicators of air distribution, such as bubbling or gurgling noises in wells, water “fountaining” out of monitoring points, etc. • It is also important to be aware of odors due to the contaminants, noise due to the equipment, or other environmental factors. • These factors may not make air sparging infeasible from a technical standpoint, but may make the system less acceptable for the community.

TABLE G-1. Summary of Pilot Test Activities (page 4 of 4)

Activity	Question(s) Answered	Standard Pilot Test Approach	Site-Specific Pilot Test Approach	Comments
SF_6 distribution test	What is the vertical and lateral extent of the air distribution in the target treatment zone? What are the oxygen transfer rates to groundwater?		X	• SF_6 is used as a tracer that mimics oxygen to determine the distribution of air in the groundwater (Johnson et al., 1996). • SF_6 has a water solubility that is similar to oxygen; however, SF_6 has several advantages over oxygen and as a result the test can be both more sensitive and more quantitative. • SF_6 is blended with the injection air stream at a known concentration for a period of 12 to 24 hours. At the end of the SF_6 injection period, groundwater samples are collected and analyzed for $SF_{6.}$ The duration of SF_6 injection and the cumulative volume of groundwater sample are recorded. Based on the concentration of SF_6 in the injected air, and the Henry's law constant for SF_6, the percent saturation of SF_6 in the groundwater sample can be determined. • In general, the results can be divided into three groups: (a) values approaching saturation (e.g., >40% of theoretical solubility) indicate that the sample location lies within the "zone of aeration" of the air sparging system; (b) samples with low concentrations of SF_6 (e.g., <10%) indicate that an air channel may be in the vicinity of the sampling location (e.g., it may be within the "zone of treatment") but the air saturation in the aquifer at that point is probably low; and (c) samples that have no SF_6 present are presumed to lie outside both the aeration and treatment zones.
Other geophysical tools	What is the vertical and lateral extent of the air distribution in the target treatment zone?		Optional	• Air distribution patterns can be measured by the use of neutron probes, capacitance probes, and electrical resistance tomography as reported in the literature (e.g., Acomb et al., 1995; Lundegard and LaBreque 1998). These techniques generally have the ability to detect the presence of air in the subsurface at the 10% by volume level. • Once again, it is important to remember that all of these techniques require background (i.e., pre-air sparging) measurements.

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APPENDIX H

TROUBLESHOOTING OPERATIONAL MATRIX

This appendix provides a troubleshooting guide for common air sparging performance problems. This guide will help RPMs anticipate common problems, isolate their cause, and develop potential solutions to improve air sparging implementation.

TABLE H-1. Air Sparging Troubleshooting and Performance Optimization Guide

Performance Issue	Potential Cause	Potential Solution
Extent of contamination is greater than initially expected.	• Limited initial site investigation. • Free product is identified.	• Define extent of contamination • Use free-product recovery methods as necessary (Hoeppel and Place, 1998). • Extend the air sparging system by installing new injection/extraction wells focused on source zones.
Groundwater monitoring shows an increase in VOC concentrations.	• Sorbed or residual free product has been liberated for dissolution into the groundwater. • Hydraulic mounding may be a problem at this site causing a spreading of the contaminant.	• The concentrations should decline once the residual or sorbed contaminants have been sparged. • Hydraulic mounding can be mitigated by pulsed operation, which allows the water table levels to return to normal. Pulsed operation involves cycling the sparge system on and off over periods of hours to weeks. • If trend continues over several quarters, modify downgradient control either via more sparge "barrier" wells or use of groundwater recovery wells.
Increasing injection pressure needed to maintain target flowrate.	• Injection well biofouling or plugging.	• Clean well and associated piping.
Off-gas treatment costs increase.	• VOC recovery is declining as cleanup continues. There is not enough heat value in the process gas to maintain autothermic combustion in the thermal/catalytic oxidizer.	• Evaluate other air pollution control options including activated carbon. • Operate the system in pulsed mode. • Use other technologies to speed up vapor removal such as thermal enhancements.
Air distribution is limited.	• Poor well construction. • Soil permeability or preferential channeling may be a problem.	• Check wells for clogging or short-circuiting. • Another site investigation (helium or other tracer tests) might be necessary to further assess the location of impermeable zones or lenses. Adjust well depth or location as appropriate. • Adjust design to change the number of wells or well density.
Remediation system cannot be installed as planned.	• Subsurface structures (gas lines, utility lines, etc.). • Surface structures (buildings).	• Reevaluate injection/extraction well placement. • Consider drilling at an angle or installation of horizontal wells (rare).
VOC concentrations reduced in only a few wells.	• The air sparging may not be evenly distributed on the site.	• Reduce flow to some wells. • Check for unidentified source zone. • Add additional wells.
VOC recovery by the SVE system gradually decreases.	• A gradual decrease in VOC concentrations from initial levels is to be expected. It is due to diffusion limitations that occur as the product is cleaned up.	• Using a pulse operation can improve system performance. The system can be cycled on and off for periods of hours to weeks which allows the VOC concentrations to rebound. • If appropriate, propose shutting down of air sparging/SVE system in favor of monitored natural attenuation.
VOC recovery by the SVE system rapidly decreases.	• Flooding of SVE system. • Check and empty knockout tank(s)	• Use water level measurements to check water table elevation with respect to the SVE well screen depth. Temporarily shut down system until water table drops. If the problem persists, consider design changes including reinstallation of SVE wells at a lesser depth or multiphase extraction with liquid/vapor pumps.

VOC recovery is at or near lower explosive limits.	• Presence of free product.	• Dilute SVE airstream at extraction wellheads. • Check for free product and use recovery methods as necessary (Hoeppel and Place, 1998).

