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

STEP
Strategies for Today's Environmental Partnership

American Petroleum Institute

STEP
Strategies for Today's Environmental Partnership

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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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Figure 2-2 on page 2-7 was reprinted from the article, "A Conceptual Model of Field Behavior of Air Sparging and Its Implications for Application," pages 132-139 as published in the Fall 1994 issue of *Ground Water Monitoring and Remediation*, by D.P. Ahlfeld, A. Dahmani and W. Ji.

# 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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Terry Walden, BP Oil

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.

# TABLE OF CONTENTS

APPENDIX

# LIST OF FIGURES



# LIST OF TABLES

# 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 (Hinchee *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 quanities 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

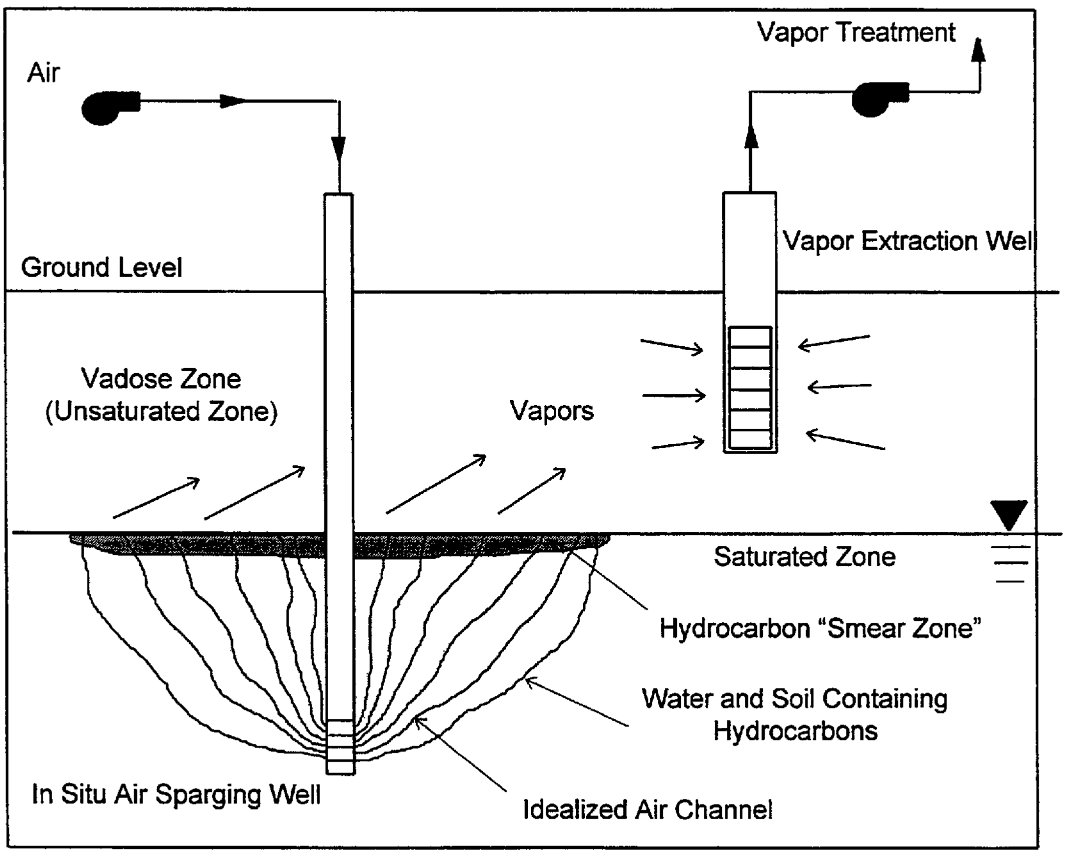
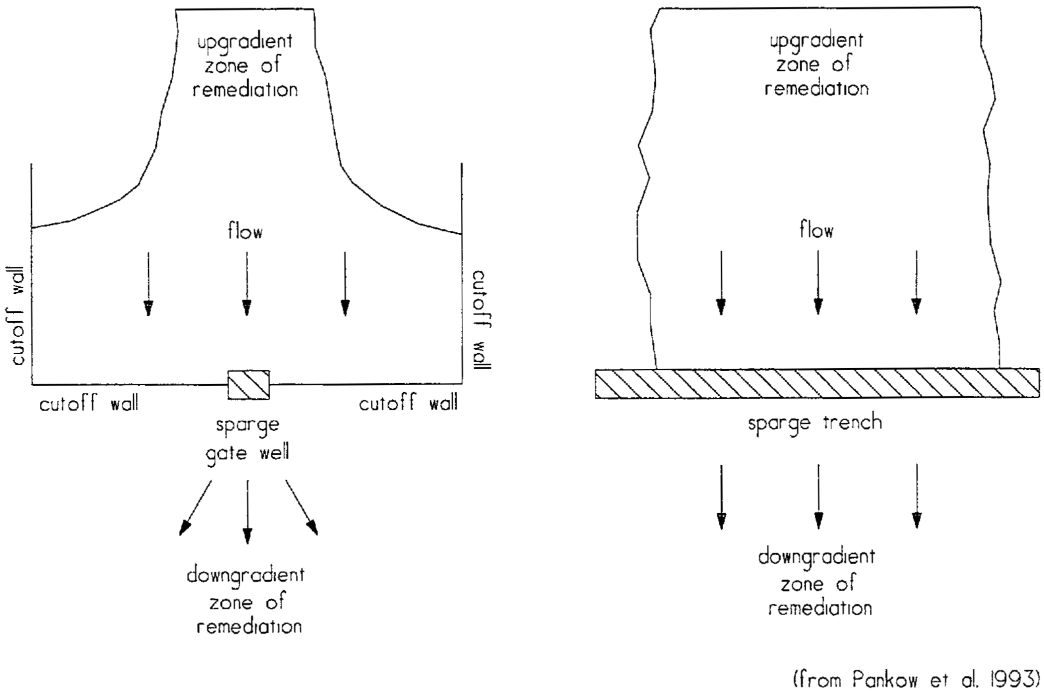


Figure 1-2. Concept of Sparging Gate-Well and Trench




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 defendable 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 $4.15 \times 10^{-4}$ (alternate units $10^{-5}$ atm-m$^3$-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-m$^3$-mole$^{-1}$ is given by
H(atm--m$^3$-mole$^{-1}$) = H(Dimensionless) * RT;
where
R = universal gas constant (atm-m$^3$-mole$^{-1}$ - $^o$K$^{-1}$) and T = Temperature ($^o$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.

