

HEALTH AND
ENVIRONMENTAL
SCIENCES
DEPARTMENT

API PUBLICATION
NUMBER 4609

APRIL 1995

***In Situ* Air Sparging:
Evaluation of Petroleum
Industry Sites and
Considerations for
Applicability, Design
and Operation**





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***In Situ* Air Sparging:
Evaluation of Petroleum Industry Sites
and Considerations for Applicability,
Design and Operation**

Health and Environmental Sciences Department

API PUBLICATION NUMBER 4609

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ACKNOWLEDGMENTS

THE FOLLOWING PEOPLE ARE RECOGNIZED FOR THEIR CONTRIBUTIONS OF TIME AND EXPERTISE DURING THIS STUDY AND IN THE PREPARATION OF THIS REPORT:

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Envirogen would also like to thank Krishna S. Mummareddi of the University of Lowell and Matthew T. Walsh, Karen DiSciullo and Raphael J. Cody of Envirogen for their assistance in the completion of this work. Mr. George Mickelson (Wisconsin Department of Natural Resources) and Mr. Gary Gilbert (Remediation Engineering, Inc.) also provided valuable input and site data which have been included in the report.

Envirogen would also like to express appreciation to the Wisconsin Department of Natural Resources for allowing portions of the document titled "Guidance for Design, Installation and Operation of *In Situ* Air Sparging System" (DNR, 1993) to be incorporated into this document.

API would also like to thank its member companies for providing the site data used in this study.

ABSTRACT

In situ air sparging (IAS) is a remediation technology primarily applied for the removal of volatile organic compounds (VOCs) from groundwater aquifers. Conceptually, IAS is simple: clean air is injected into the aquifer beneath the water table to induce mass transfer of VOCs to the vapor phase. The technology also has application for destruction of volatile and semi-volatile compounds due to biostimulation in the aquifer resulting from groundwater oxygenation. This document was developed to provide information to site managers on the feasibility of installing an IAS system and its design and operation. The document was prepared primarily from a review of existing literature and an evaluation of data detailing IAS systems at 59 sites. The site data was supplied by American Petroleum Institute (API) member companies and environmental consultants.

The key to IAS success is the ability to design and operate a system to achieve effective contact between the sparge air and the target organic compound. IAS appears to work best in uniform coarser grained materials (gravels and sands) where air flow distribution is more predictable and is largely due to buoyancy. Due to the current level of understanding of IAS technology, the radius of influence (ROI) of an IAS well is determined on an empirical basis. The ROI is generally evaluated based on changes in a number of physical, chemical or biological monitoring parameters. Each of the monitoring parameters have potential limitations. From a review of the API-IAS Database, the radius of influence of an IAS well generally falls within the range of 10 to 25 feet.

Presently, very limited reliable data are available on the performance of IAS systems. The mechanisms governing air channel distribution and associated groundwater movement are not well understood. Additional research is needed to further evaluate the factors governing the successful operation of IAS systems and to provide a higher level of confidence in the prediction of required treatment times and the degree to which IAS can be expected to reduce hydrocarbon mass in the subsurface.

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EXECUTIVE SUMMARY

In situ air sparging (IAS) is a remediation technology primarily applied for the removal of volatile organic compounds (VOCs) from groundwater aquifers. Conceptually, IAS is simple: clean air is injected into the aquifer beneath the water table to induce mass transfer of VOCs to the vapor phase. The technology also has application for destruction of volatile and semi-volatile organic compounds due to biostimulation in the aquifer resulting from groundwater oxygenation. This document was developed to provide information to site managers on the feasibility of installing an IAS system and its design and operation. This document was prepared primarily from a review of existing literature and an evaluation of data detailing IAS systems at 59 sites which have been assembled into an API - IAS database. IAS site data was supplied by American Petroleum Institute member companies and environmental consultants.

The analysis of the API - IAS Database has provided valuable insights concerning the application, design and operation of IAS systems. This information is discussed throughout the document and is summarized in the following sections.

IAS technology is generally being applied within sandy soils. In silty or clay soils IAS requires higher overpressures to achieve flow and the potential for soil fracturing is high. The application of IAS technology was deemed infeasible at seven sites where soils contained high levels of silts or clays.

A field pilot-scale evaluation is usually required to determine the feasibility of applying IAS technology and to optimize IAS system design. Pilot tests of IAS technology were usually less than one day in duration. Over such a short term test period, one may be limited to looking for “Red Flags” that may suggest potential problems with the application of IAS at a site. The major finding of pilot scale evaluations was the determination of an IAS well radius of influence (ROI).

The ROI is often evaluated based on changes in a number of physical, chemical or biological monitoring parameters. Measurements of groundwater dissolved oxygen levels was the technique used most often to determine the ROI. Other parameters such as pressure changes in the vadose and saturated zones, groundwater mounding, air bubbling in wells and tracer gases were also used to aid in the determination of the ROI. Limitations for each of the monitoring parameters are presented.

A review of 37 pilot studies revealed that the ROI is generally between 10 and 25 feet. Analysis of design and operation data at 40 IAS sites revealed that a typical IAS well is 2 inches in diameter, with a 2 foot screen, positioned 5-10 feet beneath the water table. The wells typically were operated at an over-pressure of less than 5 psi with a flow rate of less than 5 cfm.

Presently, very limited reliable data is available on the long term performance of IAS systems. While dissolved phase VOC concentrations have been reduced significantly at a few sites, long term water quality data following IAS system shut down does not exist. Furthermore, the mechanisms governing air channel distribution and groundwater mixing at the macro and microscale are not well understood. Additional research is needed to more definitively evaluate the impact of various modes of operation of IAS on system performance.

Section 1

INTRODUCTION

NAPL RELEASE AND GROUNDWATER REMEDIATION

The release of a non-aqueous phase liquid (NAPL) hydrocarbon to a groundwater system potentially results in three distinct types of hydrocarbon distribution which are: 1) immiscible hydrocarbons floating on the capillary fringe or water table; 2) soils with residual immiscible hydrocarbons; and 3) the special problem of immiscible hydrocarbons trapped below the water table as a result of water table fluctuations and/or dissolved hydrocarbons (Fetter, 1993). This problem is further exacerbated when dealing with dense non-aqueous phase liquids (DNAPLs) such as chlorinated solvents (Gudemann and Hiller, 1988). Each type of contaminant distribution often requires different remediation technologies or possibly a combination of technologies.

After a hydrocarbon release, various collection strategies are used initially to recover any mobile floating NAPL. In many cases these hydrocarbons as well as the soils with trapped residual hydrocarbons, can be remediated using technologies such as soil vapor extraction or bioventing (Baehr *et al.*, 1989; Miller *et al.*, 1991). To address hydrocarbons located beneath the water table, technologies such as groundwater extraction, also known as “pump and treat,” are conventionally used. Because most hydrocarbons have relatively low aqueous phase solubilities, large quantities of water must be pumped through the site to solubilize and mobilize organic compounds (Hinchey *et al.*, 1987). The water is then pumped to the surface for treatment. Following treatment, permits may be required before it can be re-injected back into the aquifer or pumped to a sewer for disposal.

An alternate approach to the pump and treat method would be to lower the groundwater table to expose previously submerged contaminated soils to allow *in situ* vadose zone treatment technologies to be used. Depending on the site geology, this strategy may be successful. However, at some sites withdrawal and treatment of large quantities of groundwater may be needed to lower the water table.

To simplify the process of remediating soils below the water table and groundwater, engineers are utilizing *in situ* technologies such as in-well air sparging (Gvirtzman and Gorelick, 1992; Pankow *et al.*, 1993) and air sparging within soils (Gudemann and Hiller, 1988; Ardito and Billings, 1990; Loden and Fan, 1991; Marley *et al.*, 1991, 1992) also known as *in situ* air sparging (IAS). The major difference between in-well air sparging and IAS is that with in-well air sparging the air is injected and rises vertically within the casing of the well, whereas for IAS the air is injected and rises within the soil matrix. Therefore, with in-well air sparging, treatment by volatilization occurs in the well and oxygenated water is forced out of the well into the soil matrix, whereas with IAS the volatilization and groundwater oxygenation processes occur directly in the soil matrix.