Reference

Hoeppel, R., and M. Place. 1998. *Application Guide for Bioslurping.* NFESC Technical Memorandum No. TM-2300-ENV. Prepared for NFESC by Battelle. October.

APPENDIX I

AIR SPARGING PROJECT STATEMENT OF WORK GUIDANCE

This Statement of Work (SOW) Guide outlines, in tabular form, the technical information required to define tasks and performance standards. All of the work elements that might be required to assess and implement an air sparging treatment system under any one of a wide range of regulatory frameworks are listed in the tables. Potentially applicable regulatory frameworks include the following:

- ☐ CERCLA
- ☐ Corrective action (CA) provisions of RCRA
- ☐ Underground storage tank (UST) provisions of the RCRA (federally regulated)
- ☐ State-regulated or administered UST cleanup programs.

This document will assist in preparing an SOW that fosters timely, concise, cost-effective submissions from potential contractors. Project tasks are grouped into the following six phases:

- ☐ Project planning and management
- ☐ Preliminary assessment of air sparging
- ☐ Detailed site evaluation and feasibility analysis
- ☐ System design and installation
- ☐ System operation and optimization
- ☐ Long-term monitoring and site closure.

Some of the tasks described may not be required for a particular site because of site conditions or the regulatory framework. The personnel preparing the SOW must select applicable tasks in the tables in Section I.3, and use the tabulated information to assist in preparing a SOW.

This SOW Guide can be used to develop an SOW that describes the technical requirements for the project and to define the basis for evaluating the technical quality and value of a contractor's proposal. Preparing an effective SOW requires careful thought and planning to identify the key tasks that must be performed and the criteria that must be met without limiting the contractors' flexibility to provide their best value option. The criteria must be clearly stated so that the quality of the result can be determined. They must be sufficiently demanding to provide an acceptable result, but not so demanding as to be uneconomical or impractical. More detailed information on preparing a performance-based SOW is available in U.S. Environmental Protection Agency guidance (U.S. EPA, 1995).

A typical air sparging project starts with a review of existing data followed by data collection and feasibility analysis to determine if air sparging is indeed applicable to a specific site. If it is determined that the technology is applicable to the site in question, the next step is to design the system. Following system design and installation is system operation. In addition to running the system, the operation period also includes system optimization tasks and site monitoring. The final step in the remedial process is site closure and project closeout. Tasks in the SOW must be defined to allow input from regulators and, where necessary, the public through formal and informal forums frequently throughout the evaluation and implementation process. The SOW should require a staged approach to the evaluation and implementation of the remedial action to determine that air sparging is applicable and will be effective at a site before making a significant commitment of resources to this alternative. Once these decisions have been made, the complexity of the site, contaminant conditions, and remedial objectives determine the design of the system, length of system operation, monitoring requirements and details regarding site closure.

The SOW clearly defines the roles and responsibilities of the participants in the work. Related work that has been completed as part of a prior project or is to be performed in parallel under a separate SOW must be described, and the relation to the planned work explained. Key decision points and interfaces must be clearly described so that all participants understand who is to perform each work element, what is to be done, and where the authority lies for accepting the results.

The SOW requires the contractor to provide separate costs for each task specified using the Work Breakdown Structure (WBS) specified by the Navy. Having detailed cost information for each task allows more effective comparison of the bids. Appendix D of this guidance document presents a discussion of air sparging economics and will assist Naval personnel in estimating costs so they can evaluate the value offered by each proposal.

This SOW Guide is organized to cover the sections that appear in a typical SOW, as shown in Figure I-1.

I.1 Scope

I.1.1 General

Figure I-2 shows an example of a typical scope statement for a project to implement air sparging.

I.1.2 Background

An SOW is required when the facility has identified the need to remediate a site that has groundwater contaminated with strippable or aerobically biodegradable compounds and is interested in using air sparging. The SOW must clearly summarize any completed site characterization, review of regulatory constraints, and technical analyses to establish site-specific remediation goals. Figure I-3 lists the typical background information summarized in the SOW. This SOW Guide assumes that efforts under the contract make maximum use of the existing data and monitoring points installed at the site. Necessary background information often is contained in project reports, manuals, and photographs summarizing the current state of knowledge. These reports can be attached to the SOW or otherwise made available to the contractor. If possible, the SOW should allow time for a site visit by contractors during proposal preparation.

The SOW must define the regulatory constraints applicable to the site. In particular, the lead regulatory agency must be identified. Other interested regulatory and public interest groups and their relationships to the project must also be summarized in the SOW.

I.2 Reference Documents

The SOW provides a listing of documents that describe the data, methods, or requirements applicable to the work necessary for evaluating and/or implementing air sparging at petroleum hydrocarbon-contaminated sites. Examples of documents that may be applicable for sites planning to implement air sparging for petroleum contamination include the following:

I.2.1 Air Sparging Site Assessment

a. American Society for Testing and Materials. 1997. “Standard Guide for Corrective Action for Petroleum Releases.” D 1599. *Annual Book of ASTM Standards, Volume 11.04*, ASTM, West Conshohocken, PA.
b. American Society for Testing and Materials. 1995. *Standard Guide for Risk-Based Corrective Action Applied at Petroleum Release Sites.* ASTM-E 1739-95. ASTM, West Conshohocken, PA.
c. American Society for Testing and Materials. 1995. *Standard Guide for Developing Conceptual Site Models for Contaminated Sites.* ASTM-E 1689-95*,* ASTM, West Conshohocken, PA.