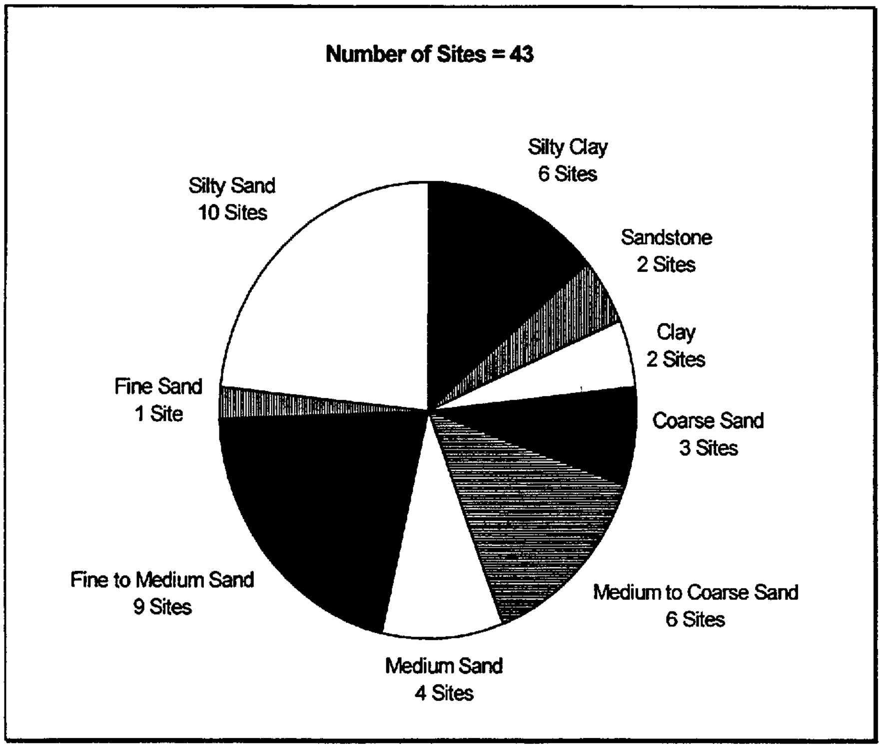
Figure 2-1 shows the distribution of soil types examined for the application of IAS as determined through the API - IAS Database.

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



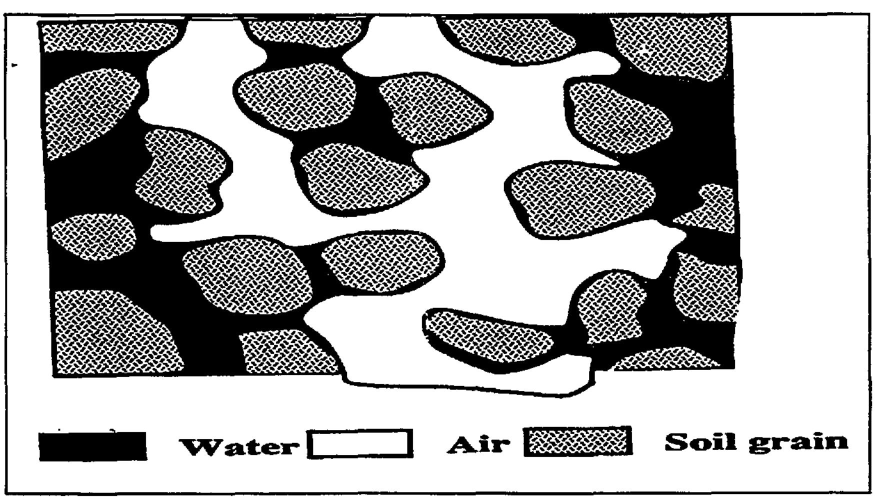

AIR FLOW IN POROUS MEDIA

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




(from Ahlfeld *et al.,* 1994)

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).

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).