IN SITU AIR SPARGING TECHNOLOGY OVERVIEW

In situ air sparging (IAS) is a remediation technology primarily applied for the removal of volatile organic compounds (VOCs) from groundwater aquifers. IAS can promote aquifer remediation by a series of physical, chemical and biological processes. Conceptually, the standard IAS process is quite simple: clean air is injected into the aquifer beneath the water table to induce mass transfer of VOCs to a vapor phase and to add oxygen to the groundwater, as shown in Figure 1-1. Contaminated vapors then migrate from saturated portions of the aquifer to the vadose (unsaturated) zone. A portion or all of the VOCs may be biodegraded within the vadose zone. To control the potential migration of hydrocarbon vapors, soil vapor extraction (SVE) is often applied in conjunction with IAS (Brown and Jasiulewicz, 1992; Marley *et al.*, 1992). In this combined system, the sparged contaminants are directed to the soil vapor extraction wells and are then subjected to *ex situ* treatment such as carbon adsorption, catalytic oxidation, or biofiltration.

A number of additional techniques of applying air sparging exist. The containment and remediation of VOC contaminated groundwater through the application of sparging gate-wells, trenches or “curtains” has been used in remediation schemes (Pankow *et al.*, 1993; Marley *et al.*, 1994). The concepts of sparging gate-wells and trenches are illustrated in Figure 1-2.

The sparging gate-well utilizes hydraulic barriers to direct contaminated groundwater flow through a treatment zone (sparge gate-well). The sparging trench is a constructed trench laid perpendicular to the contaminated groundwater plume flow direction. The contaminants in the groundwater may be remediated while passing through the sparging gate-well or trench through volatilization, biodegradation or other physical/chemical processes.

A sparging curtain resembles a sparging trench in that it is installed perpendicular to the flow of the contaminated groundwater plume. However, vertical sparging wells are generally spaced equally along the length of the curtain to emulate the performance of the sparging trench. Very limited data is available on the design and operation of these additional sparging techniques. Therefore, the primary focus of this document will be on the standard IAS process as depicted in Figure 1-1.

Figure 1-1. Schematic of an *In situ* Air Sparging (IAS) System

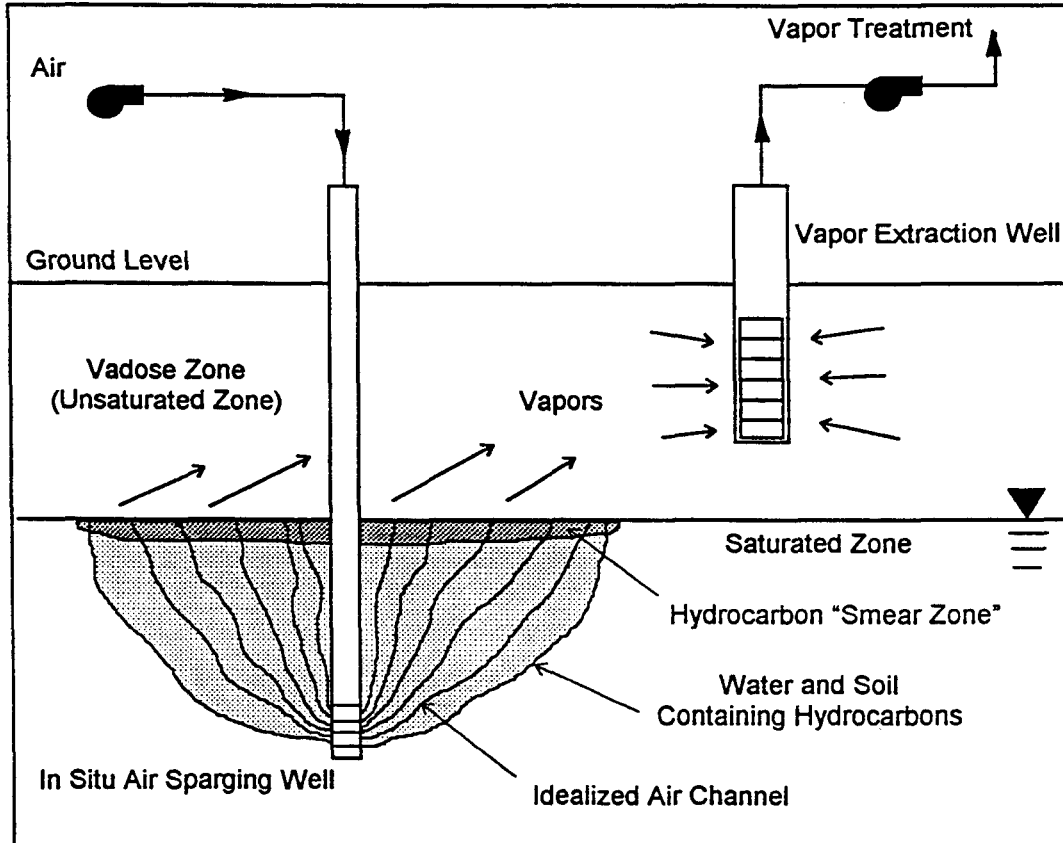
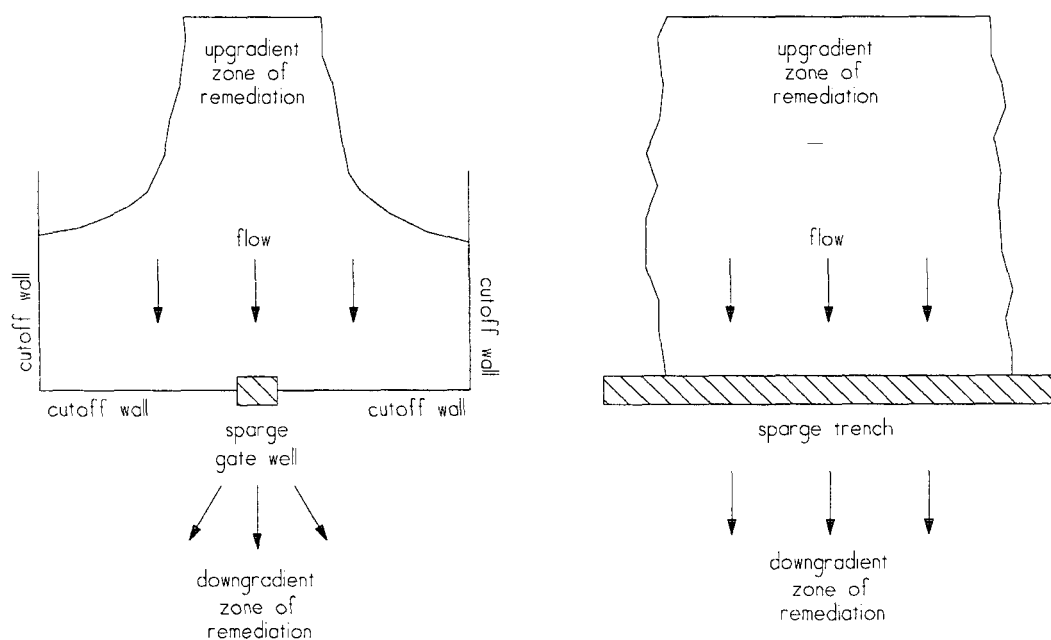


Figure 1-2. Concept of Sparging Gate-Well and Trench



(from Pankow et al. 1993)

API SITES DATABASE OVERVIEW

To assemble a database describing the practice of *in situ* air sparging at field sites, information was provided to API from member petroleum companies and consultants. Data from the reports and technical papers were included in the database (see Appendix). Generally, the data interpretations presented here are those of the consultants that authored the reports. Information on a total of 66 sites was received. Of these sites, 59 were accepted for inclusion into the database. Only 19 out of the 59 sites were full-scale IAS systems. A total of 53 pilot-scale investigations were examined.

Fifteen sites were rejected for inclusion within the database analysis for several reasons. Many of these site files contained fragmented data and figures which made defensible data interpretation impossible. Often it was impossible to establish a time-line of events to determine when sampling was conducted and when measurements were made in relation to IAS/SVE

activities. At many sites, boring logs or descriptions of soil characteristics were not provided. In some cases, details of IAS/SVE system lay-out were not clear.