1.0 Scope
    1.1 General
    1.2 Background
2.0 Reference Documents
3.0 Requirements of the RNA Project
    3.1 Project Planning and Management
    3.2 Preliminary Assessment of Air Sparging
    3.3 Detailed Site Evaluation and Feasibility Analysis
    3.4 System Design
    3.5 System Operation and Optimization
    3.6 Long-Term Monitoring and Site Closure
4.0 Government-Furnished Property
5.0 Government-Furnished Facilities
6.0 Deliverables

FIGURE I-1. Organization of a Typical Statement of Work

The purpose of this Statement of Work is to set forth the requirements for implementing remediation by air sparging in accordance with the provision of _______ (decision document, e.g., permit issued by the state or regional water control board, Record of Decision [ROD], or permit modification or order) issued on _______ (date). The required efforts will include the following:

- Project management and planning
- Preliminary assessment of air sparging
- Detailed site evaluation and feasibility analysis
- System design and installation
- System operation and optimization
- Long-term monitoring and site closure

Air sparging and the related technology of biosparging are defined as follows:

Air sparging is an innovative treatment technology that uses injected air to remove volatile or biodegradable contaminants from groundwater. Air sparging can remove contaminants such as gasoline, solvents, and selected jet fuels. The basic process involves the injection of air directly into the saturated subsurface to (1) volatilize contaminants from the liquid phase to the vapor phase for biodegradation and/or removal via soil vapor extraction (SVE) in the vadose zone, and (2) degrade contaminants in the saturated zone via microbial metabolism stimulated by the introduction of oxygen.

This SOW provides the framework for conducting remediation of contaminated groundwater at _____________ _____________________ (site). The goal is to complete remedial design by _______ (date) and site closure by _______ (date).

FIGURE I-2. Example SOW Scope Statement

- Initial site conditions
    - Location and physical layout
    - Availability of utilities
    - Restrictions on access or road use
- Documentation of state concurrence with air sparging application to site
- Relevant documents prepared by the local water control board (or equivalent)
- Existing permits
- Cleanup standards and regulatory requirements
- Nature and extent of contamination
- Approximate volume to be remediated
- Geomorphology and surface water hydrology
- Geology and geohydrology
    - Location and types of strata
    - Depth to groundwater
    - Direction of groundwater flow
- Unresolved issues

FIGURE I-3. Example of Site Information Typically Summarized in the SOW

d. American Society for Testing and Materials. 1997. "Conceptualization and Characterization of Ground-Water Systems." D 5979. *Annual Book of ASTM Standards, Volume 4.09.* ASTM, West Conshohocken, PA.
e. American Society for Testing and Materials. 1997. "Standard Guide for Application of a Ground-Water Flow Model to a Site-Specific Problem." D 5447. *Annual Book of ASTM Standards, Volume 11.05.* ASTM, West Conshohocken, PA.
f. American Society for Testing and Materials. 1997. "Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information." D 5490. *Annual Book of ASTM Standards, Volume 11.05.* ASTM, West Conshohocken, PA.
g. American Society for Testing and Materials. 1997. "Standard Guide for Defining Boundary Conditions in Ground-Water Flow Modeling." D 5609. *Annual Book of ASTM Standards, Volume 11.05.* ASTM, West Conshohocken, PA.
h. American Society for Testing and Materials. 1997. "Standard Guide for Defining Initial Conditions in Ground-Water Flow Modeling." D 5610. *Annual Book of ASTM Standards, Volume 11.05.* ASTM, West Conshohocken, PA.
i. American Society for Testing and Materials. 1997. "Standard Guide for Conducting a Sensitivity Analysis for a Ground-Water Flow Model Application." D 5611. *Annual Book of ASTM Standards, Volume 11.05.* ASTM, West Conshohocken, PA.
j. U.S. Navy. 1998. "Performance-Based Statement of Work." Available from http://www.acq-ref.navy.mil/turbo/arp34.htm.

I.2.2 Technology Review and Selection

a. U.S. Environmental Protection Agency. 1988. *Guidance for Conducting Remedial Investigations and Feasibility Studies under CERCLA*. EPA/540/G-89/004. OSWER Directive 9355.3-01. Office of Solid Waste and Emergency Response, Washington, DC.
b. U.S. Environmental Protection Agency. 1989. *Guidance for Preparing Superfund Decision Documents*. EPA/540/G-89/007. Office of Solid Waste and Emergency Response, Washington, DC.
c. U.S. Environmental Protection Agency. 1989. *CERCLA Compliance with Other Laws, Part 1.* EPA/540/G-89/006. Office of Solid Waste and Emergency Response, Washington, DC.
d. U.S. Environmental Protection Agency. 1989. *CERCLA Compliance with Other Laws, Part 2*. EPA/540/G-89/009. Office of Solid Waste and Emergency Response, Washington, DC.
e. U.S. Environmental Protection Agency. 1996. *A Citizen's Guide to In Situ Soil Flushing*. EPA/542/F-96/006. Office of Solid Waste and Emergency Response, Washington, DC.
f. U.S. Environmental Protection Agency. 1996. *A Citizen's Guide to Bioremediation*. EPA/542/F-96/007. Office of Solid Waste and Emergency Response, Washington, DC.
g. U.S. Environmental Protection Agency. 1996. *A Citizen's Guide to Natural Attenuation*. EPA/542/F-96/015. Office of Solid Waste and Emergency Response, Washington, DC.
h. U.S. Environmental Protection Agency. 1998. *Field Applications of In Situ Remediation Technologies: Ground-Water Circulation Wells*. EPA/542/R-98/009. Office of Solid Waste and Emergency Response, Washington, DC.
i. U.S. Environmental Protection Agency. 1998. *Technical Protocol for Evaluating Natural Attenuation of Chlorinated Solvents in Ground Water*. EPA/600/R-98/126. Office of Research and Development, Washington, DC.