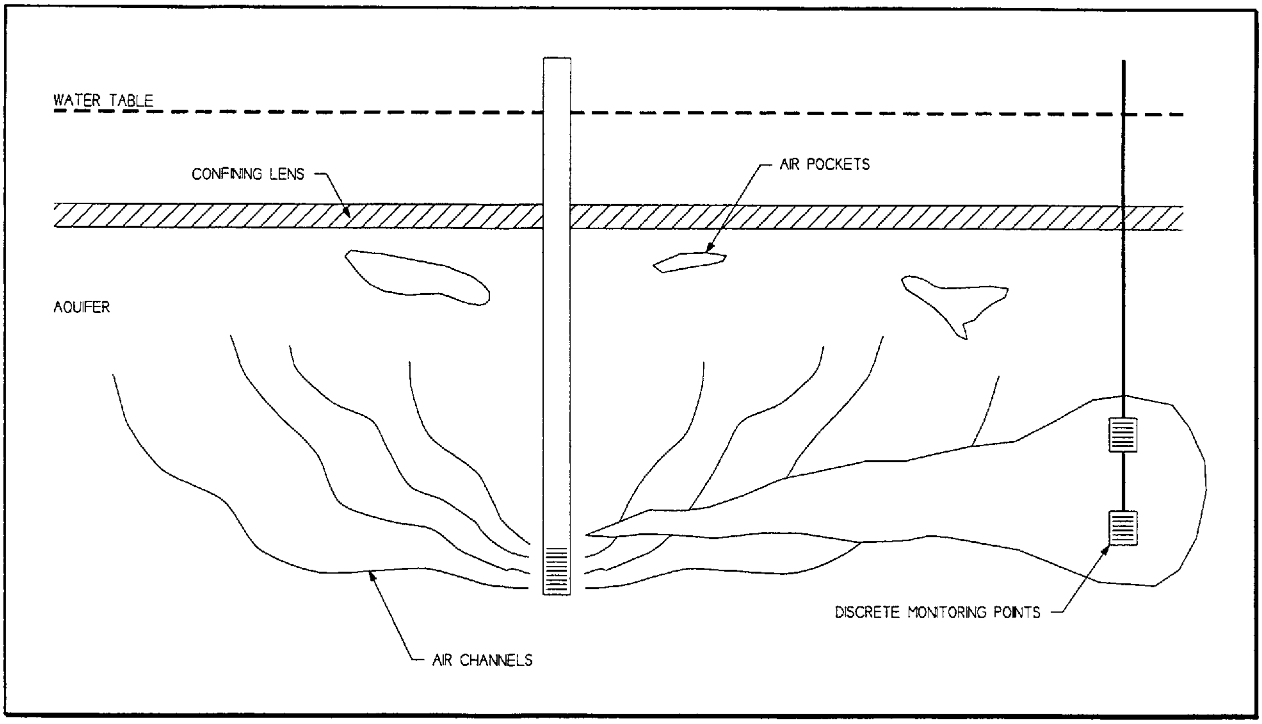
> ***In concurrence with the studies by Ji et al. (1993) it was observed that the radius of influence of air channels developed around a single sparge point was not significantly impacted by increases in the air injection rate. However, an increase in the density of the air channels within the radius 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.

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

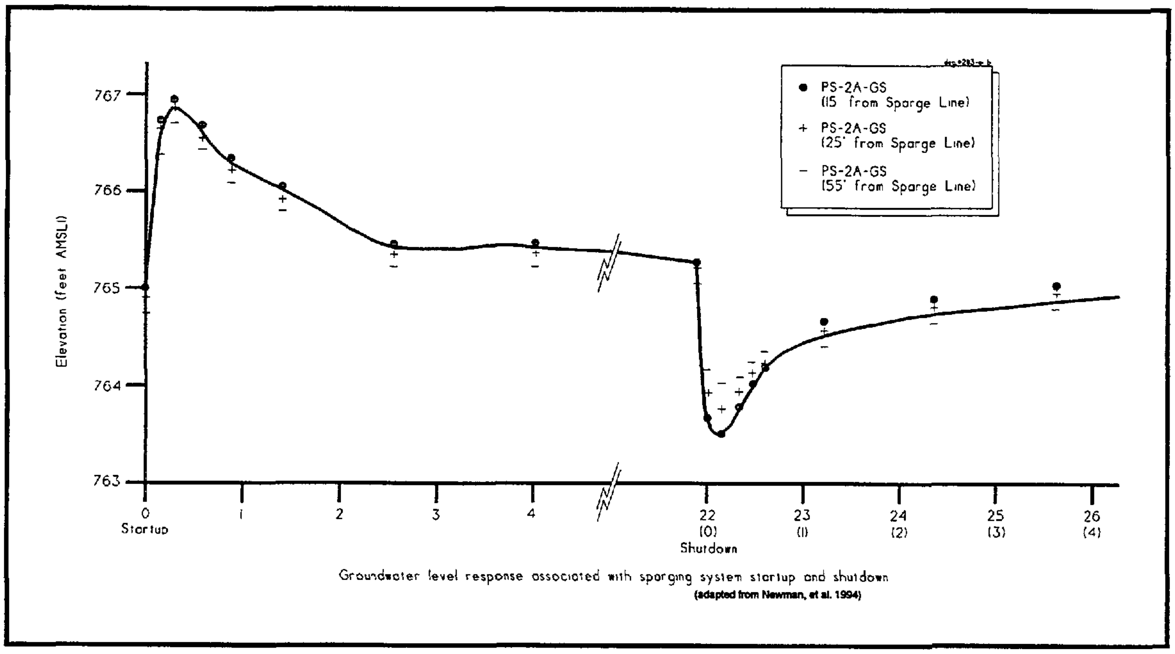



It has also been observed that following IAS system shut-down, a transient depression of the groundwater table forms around the sparge well (Marley *et al.*, 1993b; Newman *et al.*, 1994).

> ***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).