A variety of approaches were used in conducting pilot-scale evaluation of IAS systems and in the analysis of the *in situ* air sparging data. Some of the studies reviewed focused on physical measurements such as soil characteristics (i.e., description, permeability, hydraulic conductivity), measurements of pressures in monitoring wells, and observations of bubbling and groundwater mounding. Other studies focused on chemical (or biological parameters) such as extensive monitoring and measurement of water quality in numerous monitoring wells and monitoring of effluent gases during the pilot-scale testing. The majority of reports described short term pilot-scale tests, often less than 8 hours in duration. Analysis of data describing IAS system components such as compressor sizing or groundwater quality derived from short term pilot-scale studies is of limited value. The major benefit of the short term pilot-scale evaluations is the determination of an IAS radius of influence.

OBJECTIVES OF THIS DOCUMENT

The information presented in this document is based on a review of the relevant literature, an analysis of the API - IAS Database, and excerpts from a document entitled "Guidance for Design, Installation and Operation of *In situ* Air Sparging Systems," prepared by the Wisconsin Department of Natural Resources (DNR, 1993). The database reflects the petroleum industry's collective experience with IAS technology. These files have been supplied by API member companies and several consulting firms with the understanding that site ownership and location would be kept confidential.

The objectives of this document are:

- to collect and evaluate API member companies' available data on the design and performance of IAS systems,
- to provide to site managers a document with state-of-the-art information on the design and operation of air sparging systems and on the evaluation of design plans developed by consultants, and

- to highlight gaps in our understanding of the technology and identify the research areas to address them.

The remainder of the document is organized to present technical considerations in the application of IAS technology and to provide details on site characterization, pilot testing procedures and data evaluation.

Section 2 describes the state of the art in the knowledge of the mechanisms governing the IAS process. The impacts of IAS on the movement of groundwater and the potential for aquifer clogging and contaminant destruction by biodegradation are addressed in Section 2.

Section 3 briefly describes some of the methodologies utilized in characterizing sites at which IAS technology is proposed.

Section 4 provides a conceptual, state-of-the-art description of the methods used and parameters measured in conducting IAS pilot studies. Section 4 also describes the most common methods used in deriving the effective radius of influence of an IAS well.

Section 5 provides more detail on the materials, methods and equipment commonly used in the installation and operation of IAS systems.

Section 6 presents the common and suggested modes of operation and monitoring of IAS systems. The available performance data on IAS systems, to date, is also presented in Section 6.

Section 7 summarizes the current level of knowledge of IAS technology and describes the potential limitations and knowledge gaps in IAS system design and effectiveness. Suggestions for future research in IAS technology are provided.

Throughout the document key points or issues are presented in bold text to aid the reader in understanding the essentials of IAS technology.

Section 2

TECHNICAL CONSIDERATIONS

APPLICABILITY OF *IN SITU* AIR SPARGING

Contaminant Types Suitable for *In situ* Air Sparging

IAS technology has been utilized for chemical contaminants that are volatile (i.e., VOCs) and/or aerobically biodegradable. These include benzene, toluene, ethylbenzene and xylenes found in petroleum products (e.g., gasoline and diesel fuel) and chlorinated solvents (e.g., TCE and DCE). IAS technology has been applied to remove these contaminants whether they are dissolved in an aqueous phase or held immobile at a residual saturation within a soil matrix (Brown *et al.*, 1991; Gudemann and Hiller, 1988; Marley *et al.*, 1992a).

With respect to contaminant removal by volatilization, IAS depends on mass transfer from the aqueous or residual phase to the vapor phase. The mass transfer rate will depend on the ability to achieve effective contact between the sparged air and the volatile compound. The potential for mass transfer is generally controlled by the partitioning of the contaminant from the aqueous phase. A predictor of the partitioning behavior from the aqueous phase is Henry's constant. For VOCs, it has been reported that a contaminant must have a dimensionless Henry's constant (H) greater than 4.15×10^{-4} (alternate units $10^{-5} \text{ atm-m}^3\text{-mole}^{-1}$) to be successfully sparged from an aqueous phase (Brown *et al.*, 1991). Henry's constants of some potential groundwater contaminants are provided in Table 2-1.

Contaminant Distributions Suitable for *In situ* Air Sparging

The key to IAS success is the ability to design and operate a system to achieve effective contact between the sparged air (or dissolved oxygen) and the target contaminant.

IAS works best when applied to residual phase or "smeared" hydrocarbons below the water table. The technology is also applicable to contaminants dissolved in the aqueous phase. However, due to the perceived potential of spreading freely mobile NAPL, it is suggested that provisions should be made first to remove as much NAPL as possible using conventional skimming techniques, soil vapor extraction or bioventing before implementing IAS.

Table 2-1. Henry's Constants of Selected Compounds

Compound	Henry's Constant (dimensionless) ⁽¹⁾
Benzene	0.23
Toluene	0.28
Ethyl Benzene	0.36
Xylenes	0.22
Tetrachloroethylene, a.k.a. perchloroethylene (PCE)	0.63
Trichloroethylene (TCE)	0.41
Trans-1,2, Dichloroethene (DCE)	0.39
Naphtalene	0.019
Tert-Butyl Alcohol (TBA)	0.0005
Methyl tertiary Butyl Ether (MTBE)	0.02
Di-isopropyl Ether (DIPE)	0.42

- ⁽¹⁾ Conversion of Henrys Constant to units of atm-m³-mole⁻¹ is given by
 $H(\text{atm-m}^3\text{-mole}^{-1}) = H(\text{Dimensionless}) * RT$;
 where
 R = universal gas constant (atm-m³-mole⁻¹ - °K⁻¹) and T = Temperature (°K).

Table compiled from Brown *et al.*, (1991), Thibodeaux (1979), and Montgomery (1991).

When DNAPLs enter an aquifer and sink as a result of density differences, they leave in their path droplets or globs of interstitial contaminant trapped within the water saturated soil pores beneath the water table (Schwille, 1988). It is theorized that the primary mechanism of removal of these contaminants by IAS is not by direct contact of sparging air with the DNAPLs, but rather as a result of enhanced dissolution of the DNAPL and subsequent stripping by the sparging air (Roberts and Wilson, 1993). Roberts and Wilson (1993) have conducted theoretical modeling of DNAPL droplet dissolution and diffusion through a thick stagnant water layer in a porous medium to the advecting water under IAS conditions. They concluded that DNAPL distribution or droplet size greatly influenced the length of time required to achieve the clean-up of an aquifer. Once the contaminant is dissolved in the aqueous phase, basic mass transfer principles apply.

Soil Types Suitable for *In situ* Air Sparging

IAS appears to work best in uniform, coarser grained materials (gravels and sands) where air flow is more predictable and is largely due to buoyancy.

It is expected that in uniform, coarser grained soils the injected air will display a more uniform, distribution and will influence a higher percentage of the soil pores in the vicinity of the sparging well (Marley *et al.*, 1992a).

A potential drawback of highly permeable soils (gravels and coarse sands) is that injected air will travel primarily in the vertical direction limiting the radius of influence (Nyer and Suthersan, 1993). It has been reported that a soil hydraulic conductivity of 0.001 cm/sec or greater is required to allow adequate air flow for IAS (Loden and Fan, 1992; Middleton and Hiller, 1990).

As a result of geologic sedimentation, horizontal permeability can be 10 to 1000 times greater than vertical permeability (Freeze and Cherry, 1979). In the ideal case, the horizontal to vertical permeability ratio will serve to increase the radius of influence in which desired vertical air movement will occur.

However, if the vertical air movement is restricted due to the presence of a confining soil layer or by a large horizontal to vertical permeability ratio within a stratum, sparging can result in spreading of the contaminants in the horizontal direction (Marley et al., 1992a; Martin et al., 1992; Nyer and Suthersan, 1993).

Therefore, IAS technology may be inappropriate where soil stratifications limit the vertical migration of air to the water table surface.

Finer grained soils (silts and clays) or heterogeneous soils are expected to increase the occurrence of preferential air channeling and poor air distribution (Johnson et al., 1993; Marley et al., 1992a).

In silt and clay soils, IAS may achieve a limited volumetric flow rate into the soil mass. If the air injection pressure exceeds the overburden pressure, then soil heaving, cracking and fluidization can occur (Marley *et al.*, 1992a; Johnson *et al.*, 1993). A breakthrough of this type will result in short-circuiting of the air flow and may greatly reduce the effectiveness of the system

(Gudemann and Hiller 1988; Marley *et al.*, 1992a). Therefore, IAS technology may not be suitable for these types of soils.