I.2.3 System Design and Installation

a. American Society for Testing and Materials. 1997. "Standard Practice for Design and Installation of Ground Water Monitoring Wells in Aquifers." D 5092. *Annual Book of ASTM Standards, Volume 4.09*. ASTM, West Conshohocken, PA.
b. Aelion, C.M., and B.C. Kirtland. (2000). *Physical versus Biological Hydrocarbon Removal during Air Sparging and Soil Vapor Extraction*. Environ. Sci Technol. v34, no. 15, 3167-3173.
c. Herrling, B. J. Stamm, E.J. Alesi, G. Bott-Breuning, and S. Diekmann. 1994. "In Situ Bioremediation of Groundwater Containing Hydrocarbons, Pesticides, or Nitrate Using Vertical Circulation Flows." In: Air Sparging for Site Remediation. R.E. Hinchee (Ed.). CRC Press, Inc. Boca Raton, FL.
d. Leeson, A., P.C. Johnson, R.L. Johnson, R.E. Hinchee, and D.B. McWhorter. 2001. Air Sparging Design Paradigm. In Press. December 31.
e. Marley, M.C., and C.J. Bruell. 1995. In Situ Air Sparging: Evaluation of Petroleum Industry Sites and Considerations for Applicability, Design and

Operation, American Petroleum Institute, Washington, DC, Publication Number 4609.

I.2.4 Performance Monitoring/Site Closeout

a. Tri-Service/U.S. Environmental Protection Agency Working Group. 1998. Environmental Site Closeout Process. Working draft.

b. U.S. Environmental Protection Agency. 1992. *Methods for Evaluating the Attainment of Cleanup Standards, Volume 2: Groundwater*. EPA/230/R-92/014. Office of Solid Waste and Emergency Response, Washington, DC.

c. U.S. Environmental Protection Agency. 1989. *Statistical Analysis of Ground-Water Monitoring Data at RCRA Facilities*. EPA/530/SW-89/026. Office of Solid Waste and Emergency Response, Washington, DC.

d. American Society for Testing and Materials. 1997. "Standard Guide for Site Characterization for Environmental Purposes with Emphasis on Soil, Rock, the Vadose Zone, and Ground Water." D 5730. *Annual Book of ASTM Standards, Volume 4.09.* ASTM, West Conshohocken, PA.

e. American Society for Testing and Materials. 1997. "Provisional Standard Guide for Developing Appropriate Statistical Approaches for Ground-Water Detection Monitoring Programs." PS 64. *Annual Book of ASTM Standards, Volume 4.09.* ASTM, West Conshohocken, PA.

f. American Society for Testing and Materials. 1993. *Standard Guide for Decommissioning of Ground Water Wells, Vadose Zone Monitoring Devices, Boreholes, and Other Devices for Environmental Activities.* D 5299-92. ASTM, West Conshohocken, PA.

g. Naval Facilities Engineering Service Center. 2000a. *Interim Final Guide to Optimal Groundwater Monitoring*. Prepared by Radian International, White Rock, NM. January. Available at: http://erb.nfesc.navy.mil/erb_a/support/wrk_grp/raoltm/case_studies/Int_Final_Guide.pdf.

I.3 Requirements

The following subsections provide the technical background about the tasks that are specified in an SOW to obtain a proposal for implementing air sparging. The project is divided into the following six phases:

- ☐ Project planning and management
- ☐ Preliminary assessment of air sparging
- ☐ Detailed site evaluation and feasibility analysis
- ☐ System design and installation
- ☐ System operation and optimization
- ☐ Long-term monitoring and site closure.

The tasks specifically related to implementing air sparging are tabulated for each phase. Tasks that are appropriate for a particular site should be selected and the SOW should then be prepared based on the scope and typical preparation time, as stated in the tables. The information provided under the heading "Task Guidance and Information" in each table can be used to assist in preparing the SOW and evaluating responses from the bidders.

I.3.1 Project Planning and Management

The purpose of this project phase is to provide overall management to maximize the effectiveness of expenditures throughout the project. The SOW requires the contractor to provide the labor, equipment, materials, and facilities to prepare the required plans and effectively manage the air sparging project. The major tasks included in this phase are summarized in Table I-1.

Contractors are required to furnish a description of each of the following project management components as part of their proposal:

- ☐ Overall organizational structure proposed for the project

- ☐ Qualifications of the project management team

- ☐ Project management system to be used

- ☐ Subcontracting systems to be used

- ☐ Relevant corporate experience.

Contractors are required to furnish, as a part of their proposal, a current corporate Quality Assurance/Quality Control (QA/QC) Program Plan setting forth their QA/QC capabilities. The QA/QC Program Plan must address, at a minimum, the following topics:

- ☐ A statement of the corporate QA/QC policy

- ☐ An organization chart showing the position of the QA/QC function in the organization

TABLE I-1. Statement of Work Requirements for Air Sparging: Project Planning and Management

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Project management plan[a]	Document overall strategy, budget, and schedule for performing the design, installation, performance monitoring, and close out of air sparging project	• Document responsibility and authorities of all organizations • Identify key personnel • Document qualifications of key personnel	1 to 3 months
Community relations plan[a]	Plan for information transfer and consensus building with local representatives, as necessary	• Reflect knowledge of citizen concerns • Provide for citizen involvement • Often not required for underground storage tank (UST) remediation projects • Typically performed as a revision of the community relations plan	• 1 to 3 months • Prepared in parallel with project management plan
Permitting	Obtain permits or comply with substantive requirements, as applicable	• Provide for installing new monitoring wells • Provide for management of investigation-derived waste (IDW) • Projects conducted under CERCLA are not required to obtain permits, but must meet substantive permitting requirements	• As needed, usually prior to the detailed site characterization • 1 to 4 months
Reporting	Provide adequate documentation of project activities, status, problems, and corrective actions	• Provide written monthly reports • Perform site trips and provide verbal progress updates, as required • Document significant decisions with written telephone record • Provide meeting agenda and minutes	Continues throughout the project

(a) Only required under CERCLA or RCRA CA regulatory framework.