# Section 3
# 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 $4.15 \times 10^{-4}$ 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 chemicals 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

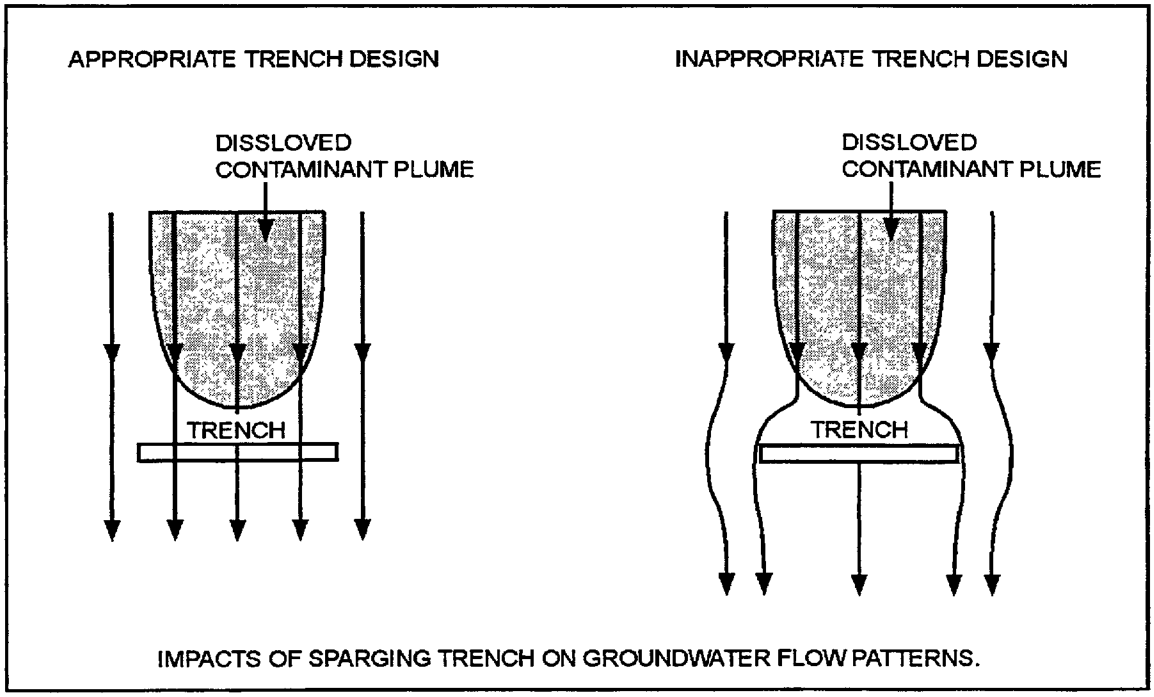
The depth to and seasonal variation in the water table level are necessary design information. These data are needed to design and place the IAS wells, to select air injection equipment, and to predict the maximum test or operational air injection pressures (to avoid soil fracturing).

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



# Section 4
# 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

<u>Purpose of Pilot Test</u>

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

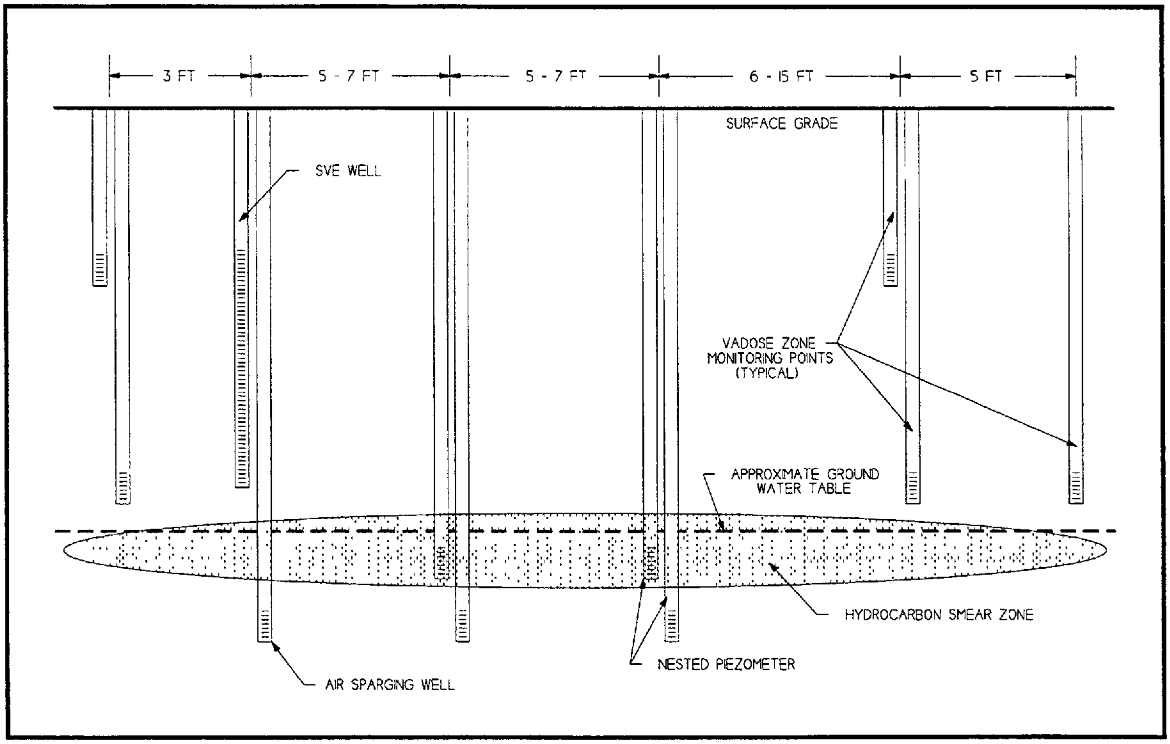
An air sparging pilot test generally includes the design of an IAS test well network, operation of air sparging equipment, performance of physical/chemical static (background) and dynamic measurements, analysis of test data, and development of a pilot test report.

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.