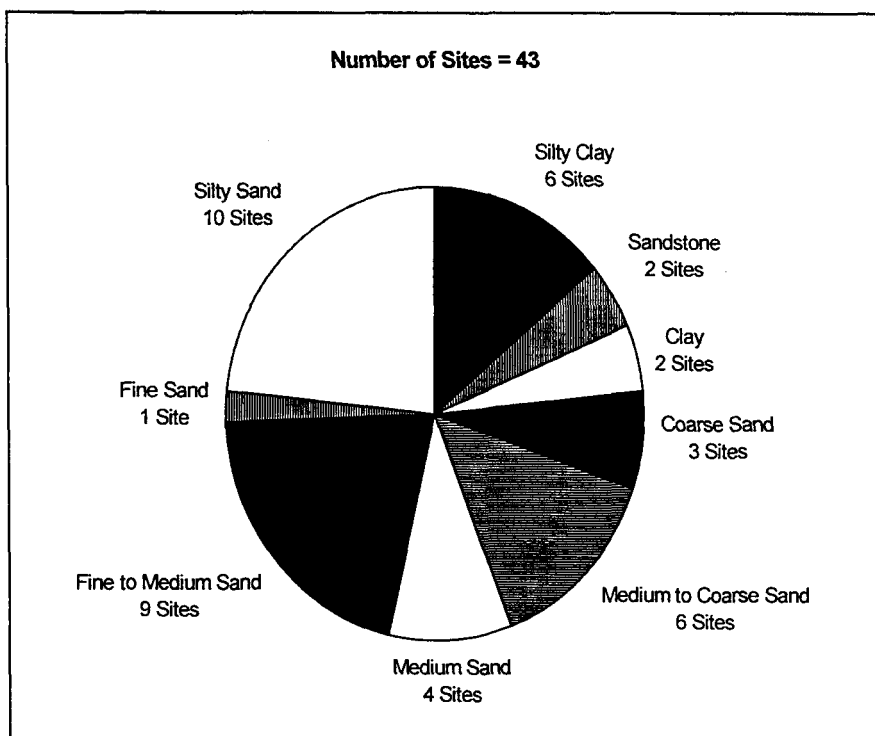
Figure 2-1 shows the distribution of soil types examined for the application of IAS as determined through the API - IAS Database.

Since IAS is highly dependent on contact of the sparging air or dissolved oxygen with the target contaminant, the presence of soil heterogeneities will impact the effectiveness of the process. In situations where the heterogeneities prevent effective contact with the contaminants, the success of the IAS process may be limited by mass transport of the contaminants from the non-contacted soil to an effective sparging area. In such cases, sparging would require extensive treatment times and following IAS system shut-down, rebound in groundwater hydrocarbon content is likely. Some practitioners speculate, however, that effective contact with the contaminated soils may not necessarily mean direct contact with an air channel but may be as a result of groundwater movement associated with IAS system operation. The mechanisms and impacts of groundwater movement are described in Section 2 under the heading Groundwater Mounding and Hydraulics.

Sites Where IAS Technology was Deemed Infeasible

The use of IAS technology was determined to be infeasible at seven pilot-scale investigations in the API - IAS Database. Soil descriptions at these test locations were: clay; clay/silt layers; very silty clays; and fine grained, poorly sorted sand and silt (these seven site soil descriptions are included within Figure 2-1). When pressurized air was injected into these soils the resulting flow was along highly preferential pathways or in one case no flow was achieved. At all of these sites the controlled movement of air through the area of contamination did not seem possible. Presently, insufficient full scale system operating data are available to demonstrate a trend in IAS failure through system performance.

Figure 2-1. Soil Type vs. Number of Sites



AIR FLOW IN POROUS MEDIA

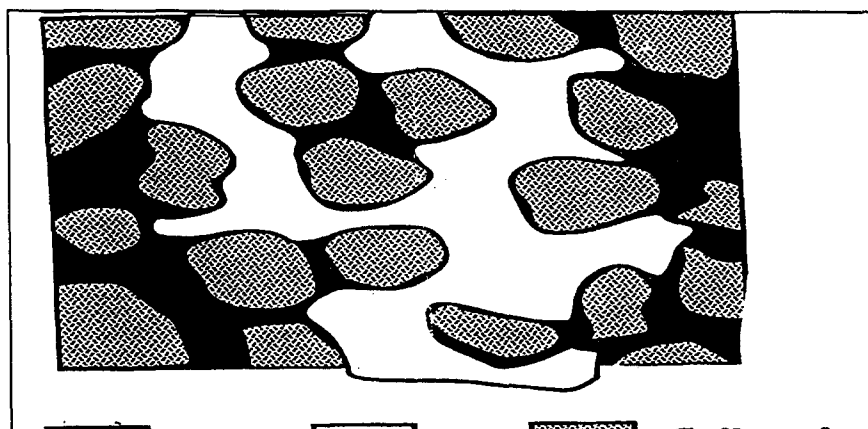
Generally, IAS is implemented through the use of small diameter wells (i.e., 1 to 4 inches diameter) with the screened portion of the well located several feet beneath the water table. Air injection rates are often a few cubic feet per minute (cfm). To inject air into a saturated aquifer, it is necessary to overcome the sum of the hydrostatic pressure of the overlying groundwater and the air-entry pressure of the formation. Hydrostatic pressure is equivalent to 1 psig for every 2.3 feet of water column or 0.433 psi/ft. The magnitude of the air-entry pressures can range from less than one inch of water column for gravels to several feet of water column for silty or clayey soils (Johnson *et al.*, 1993).

In the process of IAS, the behavior of pressurized air once released into a water saturated porous media has been debated in the literature. Ji *et al.* (1993) conducted a series of flow visualization experiments in plexiglass tanks using 0.2 to 4 mm diameter spherical glass beads as a porous media to simulate soils. In 4 mm diameter beads, which corresponds to medium to coarse gravels, “bubbly” flow was observed, and air bubbles ranging from 1 to 3 bead diameters in size

were observed to move upward with a “stumbling motion.” In 0.75 mm beads, which corresponds to sands and silts, air flow was observed to be confined to continuous pore-scale air channels formed inside the medium (Figure 2-2). These channels were discrete and stable. When using 2 mm beads, both channelling and bubbly flow was observed. Therefore, it was concluded that 2 mm is the particle diameter where a transition between flow regimes occurs. Increases in air flow rates generally did not result in significant lateral expansion of the radius of influence (ROI) in the experimental tanks; instead, the number of air channels within the ROI increased. No relationship was observed or derived between bead size and the ROI. Observations of air flow in mixtures of bead sizes revealed that air channel formation and distribution were distorted by even small media heterogeneities. Lateral migration of air flow did occur in experiments where low permeability soil stratifications were simulated using layers of 0.4 and 0.2 mm beads in a tank filled with 0.75 mm beads. The authors concluded that in natural soils, that small-scale soil heterogeneities will prevent symmetric air distribution patterns.

Wehrle (1990) conducted model-scale experiments which observed the flow of air in saturated soils. These experiments demonstrated that in coarse-grained soils, air could rise solely because of hydraulic uplift, while in fine-grained soils, additional external pressure was necessary to overcome pore entry pressures. The dividing line between these two cases occurred with a coarse sand ($d_{50} = 0.8$ mm).

Figure 2-2. Air Transport in Porous Media



experiments in plexiglass tanks using 0.2 to 4 mm diameter spherical glass beads as a porous media to simulate soils. In 4 mm diameter beads, which corresponds to medium to coarse gravels, “bubbly” flow was observed, and air bubbles ranging from 1 to 3 bead diameters in size

In soils coarser than this, the air rose as pulsating bubbles and groups of bubbles. This flow caused displacement of the water above and resulted in considerable mixing of the water.

A number of observations on the behavior of air sparging systems were recorded at two field research sites where the water table rose above the ground surface (Marley, 1994).

In concurrence with the studies by Ji et al. (1993) it was observed that the radius of influence of air channels developed around a single sparge point was not significantly impacted by increases in the air injection rate. However, an increase in the density of the air channels within the radius of influence of a single sparge point was observed both at increased air flow rates and during concurrent operation of adjacent sparge points.