- ❑ A delineation of the authority and responsibility of the QA/QC function
- ❑ A description of the organization’s total concept, requirements, and scope of effort for achieving and verifying quality.

I.3.2 Preliminary Assessment of Air Sparging

The purpose of the preliminary assessment is to allow the contractor to establish an understanding of the conditions and challenges at the site based on existing data and reports, to evaluate the feasibility of air sparging, and to prepare a plan for the detailed assessment, if needed. The major tasks included in the preliminary assessment are summarized in Table I-2. The SOW requires the contractor to provide the labor, equipment, materials, and facilities to accomplish the following objectives:

- ❑ Review available data, develop a conceptual model, and assess site conditions
- ❑ Make a preliminary determination of the feasibility of air sparging for the site
- ❑ Develop a work plan for the detailed site characterization and assessment.

I.3.3 Detailed Site Evaluation and Feasibility Analysis

The purpose at this stage is to collect site data and document site conditions to allow definitive assessment of the feasibility of air sparging, document the basis for recommending air sparging, build a consensus with regulators and the public for using air sparging, and document the acceptance of air sparging at the site. The major tasks included in the detailed site evaluation are summarized in Table I-3. The SOW requires the contractor to provide the labor, equipment, materials, and facilities to accomplish the following objectives:

- ❑ Develop all required assessment information to demonstrate that air sparging is an applicable

TABLE I-2. Statement of Work Requirements for Air Sparging: Preliminary Assessment in Support of Air Sparging

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Review regulatory acceptance of air sparging	Determine if existing regulations in the applicable jurisdiction allow air sparging as a remedial alternative	The contractor should demonstrate specific experience with regulatory status of air sparging under the applicable jurisdiction and regulatory framework	1 to 2 months
Collect and organize existing data	Review and organize existing data into a usable format	• Organize data into a comprehensive database consistent with the Geographic Information System (GIS) or other format specified by the Navy • Perform QA review to validate data for completeness and accuracy • Specify acceptable electronic data formats in SOW to ensure compatibility	1 to 3 months
Develop a preliminary conceptual site model to assess applicability of air sparging based on risk factors	Use existing data to develop an understanding of site location, history, description, climate, demography, and land use	Develop map(s) showing major site features such as property boundaries, land use, populations, ecological features, and groundwater uses	1 to 4 months
	Use existing data to develop an understanding of the COCs and nature and extent of contamination	Review/develop maps and figures defining the location of sources and the distribution of contaminants in the environment above regulatory limits and conservative risk-based screening concentrations	
	Use existing site geology and hydrology data to develop an understanding of groundwater flow regimes	• Document current status of information about site geology and hydrology • Define groundwater flow regimes, including principal aquifers and direction and rate of groundwater flow	
	Use existing data to identify potential exposure pathways and assess the presence of immediate or imminent threats that could preclude air sparging	• Develop a basic understanding of contaminant behavior in the environment and identify potential migration pathways, exposure points, exposure routes, and receptors • Identify potential compliance points	
	Determine if the presence of free product or other site factors constrain the ability to implement air sparging	• Identify technical constraints that eliminate air sparging as an alternative • Consider supplemental technologies to mitigate constraints • Ensure that releases have been adequately assessed and that sources are understood and controlled	
	Establish a conceptual model with sufficient detail to allow a preliminary assessment of the applicability of air sparging	Assess immediate and/or imminent effects of contaminants on potential human and environmental receptors	
Assess applicability of air sparging to achieve remedial objectives based on the site-specific characteristics	• Use site data to determine if air sparging is applicable at site • Determine the extent of additional characterization required	Air sparging does offer many advantages over competing remediation technologies, but is not applicable in all situations. See Guidance Document for details on advantages and limitations of air sparging.	• 1 to 2 months • Performed in parallel with conceptual model development

TABLE I-2. Statement of Work Requirements for Air Sparging: Preliminary Assessment in Support of Air Sparging (continued)

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Prepare preliminary assessment report and work plan and submit to regulatory agencies	Prepare a report describing the conceptual model, preliminary evaluation, and plans for collecting data required for detailed evaluation; incorporate regulatory input	• Document site status • Define technical basis supporting applicability of air sparging • Document extent of additional characterization if any is required	1 to 4 months
Prepare preliminary data collection Quality Assurance Project Plan (QAPP)	Prepare a plan to control the quality of preliminary data collection	• Define QA/QC organization, responsibilities, and authorities • Specify definable features of work and quality measures • Describe field QA/QC • Describe sampling and analytical QA/QC • Describe equipment maintenance QA/QC • Describe change control methods • Describe corrective action methods	• 1 to 2 months • Performed in parallel with work plan preparation
Prepare preliminary data collection HASP	Prepare a plan to maintain safe working conditions during preliminary data collection	Compliance with OSHA requirements; specifically 29 CFR 1910.120, 29 CFR 1910.1200, and 29 CFR 1926	• 1 to 2 months • Performed in parallel with work plan preparation
Support public meetings	Prepare materials and attend public meetings	• Prepare presentation materials, technical summaries, and handouts • Attend public meetings to support Naval personnel • Allow for two-way communication and response to community concerns in project plans	As required

TABLE I-3. Statement of Work Requirements for Air Sparging: Detailed Site Evaluation and Feasibility Analysis