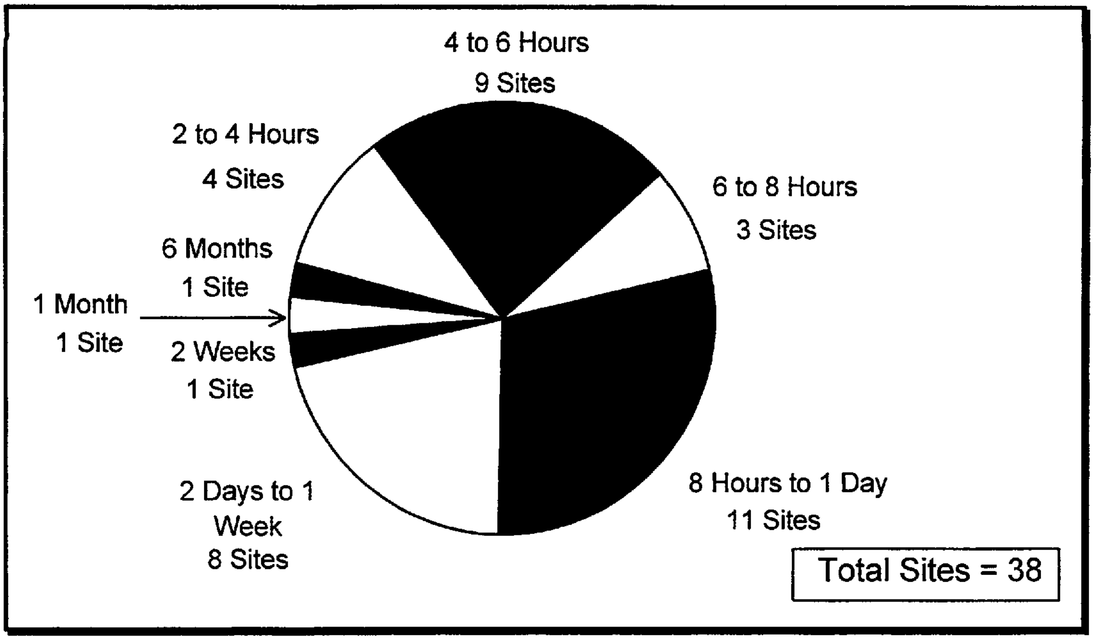
Figure 4-1. Typical Air Sparging Pilot Test Network




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




<u>IAS System Monitoring Points</u>

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, $O_2$, $CO_2$ 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.

Pilot Test Equipment

In addition to SVE equipment (if appropriate), the basic equipment typically used to conduct an air sparging pilot test includes an air supply (typically an air compressor), high-pressure air hose, pressure gauges, in-line flowmeter, control valves, and an IAS well head assembly.

The air compressor should be large enough to inject sufficient flow at sufficient pressure to at least one well and possibly to multiple wells simultaneously. An appropriate minimum capacity range is 3 to 10 scfm and 6 to 20 psig. Designers generally avoid using high-pressure compressors that may, if improperly operated, pneumatically fracture the aquifer and/or rupture the IAS borehole annular seal(s). Failures of borehole seals with subsequent short circuiting of the injected air flow or upward movement of the IAS well have been recorded. Suggested maximum injection pressures for unconsolidated materials is approximately 0.6 to 0.8 psi per foot of overburden (see Section 5: Estimation of Maximum Air Pressure).

Air compressors are generally equipped with a pressure gauge to monitor pressures, a pressure relief valve to control maximum pressures, and a regulator to regulate the pressure from the compressor. It is desirable that the pressure relief valve be set manually as most air compressors are capable of air pressures above the suggested maximum injection pressure.

Flexible high-pressure (0-100 psi) air hoses equipped with quick-disconnect air fittings (couplers and plugs) provide a cost effective method of manifolding the compressor to the IAS test well(s). Couplers and plugs also provide ease and flexibility of operation in the setup of the test system. A pressure gauge is generally added to the IAS well head assembly in order to determine the air pressure in the IAS well. Typically, the gauge should be capable of reading 0-15 psig.

To measure the rate of air injection, a flow meter is installed in line. The meter may be a heated wire anemometer, a rotameter or orifice plate flow gauge; other devices are also acceptable. In general, Pitot tubes generally require an air velocity of 1,000 feet per minute or more. If designers use a Pitot tube, they should install it on a pipe with a small enough diameter that provides sufficient air velocity for accurate flow measurement. Because air is heated as it is compressed, the flow rate should be corrected to standard temperature and pressure conditions (scfm, not cfm). This is important in selecting a full scale system air source.

A temperature gauge is typically used to verify that heat from compressing the air will not damage the test equipment or well. If the temperature rises above 140°F, PVC may become too weak to hold pressure. Installing a length of metal pipe from the compressor outlet to a PVC manifold is generally sufficient to dissipate excess heat. Temperature measurements may also be necessary for calculating a correction factor to flow meter readings.

A well head assembly will be necessary for delivery of the air to the IAS well. Typically, the well head assembly can be constructed to allow for temporary attachment/detachment to the IAS well. The well head assembly should include sampling port(s). The well head assembly can also allow for the temporary insertion of a drop tube for air lifting fines which may accumulate in the IAS well.

Pilot Test Emissions Control

In many instances, the performance of a short-term IAS feasibility test may not require emissions control. This will depend upon the volume and hydrocarbon concentration of the air being emitted, an individual State's regulatory requirements governing the conduct of pilot tests, and on health or safety requirements. If performance of the pilot test requires air emissions control, then typically vapor phase carbon or a mobile catalytic oxidation unit are the most cost effective alternatives.

An acceptable monitoring instrument for gasoline-range VOC emissions is a hand-held total organic vapor analyzer (OVA) equipped with a flame ionization detector (FID). Response of the FID is generally linear across a wide range of hydrocarbons and over a large concentration range, 0-1000 ppmv, a dilution apparatus may be used for higher VOC concentration streams. The methane content of the emission stream should be subtracted from the FID reading to obtain an accurate VOC measurement.