Due to dependence of air channelling on both micro and macro scale heterogeneities, individual channel distribution around a sparge well was observed to be random and unpredictable. In addition, at the two field research sites it was observed that while discrete air channels were observable, the stability of the channels was variable. At both sites, a number of the channels were observed to fluctuate in the intensity of flow in the channels (likely due to subsurface air pressure fluctuations). A number of the discrete air releases were also observed to exhibit pulsing (i.e., the air release would stop and start at variable frequencies).

Further, field observations have indicated that at a number of sites, the air injected into the saturated zone can form large fingers or pockets of air (Marley et al., 1992; Marley, 1994).

The formation of air pockets has been evidenced by the drying up of discretely located monitoring points and by excessively prolonged air releases from the saturated zone following sparging system shut-down. The formation of large air pockets may cause lateral migration of aqueous phase contaminant plumes as shown in Figure 2-3 (Martin et al., 1992). Insufficient data are available on the behavior of the air pockets to presently provide definitive conclusions on the impacts of the air pockets on the local groundwater movement associated with IAS system operation.

In cases where large air pockets form it is likely that the rate of oxygen transfer into the groundwater will be reduced. The rate of oxygen transfer is dependent on the surface area of contact; it would be expected that a single large air pocket would have a significantly reduced surface area of contact with the contaminated groundwater than would a high density of air channels.

The behavior (i.e., morphology, distribution and movement) of injected air within porous media is highly dependent on the site stratigraphy. Groundwater movement resulting from air sparging also is site-specific. Therefore, the prediction of aquifer response to the operation of an IAS system generally requires a field pilot-scale evaluation.

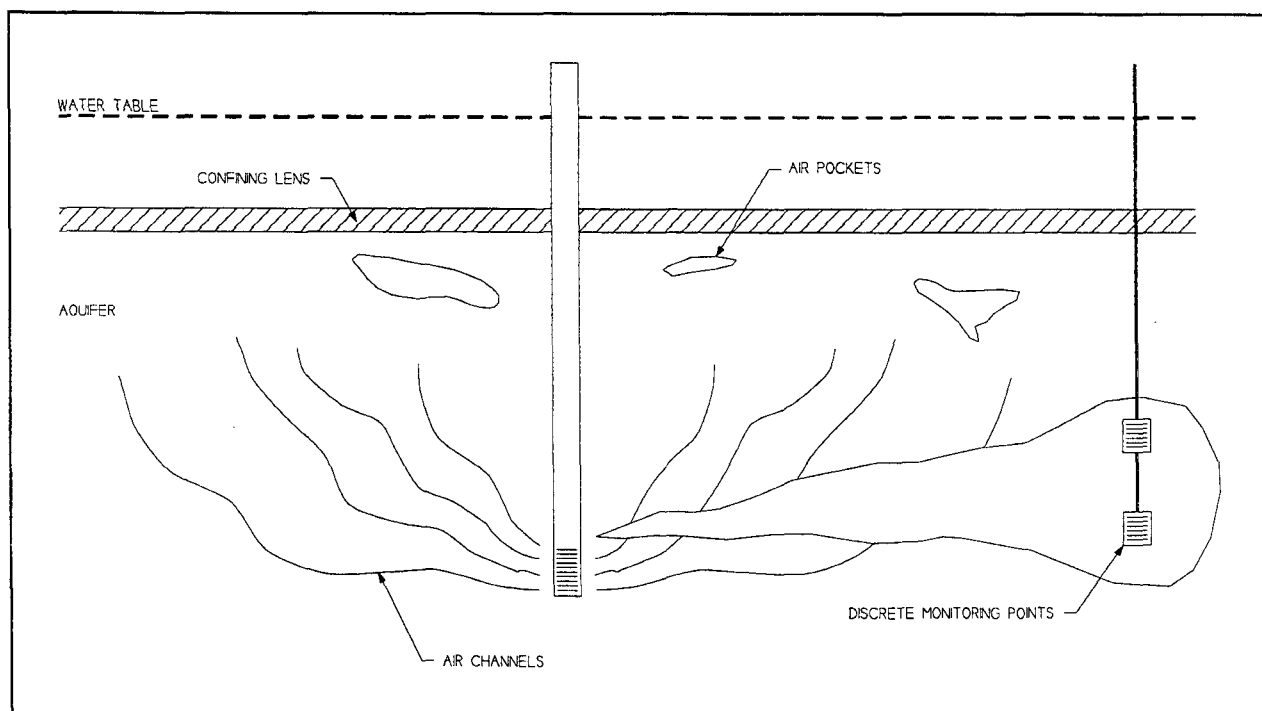
IAS MODELS

Several preliminary models have been proposed to describe IAS systems (Marley and Li, 1992; Sellers and Schreiber, 1992; Wilson *et al.*, 1992; Lundegard and Anderson, 1993; Roberts and Wilson, 1993; Wilson, 1992). For the purpose of simplification, these models assume highly idealized aquifer conditions. While these models provide valuable insights into IAS behavior, field behavior of IAS is likely to vary significantly. Therefore, considerable modification of these preliminary models is required before they are robust enough to successfully describe the behavior of IAS under field conditions and be used for system design.

GROUNDWATER MOUNDING AND HYDRAULICS

Groundwater mounding or upwelling is a temporary increase in water table elevation observed within groundwater monitoring wells often resulting from IAS and SVE activities. It has been observed that as injected air displaces water from soil pores, mounding of groundwater occurs on top of the sparged region of the groundwater table. Generally, the magnitude and duration of the mounding is a function of the soil permeability and the rate of air injection (Marley *et al.*, 1993a; Neuman *et al.*, 1994). As the air permeability of a soil increases, the magnitude and duration of the mounding decreases (Marley *et al.*, 1994). When sustained groundwater mounding is observed, it is likely a result of the soil vapor extraction system or excessive air injection (Johnson *et al.*, 1993).

Figure 2-3. Concept of Air Pockets During IAS Operations

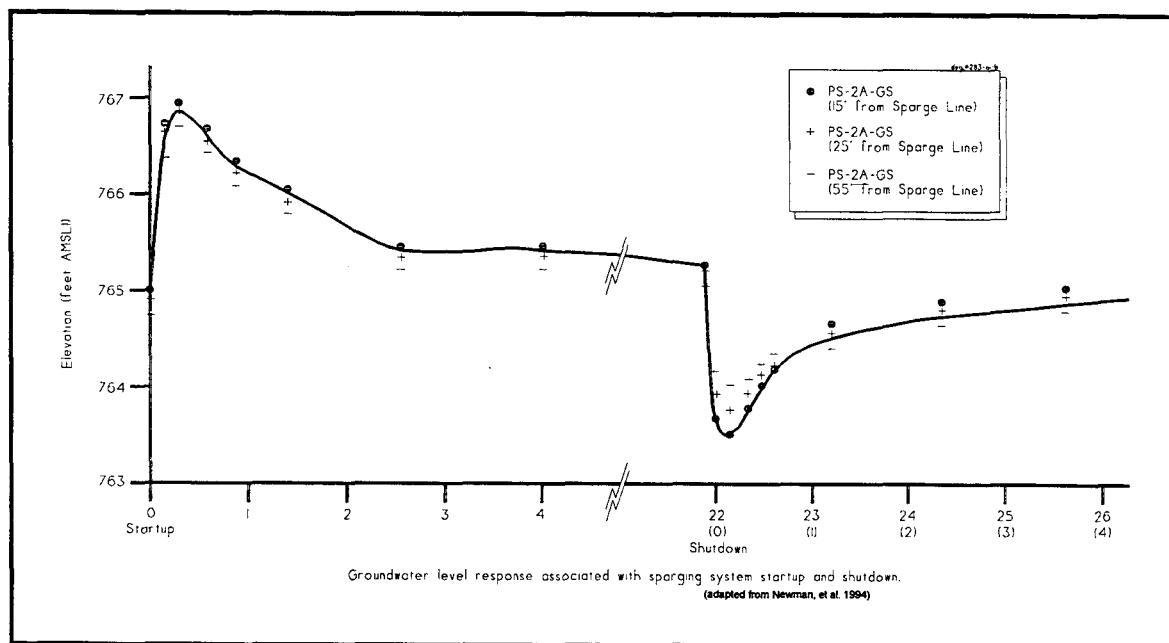


It has also been observed that following IAS system shut-down, a transient depression of the groundwater table forms around the sparge well (Marley *et al.*, 1993b; Newman *et al.*, 1994).