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Install required wells and monitoring points	Install wells as needed to ensure samples can be collected to evaluate status of air sparging	• Obtain applicable permits • Comply with applicable rules and regulations • Wells in plume at compliance point required	1 to 2 months
Establish applicability of air sparging through site characterization	Demonstrate that site conditions should allow volatilization/biodegradation of COCs upon implementation of an air sparging system	• Collect primary data (geochemical parameters and contaminant concentrations) throughout the plume and along flowpath transects • Construct contour maps for each primary COC • Evaluate data for evidence to support or rule out air sparging as an applicable remedial alternative • Identify needs for optional studies to support air sparging	Performed in parallel with evaluating plume status

TABLE I-3. Statement of Work Requirements for Air Sparging: Detailed Site Evaluation and Feasibility Analysis (continued)

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Evaluate plume status	Characterize plume chemistry and geochemistry to evaluate applicability of air sparging and for optimizing implementation	• Use historical data and collect additional site characterization data as necessary to evaluate and optimize implementation of remedial system • Evaluate significant trends • Construct contaminant contour maps • Establish if there has been a loss of contaminant mass over time	1 to 2 months
Perform fate and transport modeling as needed to demonstrate protection of human health and the environment and determine the time required to achieve site-specific remediation goals	Perform modeling to predict the time-dependent behavior of contaminant concentrations with and without biodegradation	• Refine site-specific conceptual model • Select model and define inputs • Construct and calibrate model to site conditions • Perform predictive simulations to estimate concentrations at compliance points and time to reach remediation goals	Performed in parallel with evaluation of plume status
Compare air sparging to other remediation alternatives	Conduct a technology screening to ensure that air sparging offers the best balance of effectiveness, implementability, and cost	• Identify a comprehensive listing of candidate technologies • Perform technology screening using criteria required by regulations	1 to 2 months
Prepare air sparging evaluation report and submit to regulatory agencies (and public if applicable)	Prepare a report describing the evaluation of air sparging, recommending (or rejecting) air sparging as an effective remedial alternative, and incorporating regulatory and public input	• Document evidence supporting decision to implement (or not implement) air sparging at the site • Document information and technical analysis used to demonstrate that air sparging will protect human health and the environment • Document information and technical analysis used to determine time to reach remediation goals • Provide technical basis for setting compliance points and action levels to ensure protection of human health and the environment • Provide technical basis for setting remediation goals for air sparging closeout • Project future trends to be used to evaluate performance during performance monitoring • Quantify uncertainties in predictions • Recommend air sparging, if appropriate, and obtain regulatory and public consensus • Document results of alternative screening	1 to 4 months
Support public meetings	Prepare materials and attend public meetings	• Prepare presentation materials, technical summaries, and handouts • Attend public meetings to support Naval personnel • Allow for two-way communication and response to community concerns in project plans	As required

remediation technology based on field data and previous use of air sparging at sites with similar types of contamination

- ☐ Develop all required assessment information to demonstrate that air sparging will adequately protect human health and the environment at the site
- ☐ Refine the conceptual site model
- ☐ Demonstrate that cleanup objectives for the site can be achieved within a reasonable time frame using air sparging
- ☐ Establish and document a consensus among the technical and regulatory community and the public that air sparging will adequately protect human health and the environment at the site.

I.3.4 System Design and Installation

The purpose at this stage is to design the air sparging system to achieve the established remediation goals based on the site-specific characteristics and assessments performed in the previous steps. Air sparging system design consists of identifying the target treatment area, conducting a pilot-scale test, and preparing design drawings and documentation for the full-scale installation. Once the proposed full-scale system is approved by all involved parties, the system is constructed as designed. The major tasks included in the system design are summarized in Table I-4. The SOW requires the contractor to provide the labor, equipment, materials, and facilities to accomplish the following aspects of air sparging system design and construction:

- ☐ Target treatment area identification
- ☐ Pilot-scale testing
- ☐ Air injection system design and installation
- ☐ Soil vapor extraction system design and installation
- ☐ Develop a Performance Monitoring Plan, including a Contingency Plan (and obtain regulatory acceptance)
- ☐ Monitoring well placement and construction
- ☐ Monitoring point placement and construction.

TABLE I-4. Statement of Work Requirements for Air Sparging: System Design

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Prepare HASP	Prepare a plan to maintain safe working conditions during system construction	Ensure compliance with OSHA requirements; specifically 29 CFR 1910.120, 29 CFR 1910.1200, and 29 CFR 1926	1 month
Determine Target Treatment Area	Determine in which area the air sparging system will be installed	• Based on site characterization and regulatory requirements • This may include the source zone, localized areas having elevated concentrations within the plume, or the entire plume area	1 month
Pilot Scale Testing	Perform pilot scale testing in portion of target treatment area	• May be necessary to conduct the test in more than one location if the site is large and soils types vary significantly through the site • Look for indicators of infeasibility • Characterize the air distribution and baseline parameters • Identify safety hazards to be addressed in full-scale design	1 to 3 months
Air Injection System	Design and install air injection system	• Determine injection well placement • Determine injection well design • Typically vertical wells are installed either direct-push techniques or traditional auger drilling, horizontal wells may also be necessary depending on the site conditions (rare) • Determine the air injection flowrate and pulse frequency • Identify compressors or blowers for air supply	1 to 3 months