Organic vapor meters (OVM) equipped with photoionization detectors (PID) may not be accurate for emissions monitoring. This is due to the non-linearity of the PID response to complex hydrocarbon mixtures and due to interference of soil gas moisture with PID operation. A PID may be warranted if the objectives of a test/investigation is qualification of the presence of hydrocarbons or for general, relative measurements only. However, if the objective of field analysis is quantification of VOCs for system design, an FID will provide more accurate results.

Generally, a Tedlar® bag or equivalent sample of the SVE/IAS system discharge should be shipped overnight to a certified laboratory for analysis by EPA Method TO3 or a modified Method TO14 for volatile organics. The results of the laboratory analysis will provide a correction factor for the OVA. In addition, laboratory analysis will provide documentation for permitting of emission control equipment for the full scale system.

An alternate to the Tedlar® bag is the use of sorption tubes. Charcoal or Tenax® type sorption tubes are easy to use and most laboratories are set up to perform the required analysis procedures. However, with improper use sorption tubes can easily become saturated with contaminants. Because all VOCs may not be sorbed on the sorption material, the concentration of contaminants in the vapor phase can be underestimated.

Pilot Test Monitoring

Before, during and after an IAS test, physical and chemical parameters are typically measured at all wells and piezometers. Typical parameter measurements include:

- Flow and pressure measurements;
- Groundwater level measurements;
- SVE VOC discharge concentrations;
- Water quality measurements (e.g., DO concentrations);
- Soil gas VOC concentrations in vapor probes/unsaturated zone probes;

- Soil gas $CO_2/O_2$ or tracer gas concentrations; and
- Visual observations such as the bubbling in wells or piezometers.

Further discussion on these parameters is provided in the Radius of Influence Determination sub-section.

If SVE is operating at a site, the SVE system is generally shut down for a period of time (approximately one week) to allow soil gas contaminant concentrations in the vicinity of vapor probes to re-equilibrate with the contaminants on the soils. This will enable changes in soil gas constituent concentrations, as a result of IAS pilot system operation, to be more easily quantified. Obviously, if the potential for hazardous vapor migration to a sensitive receptor exists, the SVE system should not be shut down during IAS testing without sufficient vapor monitoring to alleviate health and safety concerns.

Measurements are taken prior to the pilot test (background measurements) of aqueous phase DO and soil gas $CO_2$ and $O_2$ to determine the presence and extent of microbial degradation occurring naturally in the subsurface. Background biological degradation data is important in the evaluation of the impact of sparging on biological processes. As sparged vapors enter and transport through the unsaturated zone, the potential exists for additional biological degradation (bioventing) to occur. In this case, the apparent biological impacts of sparging in the saturated zone may be more difficult to delineate.

Ideally, if biosparging is the primary objective of an IAS system, background and source area biosparging tests (similar to vadose zone bioventing/respiration tests) may be performed. In these tests dissolved oxygen utilization would be monitored over a several day period following aquifer oxygenation through IAS. It should be noted, however, that some practitioners dispute the utility of these tests because the results are often difficult to interpret.



Start-up of a Pilot Test

Following the collection of background measurements, the pilot test can be initiated. The field engineer generally initiates and carefully increases the delivery/injection of air to the IAS well using an air pressure regulator. IAS well head pressure and flow readings are typically monitored simultaneously to evaluate whether the pressure and flow rates have stabilized. Again, excessive pressures (See section 5: Estimation of Maximum Injection Pressure) should be avoided. In order to capture the sparged vapors, the SVE flow rate should be greater than the IAS flow rate. The IAS/SVE flow ratio is variable but tends to be in excess of 1:2 (Johnson *et al.*, 1993). The IAS/SVE flow ratio may be determined on a site specific basis by demonstrating that the sparge vapors are being contained.

From the API - IAS Database, a pilot test is typically conducted for periods of less than eight hours. The duration of groundwater mounding observed during the pilot study may be used in determining an acceptable test period, as this presents a design time interval for pulsed system operation (based on the potential impacts on groundwater mixing). The mounding period is typically one to four hours in uniform, coarse grained soils. Finer grained or more complex soils may require significantly longer periods for groundwater mounding to return to static conditions. If time allows, step tests (alternate injection flow rate tests) may be performed to obtain additional well performance data.

Pilot Test Data Collection

In addition to the previously suggested pilot test parameter measurements at the test well network, changes in the conditions in existing site groundwater monitoring wells are typically monitored. Visual observations such as mounding or bubbling at the groundwater monitoring wells should be noted. Each of the test parameters are generally measured as frequently as practically possible over the duration of the test. Because the typical test duration is less than eight hours, priority should be given to the test parameters most likely to be representative of IAS feasibility and for full scale system design. The following sub-section on Radius of Influence Determination provides a discussion on typical tests parameters utilized and their limitations.

In uniform sands, representative data can be obtained from monitoring a single sparging test well. As such, the data should provide a suitable basis for a full scale system design. However, data obtained at a site with finer grained soils (silts and clays) or from stratified soils is less likely to be representative of the entire site; results from a single sparging test well may reflect biased performance as a result of local geologic/permeability heterogeneities (stratifications, or preferential air flow channels). In these situations, the test well network may include more than one sparging well.

## PILOT TEST DATA INTERPRETATION AND REPORTING

### Radius of Influence Determination

Presently, no technique exists to theoretically predict the radius of influence (ROI) resulting from IAS. Therefore, a field evaluation (pilot test) is necessary to determine the effective sparging well radius of influence. However, no standard method exists to deduce the ROI from field data. For the purposes of this document, ROI will be defined as: the distance from an air sparging well that defines a volume where air flow can be detected or the affects of air contact, groundwater mixing or groundwater oxygenation are detectable and consistent. This distance must be defined and described by one or more measurement parameters.