The transient mounding and depression of the groundwater table in response to IAS system start-up and shut-down demonstrate the development and dissipation of macro-scale groundwater gradients and mixing (Marley *et al.*, 1993a; Newman *et al.*, 1994).

In a study by Newman *et al.* (1994), the magnitude and direction of the hydraulic gradients were measured. During the mounding phase a vertical gradient was observed around and above the sparge point. When the groundwater mound began to dissipate, the direction of the hydraulic gradient reversed. During air sparging, the mound dissipated over a two- to three-hour period until static water table conditions were achieved and a relative steady state in the air channelling ensued (Figure 2-4).

Figure 2-4. Groundwater Mounding During IAS Operations



During air sparging, it has been speculated both that the location of air channels is stable (Ji *et al.*, 1993) and that temporal changes in air channelling performance could occur due to the local fluctuating subsurface air pressures (Marley, 1994). If there is no change in the air channel distribution at steady state, it has been determined that mass transfer through diffusion of contaminants to the air channels or diffusion of oxygen from the air channels into the matrix to enhance biodegradation, would require excessive time frames for site remediation (Johnson, 1993).

To accelerate mass transfer it is suggested that the IAS system be operated in the pulsed mode (Marley *et al.*, 1992a; Marley *et al.*, 1993a, 1993b; Newman *et al.*, 1994). The macro-scale groundwater movement associated with IAS system pulsing (periodic system start-up and shut-down) is expected to enhance the mass transfer process. In addition it has been speculated that pulsed operation of the IAS system, on a site-specific basis, may cause temporal and spatial changes to the air channels due to changes in the preferred air pathways as a result of fines migration, biomass growth, mineral precipitation and relative permeability changes due to air entrapment.

AQUIFER CLOGGING

The addition of large quantities of dissolved oxygen to an aquifer by IAS has the potential to lead to problems such as aquifer clogging (i.e., a localized reduction in aquifer permeability). There are several possible mechanisms that contribute to this phenomenon.

The addition of oxygen into an aquifer may cause a significant redox potential change in the aquifer with a subsequent decrease in permeability resulting from precipitation of iron oxyhydroxides, which are formed by the oxidation of iron (Berry-Spark and Barker, 1986). The oxidation of both iron and manganese could cause the plugging of well screens inhibiting air flow.

Typically, the concern for well or air stripper clogging is a result of pumping groundwater with elevated levels of dissolved solids (due to the action of microbes) to a focal point (well or air stripper) where the redox potential is abruptly adjusted causing rapid biomass or precipitate build up. In air sparging applications, redox changes (groundwater oxygenation) are generally distributed over a large area (soil matrix) thereby reducing the potential for clogging. In fact, in the field of water resource engineering there is a process (the VYREDOX[®] process) where groundwater oxygenation by aeration wells is used to precipitate iron and manganese from groundwater before it reaches a production well, indicating that aquifer clogging through aeration wells in general is not a major concern (Driscoll, 1986).

At sparging sites, where air fingers or pockets are present in the saturated zone (Figure 2-3) localized groundwater flow will be impeded. The presence of the air pockets act to reduce the effective hydraulic conductivity of the local soils. This phenomenon is of considerable importance when designing plume intercepting sparging curtains or trenches.

BIOLOGICAL DEGRADATION

Aerobic microbial degradation of petroleum hydrocarbons is much faster than anaerobic microbial degradation. It is well known that the rate of aerobic biodegradation in aquifers is normally limited by the relatively low levels of oxygen and nutrients naturally occurring in groundwater systems (Domenico and Schwartz, 1990). While indigenous bacteria can recycle existing nutrients, the flux of oxygen into groundwater under natural conditions is very slow.

Therefore, a lack of dissolved oxygen is often the rate limiting condition preventing biodegradation of aqueous phase contaminants occurring in aquifers.

Often, the primary goal of IAS systems is to remove VOCs via mass transfer mechanisms. However, an additional benefit of IAS is the accelerated biodegradation of aerobically biodegradable contaminants located in both the saturated and unsaturated zones. This stimulation of biodegradation occurs because of the addition of dissolved oxygen and aquifer mixing resulting from IAS. The process of enhancing degradation of contaminants in the aqueous phase through IAS is often termed “biosparging.” Some practitioners also refer to biosparging in the context of treating semi-VOCs and in cases where the sparging system is designed to maximize the biodegradation processes and to eliminate the requirement for VOC off-gas treatment.

The relationship of IAS and possible *in situ* biodegradation have been discussed in the literature (Ardito and Billings, 1990; Johnson *et al.*, 1993; Loden and Fan, 1992; Marley *et al.*, 1992a; Nyer and Suthersan, 1993). Only limited documentation exists which indicates the magnitude of biodegradation that occurs beneath the water table specifically as a result of IAS activity. However, the occurrence of biodegradation resulting from IAS can be deduced from case studies of similar systems where increased dissolved oxygen content in saturated aquifers has stimulated *in situ* biodegradation (Yaniga *et al.*, 1985).

SITE CHARACTERIZATION

There are a number of characteristics or parameters associated with IAS system design which should be assessed during site investigation. A brief list of site characteristics and their significance are highlighted below.

CONTAMINANT CHARACTERIZATION

Contaminant Type

The following contaminant properties should be considered with respect to the applicability of air sparging for the removal of residuals and/or dissolved phase:

- **Henry's Constant**
- **Vapor pressure**
- **Density**
- **Solubility in water**
- **Biodegradation potential**

Air sparging is an appropriate remediation technology for the removal of volatile contaminants. Typically, contaminants must have a dimensionless Henry's constant greater than 4.15×10^{-4} to be successfully sparged from an aqueous phase (Brown *et al.*, 1991). For residual contamination, vapor pressures greater than 1mm of mercury at 25°C are considered appropriate for volatilization.

Other chemical properties such as density and solubility should be considered. For instance, although some DNAPLs such as trichloroethylene (TCE) may have vapor pressures within the ideal vapor pressure range, free-phase DNAPLs are typically difficult to remediate using air sparging due to the factors which govern DNAPL distribution in saturated soils (Schwille, 1988). Polar organic compounds (e.g., alcohols) also may be difficult to remove because of their

relatively high aqueous solubilities (a chemical's solubility is generally reflected in its Henry's constant).

Air sparging also is an appropriate remediation technology for contaminants which are aerobically biodegradable. Aeration of the groundwater will then be the primary objective of the sparging system. When aeration is the primary objective, IAS may be used to promote aerobic biodegradation ("biosparging"), and can be applied for the remediation of VOCs, heavier molecular weight organic compounds which exhibit vapor pressures less than 1 mm Hg (i.e., semi-volatile organics), fuel oils, and/or water-soluble organic constituents (i.e., acetone, alcohols, methyl ethyl ketone (MEK), etc.).

Biosparging for the biodegradation of VOCs or semi-volatile organics, in site-specific cases, may be applied without an associated soil vapor extraction system. Biosparging applied without SVE requires a biofeasibility evaluation and possibly monitoring in order to ensure that off-site migration of potentially hazardous vapors does not occur.

Contaminant Distribution and Mobile NAPL

The distribution of the contaminant in the subsurface (both areally and vertically) and the phases in which it is present (dissolved, mobile non-aqueous phase liquid (NAPL), or as a residual NAPL in the soil matrix) is critical in the determination of the feasibility of sparging at a given site and in the system design.

The knowledge of the areal extent of contamination is used in conjunction with the IAS pilot test measured radius of influence, to determine the number of IAS wells which are required for site remediation. The areal extent of contamination also provides information on the proximity of the plume to site boundaries or sensitive receptors. This data can be utilized in conjunction with IAS pilot test data to determine the need for hydraulic controls (e.g., groundwater pumping).

The vertical extent of contamination will provide information to optimize the installation depth of the IAS wells. From a review of the API - IAS Database, an IAS well is typically installed

from 5 feet to 15 feet below the water table. The IAS well is located in an attempt to assure more effective contact between the developed air channels and the contaminants.