TABLE I-4. Statement of Work Requirements for Air Sparging: System Design

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Soil Vapor Extraction System	Design and install soil vapor extraction system	• In general, air sparging systems that do not require SVE are preferred • Guidance documents are available for SVE installation	1 to 3 months
Prepare Performance Monitoring Plan and submit to regulatory agencies	Develop a plan, cost estimate, and schedule for performance monitoring and evaluation to implement air sparging at the site and obtain regulatory acceptance	• Define scope and objectives of performance monitoring • Arrange wells to make maximum use of existing facilities and equipment • Establish analytical requirements • Establish sampling frequency and duration • Specify location of compliance points and protective action limits • Describe data reduction and evaluation of air sparging progress • Specify data format consistent with GIS requirements • Plan for actions if air sparging progress or operation deviates from expectations (Contingency Plan) • Provide quantitative definition of remediation goals • Identify institutional controls that are required during performance monitoring • Develop project schedule and definitive cost estimate (+15% to -5%)	2 to 5 months
Prepare monitoring QA/QC Program Plan	Prepare a plan to control the quality of performance monitoring	• Define QA/QC organization, responsibilities, and authorities • Specify definable features of work and quality measures • Describe field QA/QC • Describe sampling and analytical QA/QC • Describe equipment maintenance QA/QC • Describe change control methods • Describe corrective action methods	• 1 to 3 months • Performed in parallel with preparing the Performance Monitoring Plan
Design and Install Monitoring Wells	Install wells as needed to ensure samples can be collected to evaluate progress of air sparging toward remediation goals	• Monitoring wells are traditional wells with larger screened intervals • Comply with applicable rules and regulations	1 to 2 months
Design and Install Monitoring Points	Install monitoring points as needed to ensure sampling is adequate to evaluate progress of air sparging toward remediation goals	• Monitoring points are smaller than traditional wells and designed to collect discrete samples • Comply with applicable rules and regulations	1 to 2 months
Provide construction quality assurance	Provide on-site inspection and documentation to ensure compliance with quality requirements	• Perform daily inspections • Identify and correct deficiencies • Document results	Daily during construction

I.3.5 System Operation and Optimization

This portion of the project involves operating, maintaining, and monitoring the remediation system throughout the period of operation needed to meet the established remedial goals. Operation, optimization, and monitoring efforts must be focused on these specific remedial project objectives. Generally and typically, these include maximum mass removal efficiency with respect to both time and money, minimizing O&M costs, and achieving site closure. The major tasks included in system operation and optimization are summarized in Table I-5. The SOW requires the contractor to provide the labor, equipment, materials, and facilities to accomplish the following objectives:

- ☐ Install any required facilities (e.g., monitoring wells)
- ☐ System startup
- ☐ Optimize system operation based on initial monitoring of system performance
- ☐ Establish/implement institutional controls (if needed).

I.3.6 Long-Term Monitoring and Site Closure

The purpose of this stage is to collect site data and perform technical analyses to quantitatively evaluate the performance of air sparging; make recommendations concerning future remedial and monitoring activities, and finally, when site-specific remediation goals have been achieved, document the completion of remediation activities. The major tasks included under performance monitoring and site closure are summarized in Table I-6. The SOW requires the contractor to provide the labor, equipment, materials, and facilities to accomplish the following objectives:

- ☐ Execution of Performance Monitoring Plan, previously established
- ☐ Install any required facilities (e.g., additional monitoring wells or monitoring points)
- ☐ Establish/implement institutional controls (if needed)
- ☐ Periodically collect performance monitoring data until remedial action goals are achieved

TABLE I-5. Statement of Work Requirements for Air Sparging: System Operation and Optimization

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Prepare HASP	Prepare a plan to maintain safe working conditions during system operation and monitoring	Ensure compliance with OSHA requirements; specifically 29 CFR 1910.120, 29 CFR 1910.1200, and 29 CFR 1926	• 1 month • Performed in parallel with preparing the Performance Monitoring Plan
Install required wells and monitoring points	Install additional wells as needed to ensure samples can be collected to evaluate progress of air sparging and to optimize system efficiency	Comply with applicable rules and regulations	1 to 2 months
System startup	Perform system startup	Start up procedures include checking all components of the system to ensure the system is ready for operation and running properly as well as determining baseline preremediation conditions at the site	1 week
System optimization/ operation	Optimize the operation of system based on initial monitoring data	• Adjust operating parameters, install additional wells as necessary to improve system efficiency • Look for opportunity to transition to natural attenuation when contaminant mass that can cost-effectively be removed is removed	• 6 to 24 months • Performed throughout the duration of the operation period
Establish institutional controls as required	Provide institutional controls to protect human health and the environment during system operation and monitoring, if needed	Place access restrictions, deed restrictions, easement, and other controls as needed during operation and monitoring period	• 1 to 2 months • Performed in parallel with well installation

TABLE I-6. Statement of Work Requirements for Air Sparging: Long-Term Monitoring and Site Closure

Task Name	Task Scope	Task Guidance and Information	Typical Performance Time
Conduct performance monitoring	Collect and analyze samples to support evaluation of the progress of air sparging	• Collect samples in and around the plume and at compliance points until remedial action goals are achieved • Comply with Performance Monitoring Plan, QA/QC Program Plan, and HASP	1 to 5 years (rare)
Install required wells and monitoring points	Install additional wells as needed to ensure samples can be collected to evaluate progress of air sparging	Comply with applicable rules and regulations	1 to 2 months
Evaluate progress of air sparging	Determine if air sparging is proceeding as expected and recommend corrective action for unexpected results	• Compare plume status to site-specific remediation goals and expected progress and recommend continued monitoring (expected progress), corrective action (significant unexpected results), or closeout (remediation goals achieved) • Update conceptual model and revise model predictions • Update remediation time predictions	Performed in parallel with performance monitoring
Prepare performance monitoring and performance assessment reports	Report results and obtain regulatory approval	Document methods, results, and QA activities for monitoring period	• 1 to 2 months preparation time • Performed periodically as defined in Performance Monitoring Plan
Prepare closure report	Prepare a report documenting remediation activities and results and formal acceptance of site closure or transition to monitored natural attenuation	• Demonstrate protection of human health and the environment • Quantify, on a statistical basis, the attainment of site-specific remediation goals and level of confidence • Demonstrate removal of contaminant mass that can cost-effectively be removed and evidence to support transitioning to natural attenuation or site closure	2 to 5 months
Establish institutional or administrative controls	Establish any required institutional or administrative controls	Place any required physical access controls and legal restrictions to ensure land use is consistent with risk scenarios	2 to 5 months
Restore and close site	Perform well abandonment as required	• Conform with local regulatory requirements for closing unneeded wells • Ensure that any wells left in place cannot be used for purposes other than intended • Abandon unneeded wells using methods that prevent migration of contaminants into an aquifer or between aquifers and reduce the potential for vertical or horizontal migration of fluids in or around the well • Secure remaining wells to prevent unauthorized access	2 to 5 months