> ***Further, it should be noted, that while the term "radius of influence" is used throughout the document, the current understanding of the movement of air in the saturated zone suggests that radially symmetric air flow is unlikely in IAS system operation.***

Generally, numerous variables are monitored in the course of a pilot test. From an analysis of the API - IAS Database only selected monitoring parameters were cited as the definitive factors that were used to determine the IAS radius of influence. Figure 4-3, developed from the database, indicates the frequency of use of various monitoring parameters for determining the IAS radius of influence. It should be noted that multiple factors were often cited as determining the ROI at a given site.

Electrical resistivity tomography (ERT) is an experimental technique used at one research site to investigate the distribution of air as a result of *in situ* air sparging (Schima *et al.*, 1994). The use of ERT yields a multidimensional image of air distribution on a macro-scale basis. A comparison of the region of air flow defined by ERT with conventional monitoring data indicates that the region of air flow may be overestimated with the conventional data in many cases (Lundegard, 1994). It appears that ERT requires considerable instrumentation and data analysis and therefore it should be viewed primarily as a research tool at this time.

A comparison of vadose zone pressures in a combination IAS/SVE system while cycling the IAS system on and off has been used in the determination of the IAS ROI. The application of SVE at a site results in a negative pressure distribution within the vadose zone. When an IAS system is activated, air exiting the saturated zone can lead to a decrease in the magnitude of the negative pressures in the vadose zone. This influence is revealed by a comparison of plots of measured vadose zone pressures vs. distance from the sparging well before and after system activation.

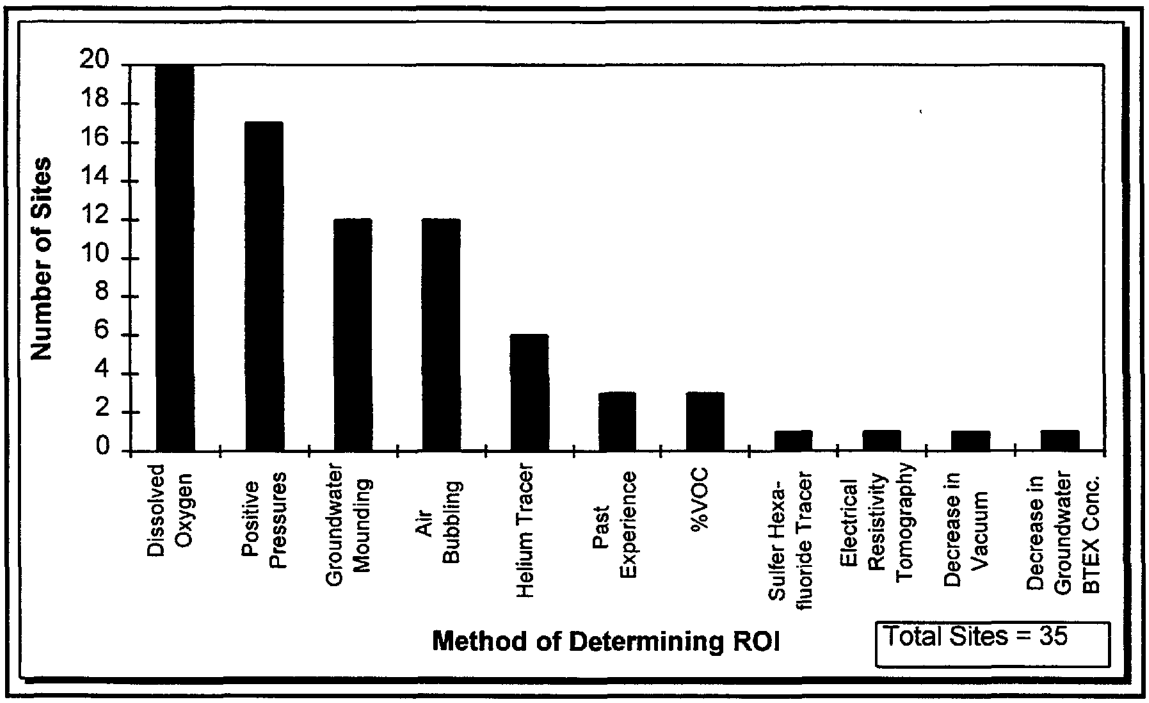
***However, due to the propagation of pressure from an air source, the potential for recording a false positive with respect to ROI is possible.***

That is, a measured change in vacuum pressure at any vadose zone monitoring point may be as a result of the propagation of a pressure wave and not necessarily as a result of sparge air emanating from the water table in the vicinity of the monitoring point. With the limited number of vadose zone monitoring points commonly available in a pilot test, the ability to determine the ROI from vacuum change data is limited.

The composition of gases within the air space of groundwater monitoring wells or in vapor monitoring probes can be indicative of IAS affects. VOCs that have been mobilized by IAS from beneath a water table can be detected within the vadose zone using a variety of portable instruments (combustible vapor sniffers, LEL meters, and gas chromatographs with flame ionization detectors {FIDs} or photo ionization detectors {PIDs}). Under this condition the VOCs behave as a tracer gas indicating the local presence of the sparged air emanating from the water table.

Concentrations of VOCs within a relatively clean vadose zone will generally increase when IAS activities are successful in stripping VOCs from the groundwater. Elevated $CO_2$ levels and depleted $O_2$ levels measured in the vadose zone are often reflective of biological degradation of hydrocarbon constituents. These trends can generally be observed during short term pilot testing. Therefore, as indicated in the API - IAS Database, monitoring of soil gas composition can in some cases be used to determine the radius of influence of an IAS system. It should be noted that $CO_2$ levels in background soils can be high, therefore, elevated $CO_2$ readings should be used with care.