There is a perceived concern with the application of IAS in an area where mobile NAPL is present. The concern arises from the development of a groundwater mound as a result of the IAS system operation. Although the existence of a groundwater mound may provide a temporary gradient for NAPL movement, no documented cases of enhanced NAPL movement have been identified from the available literature. Due to the potential for enhanced NAPL movement, NAPL (i.e., free product) removal via pumping or SVE is commonly undertaken prior to operation of an IAS system. Alternately, the IAS system or other hydraulic control (groundwater pumping) may be designed with the additional objective of containing any mobile NAPL at the site during system operation.

SOIL CHARACTERIZATION

A thorough understanding of site geology (stratigraphy) is the most important criterion in the evaluation of the feasibility of, and in the design of, a sparging system.

In situ air sparging is generally more effective in uniform, coarse-grained soils (Marley *et al.*, 1992a). Fine grained soils or soil heterogeneities are expected to increase the occurrence of preferential air channelling and poor air distribution. Excess injection pressures associated with finer grained materials, may create fractures in the soil formation which could reduce the effectiveness of the IAS system. (See Section 2: Air Flow in Porous Media and Section 5: Air Compressor Selection for more specific information).

Soil stratification can cause the injected air to form into large pockets or voids beneath the water table. The formation of the air pockets may cause a lateral movement of the dissolved phase contaminant plumes. Determination of the potential for preferred lateral air movement is important in predicting lateral displacement of groundwater. The occurrence of preferred lateral

air movement resulting from IAS activities is also an important consideration in the design of a SVE system used to capture associated VOCs in the vadose zone.

Because a detailed knowledge of site geology is important for the optimal design of an IAS system, detailed logs of site soils and a cross section of the site are beneficial. Stratigraphic logs developed from continuous split spoon sampling, direct push (e.g., cone penetrometry), or petrophysical logging methods provide a means to characterize and to determine the uniformity of the soils across the site.

Suggested soil boring characterization parameters that can be used in the evaluation of the potential for applying IAS include:

- Approximate percentages of gravel, sand, silt and clay;
- Geologic origin;
- Description of moisture content (dry, moist, wet);
- Any visual evidence of secondary permeability (fractures or burrows);
- Voids or layering;
- Blow counts;
- Pertinent field observations such as visual indications of hydrocarbons and headspace measurement with an organic vapor analyzer; and
- Description of any evidence of product smearing.

Because depth of smearing is evidence of past aquifer water level variations, the depths should be carefully recorded.

HYDROGEOLOGICAL CHARACTERIZATION

Hydraulic Conductivity

A hydraulic conductivity of 0.001 centimeters per second or higher is generally recommended to achieve an effective rate of air injection into an aquifer (Loden and Fan, 1992; Middleton and Hiller, 1990). However, soil stratifications, heterogeneities and vertical to horizontal permeability ratio are more important in determining the potential for the success of IAS at a site.

Undesirable preferential air flow is most likely to occur in glacial till and fractured consolidated deposits.

Depth to the Water Table and Water Table Fluctuations

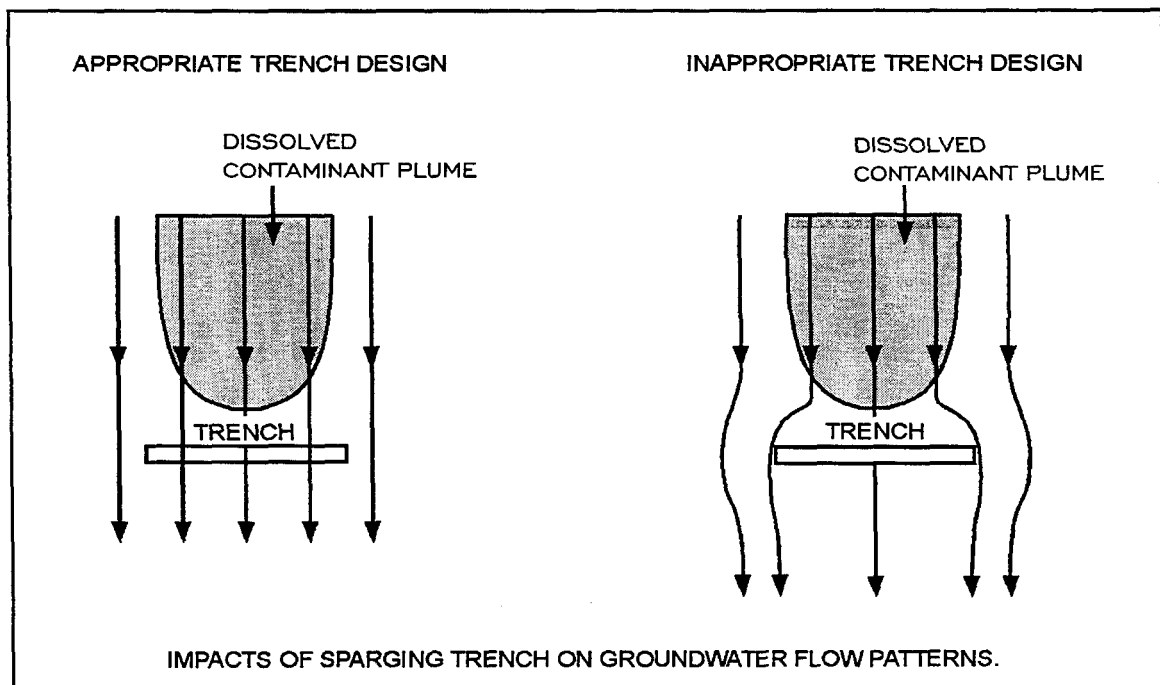
The depth to and seasonal variation in the water table level are necessary design information. These data are needed to design and place the IAS wells, to select air injection equipment, and to predict the maximum test or operational air injection pressures (to avoid soil fracturing).

Groundwater Flow Direction and Rate

The rate and direction of groundwater flow at a site has a number of implications for IAS system design. From stripping tower theory, it is well recognized that a sufficient volume of air must be passed through a given volume of contaminated water to ensure stripping of the VOCs (Pankow *et al.*, 1993). This requirement also exists when applying IAS to strip VOCs *in situ*. This is required for both standard sparging well system designs and for sparging trench or curtain designs.

Pre-sparging data on the groundwater flow characteristics of a site should be utilized in conjunction with data obtained while the IAS system is in operation to determine potential impacts on the regional groundwater flow. This is especially true in the case of sparging trench or curtain systems. Improper trench or curtain design could cause the groundwater to move around, as opposed to through, the proposed treatment zone, as depicted in Figure 3-1 (Marley *et al.*, 1994).

Figure 3-1. Groundwater Movement Associated with Sparging Trench Operation



TREATABILITY AND PILOT TESTING

LABORATORY TREATABILITY TESTS

In general, using laboratory tests to predict the effectiveness of air sparging at a field site is not necessary. In the field, the soil characteristics, with respect to air distribution, will generally be the dominant factor influencing the performance of an IAS system. Typically, sites contaminated with gasoline-range hydrocarbons do not warrant extensive laboratory biodegradation studies because most petroleum-based hydrocarbons are easily degraded aerobically. However, if biodegradation of non-BTEX compounds is a goal of the IAS remediation process at a site, assays may be conducted to determine the presence of indigenous microbes capable of degrading the target contaminants. Once the presence of an effective microbial population is confirmed, tests should be performed to assess the need for the addition of supplementary nutrients. Although environmental factors such as temperature, pH and/or other inhibitors are important for microbial metabolism/respiration, oxygen is generally the limiting parameter for *in situ* aerobic biodegradation.

PILOT TESTING

Purpose of Pilot Test

An IAS pilot test is conducted to determine the feasibility of applying IAS technology to a specific site. If the results of the pilot test indicate that IAS technology is feasible, then the data can be used in the design of a full scale system. From the API - IAS Database it can be observed that the typical air sparging pilot test is run over a period of less than one day. In that short period, it is important to consider what definitive data the pilot test can provide. For example, during a two- to four-hour test it is unlikely that significant improvements to the quality of the groundwater in the test area will be observed. If the groundwater quality change is significant in that time frame, consideration should be given to the potential that the water quality change may not be representative of the aquifer conditions but more as a result of the impact of the sparging on the groundwater in the monitoring well. It is also unlikely that changes in dissolved oxygen levels measured during the test will be representative of dissolved oxygen levels measured in the

vicinity of the well under longer term (one week or greater) testing or during full scale system operation. Further, measurements of the groundwater movement in response to the short term IAS system testing may be more representative of transient conditions, as compared to full scale system operating conditions.