❑ Periodically evaluate the progress of air sparging with respect to predicted behavior

❑ Make recommendations for continued monitoring, reassessment of the conceptual model, alternative remedial action (i.e., implementation of monitored natural attenuation) or site closure, as appropriate

❑ Document all monitoring activities and site data collected throughout operational period

☐ Report progress of remedial effort to regulators, as appropriate

☐ Document compliance with remedial goals

☐ Establish institutional controls (if needed)

☐ Complete site closure activities, including a site closure report.

I.4 Government-Furnished Property

The SOW must specify that the contractor is expected to be self-sufficient for all work to be performed (except possibly utilities [power, phone, sewer, etc.]), unless specific site conditions require use of government-furnished property.

I.5 Government-Furnished Facilities

Facility personnel must provide the implementing contractor access to the site to be remediated. The SOW must define the requirements for contractor personnel to enter the facility and work at the site.

The work elements required to perform air sparging frequently involve the use of existing sampling wells and monitoring points. The SOW must provide a description of the number, location, and construction of wells and monitoring points in and around the area to be remediated.

The SOW must clearly define responsibilities for managing investigation-derived wastes (IDW). Facility limitations and existing waste management facilities located at the site, which are appropriate for managing any IDW, must be described.

I.6 Deliverables

A list of the deliverable items to be produced during the project, with a clear indication of the due date for each item, appears in the SOW. Table I-7 is provided as an example to assist in preparation of the deliverables list. The number of days to complete each deliverable is project-specific and should be defined as the SOW is prepared. The number of copies, print and electronic format, and addresses of recipients should be defined in the SOW.

TABLE I-7. Example Deliverables for an Air Sparging Project

Deliverable	Applicable Task	Number of Copies	Due Date[(a)]
Draft program management plan[(b)]	Planning and management	5	[Number] days after project start
Final program management plan[(b)]		10	[Number] days after receiving comments on the draft plan
Draft community relations plan[(b)]		5	[Number] days after project start
Final community relations plan[(b)]		10	[Number] days after receiving comments on the draft plan
Input for permit applications (e.g., well construction permits)		5	As required
Monthly reports		1	[Number] days after the first of each month
Meeting agendas		15	[Number] days before the event
Telephone records, trip reports, and meeting minutes		1	[Number] days after the event
Draft assessment report and work plan for detailed evaluation[(c)]	Preliminary assessment	5	[Number] days after approval of project management plan
Final assessment report and work plan for detailed evaluation[(c)]		10	[Number] days after receiving comments on the draft work plan
Public meeting support		—	As required
Draft detailed evaluation report	Detailed assessment	5	[Number] days after approval of the final work plan
Final detailed evaluation report		10	[Number] days after receiving comments on the draft report
Public meeting support		—	As required

TABLE I-7. Example Deliverables for an Air Sparging Project (continued)

Deliverable	Applicable Task	Number of Copies	Due Date[a]
Draft Performance Monitoring Plan[c]	Performance monitoring	5	[Number] days after approval of the final site technology evaluation report
Final Performance Monitoring Plan[c]		10	[Number] days after receiving comments on the draft plan
Draft System Design Plans	System design and installation	5	[Number] days after approval of the final site technology evaluation report
Final System Design Plans		10	[Number] days after receiving comments on the draft plan
System Installation		—	As required
Construction QA Reports	Performance monitoring	1	Daily during field activities
Draft As-Built Drawings	System design	5	[Number] days after approval of the final site technology evaluation report
Final As-Built Drawings		10	[Number] days after receiving comments on the draft plan
Performance Monitoring/ Performance Assessment Reports	Performance monitoring	5	Periodically as required in the Performance Monitoring Plan
Draft Site Closure Report	Project closeout	5	[Number] days after approval of the final Performance Monitoring Plan
Final Site Closure Report		10	[Number] days after receiving comments on the draft report

(a) Tables in Section I.3 indicate typical task durations.
(b) These deliverables are only required under CERCLA or RCRA CA regulatory frameworks.
(c) Includes site-specific QA/QC Program Plan and HASP.

I.7 References

Battelle. 1999. User's Manual for Implementing Remediation by Natural Attenuation at Petroleum Release Sites. Prepared for the Naval Facility Engineering Command (Various Divisions). May.

Leeson, A., P.C. Johnson, R.L. Johnson, R.E. Hinchee, and D.B. McWhorter. 2001. Air Sparging Design Paradigm. In press. December 31.

Tri-Service/U.S. Environmental Protection Agency Working Group. 1998. Environmental Site Closeout Process. Working draft.

U.S. Environmental Protection Agency. 1995. Remedial Design/Remedial Action Handbook. EPA/540/R-95/059. Office of Emergency and Remedial Response, Washington, DC.

U.S. EPA, see U.S. Environmental Protection Agency.