During short term pilot tests (less than one day in duration) it is therefore important to look for signs or “red flags,” that may indicate potential problems with the application of IAS at the site. Typical problems may include bubbling of air at monitoring wells located 60 feet or more from the sparge point (indicating the potential for significant lateral migration), drying out of discrete monitoring points located in the saturated zone (indicating the presence of an air pocket), and injection pressures that significantly exceed the expected injection pressures for the site specific groundwater and soil conditions (indicating the potential for soil fracturing).

Air sparging pilot tests are usually, but not necessarily, conducted in conjunction with SVE feasibility tests. A major reason for conducting IAS in conjunction with SVE is to control the migration of VOC vapors.

Pilot Test Design

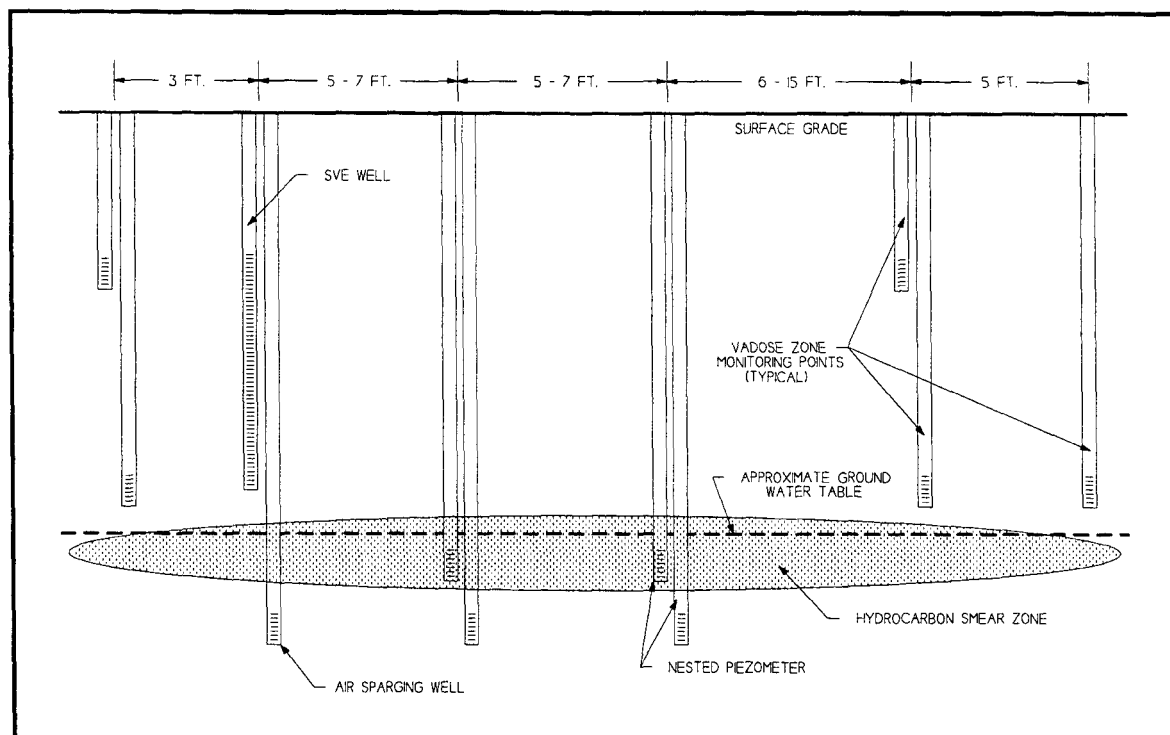
An air sparging pilot test generally includes the design of an IAS test well network, operation of air sparging equipment, performance of physical/chemical static (background) and dynamic measurements, analysis of test data, and development of a pilot test report.

An IAS test well network generally includes the following: the IAS well(s); saturated zone piezometers; vadose zone monitoring points (vapor probes); SVE well(s) and any existing appropriately located groundwater monitoring wells. Details on the methods of well installation are provided in Section 5.

The screened interval of the IAS well is generally positioned below the delineated vertical extent of contamination. The areal placement of the well(s) is generally within the suspected source area. A cross-section of a typical pilot test network is shown in Figure 4-1.

The test well network is generally designed to obtain data representative of as many of the site-specific geologic and chemical heterogeneities as possible. For instance, at a site which has contaminated areas in distinct soil types (e.g., fill and native materials) the test well network would be designed to test the physical and chemical parameters in each area.

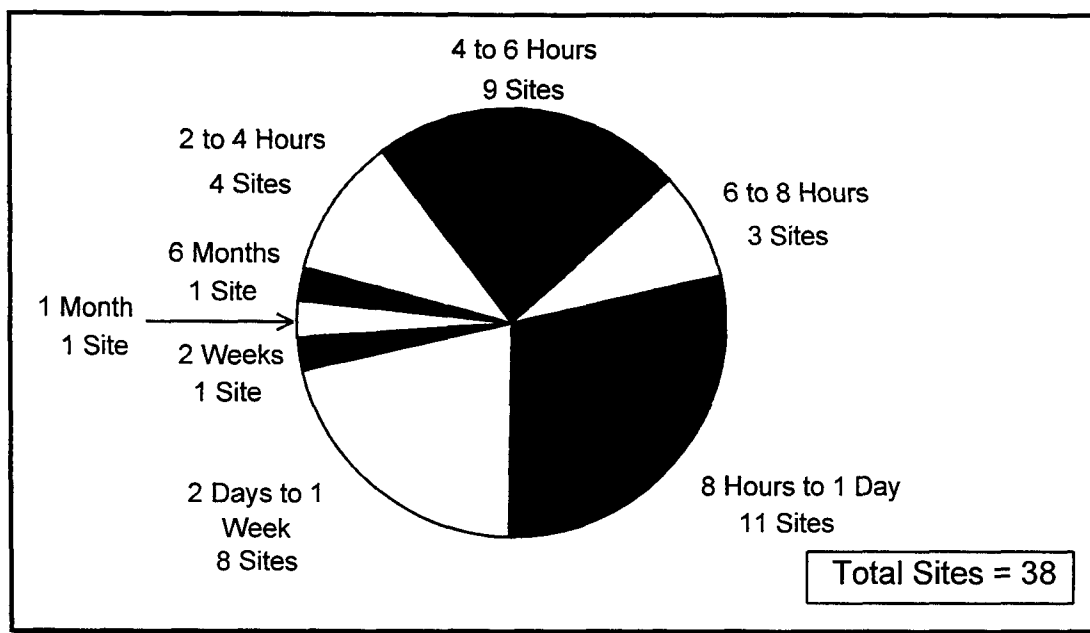
Figure 4-1. Typical Air Sparging Pilot Test Network



The API - IAS Database was reviewed to determine the state of the practice with respect to pilot test duration. The results of the database analysis are shown in Figure 4-2. As shown, the majority of pilot tests are conducted over a period of one day or less.

Due to the current level of understanding of the governing mechanisms for air sparging, present practice in pilot testing is to collect data on several potential indicators of system performance. The most common indicators used in the evaluation of IAS pilot tests are discussed in a subsequent sub-section entitled Radius of Influence Determination.

Figure 4-2. Pilot Test Duration vs. Number of Sites



IAS System Monitoring Points

Piezometers installed in the saturated zone can be used to monitor the performance of the IAS test well. The saturated zone probes are generally used to monitor water quality parameters, pressures and the presence of air flow. For optimal monitoring, nested (i.e., multi-level) sets of saturated zone probes may be installed. One set is generally installed approximately five radial feet from the IAS test well. Several additional saturated zone probes may be installed at further distances (up to 25 radial feet) from the IAS well in order to better characterize the air distribution or radius of influence of the well. In general, the saturated zone probes are positioned in varying radial directions from the IAS well to provide data on the relative symmetry of the injected air flow about the well.

Unsaturated zone vapor probes should be installed above the water table to monitor parameters such as VOC, O₂, CO₂ and inert tracer gas concentrations occurring within the vadose zone during IAS testing. Tracer gas studies are being used more frequently to determine the radius of influence and to identify preferential air flow channels.