Figure 4-3. Method Used to Determine *In situ* Air Sparging Radius of Influence vs. Number of Sites



A few limitations exist in using VOC concentration changes in the soil gas with respect to ROI determination:

- If VOC concentrations are measured only at the SVE system discharge, the data developed will indicate the potential positive impacts of IAS but will not provide information on the ROI. Measurements at discrete vadose zone monitoring points are also needed.
- Changes in VOC concentrations at the vadose zone monitoring points can result, due to contact of sparged air with vadose zone contaminated soils. While this may be an overall benefit to site remediation, it may not be indicative of effective sparging of the saturated zone. Conversely, if the vadose zone VOC level is relatively high, then the effect of VOC removed from the saturated zone by IAS may be masked by the background conditions.
- If IAS testing is performed in conjunction with SVE, then the movement of vadose zone soil gas in response to SVE should be taken into account with respect to ROI determination. This is particularly pertinent in the vicinity of the SVE well.

***The use of helium or sulfur hexafluoride ($SF_6$) as tracer gases has been shown to be an effective method to determine IAS ROI (API - IAS Database).***

The tracer test consists of injecting helium or $SF_6$ in air into the pressurized line going to the sparging well. Tracer gas content is then measured at monitoring points surrounding the IAS well. Monitoring of the tracer gas in the probes is typically performed while the SVE system is off; the advective subsurface air movement caused by the SVE system may make spacial characterization of the tracer gas difficult. This is especially true where the tracer is injected continuously, as opposed to injection as a slug.

***Under continuous injection conditions, tracers will disperse throughout the vadoze zone making ROI determination less definitive.***

An advantage of using a tracer such as helium is that it is light and inert, has a relatively low aqueous solubility and it is present at relatively low background concentrations. Also, helium can be detected at low concentrations with an easily operated, hand-held thermal conductivity detector (TCD). Characterization of background VOCs and methane which might mask or interfere with the operation of a TCD should be considered. Hand-held TCDs do not typically operate by continuously sampling and analysis of a sample; the TCD typically operates by analysis of a discrete gas sample (batch-mode). As such, the sampling and analysis of soil gas samples collected from more than one vadose zone monitoring point will need to be planned carefully.

***Air bubbling observed in monitoring wells in a pilot test is a key indicator of air movement in the saturated zone.***

As with tracer gases, bubbling is a direct sign of the presence of air channels. However, as the monitoring well is generally screened over a long interval and presents a preferred vertical pathway for air movement, care must be taken in data interpretation. It will be generally unclear whether it is one or a number of channels that are intersecting the well screen interval. Further, without the preferred vertical pathway provided by the monitoring well, the air channel would likely continue its lateral migration until a natural preferred vertical pathway was intersected. Bubbling has on occasion been observed at locations far beyond the effective ROI (as determined by other test parameters).

***Bubbling that occurs outside of what appears to be the effective ROI based on other measurement parameters should be considered a concern with respect to system design, in particular with respect to the uncontrolled migration of potentially hazardous vapors.***

Groundwater mounding (a.k.a. upwelling) is often used to determine IAS-ROI because it is easily measured. While mounding is indicative of bulk water displacement, its use as a ROI monitoring parameter may result in overestimates of the ROI. Dependent on the soil conductivity and quantity of water displaced, mounding may spread laterally beyond the ROI. If upwelling is measured, periodic measurements should be taken in multiple monitoring wells to evaluate upwelling effects over time. Plotting a graph, upwelling effects over time can provide information that may be used in evaluating the desired time interval for pulsed operation of a full scale IAS system (again, based on the potential for groundwater mixing associated with the dissipation of the mound). It should be noted that concerns have been raised on the validity of measuring mounding in monitoring points open to the atmosphere. It is thought that the mounding may be exaggerated by the open well conditions (Johnson *et al.*, 1993). Again, care must be taken to separate out the effects of the vacuum generated by a SVE system on groundwater mounding.

Measurements of positive pressure distributions in the saturated zone have been suggested as a means to determine ROI. The measurements are reported to directly represent the forced displacement of pore water. Changes in subsurface pressures resulting from IAS systems appear to vary exponentially with distance. The radius of influence of the IAS system has been defined as the location where an increase in the water column of 0.1 inches or more can be observed. However, as with the concerns discussed earlier on the use of vacuum difference in the vadose zone, the presence of pressure changes in the saturated zone is not necessarily dependent on the local presence of air channels but rather pressure propagation from an injection source.
Often groundwater dissolved oxygen (DO) content will be depleted in the vicinity of hydrocarbon spills due to the proliferation of aerobic hydrocarbon utilizing bacteria. DO levels as low as 0.2 ppm are often observed in such areas. IAS can directly impact the DO levels of water in contact with the IAS air channels or by transfer within the saturated zone due to the mixing associated with IAS system start-up and shut-down. Following several hours of sparging, groundwater DO levels are often observed to increase significantly at one or a number of monitoring points (Marley *et al.*, 1993a; API - IAS Database). Combined IAS/SVE may also

influence DO levels as a result of air transport occurring within the unsaturated zone which may contribute to elevated DO levels via equilibrium between the aqueous and air phases.

> ***Regardless of the transport mechanism, the API - IAS Database indicates that increases in groundwater DO is the most popular method for estimating the ROI of an IAS system.***

One concern with DO as a ROI indicator is that over the typical short term of an IAS pilot test, an observed DO increase may not be indicative of an increase in DO throughout the ROI, but more a representation of a localized DO increase in the vicinity of a preferred air channel. Appropriate groundwater sampling procedures, which typically involve surface monitoring techniques, should help to determine the extent of the aquifer DO change. Consideration should also be given to the potential for attaining a false negative with respect to the availability of DO. This may occur as a result of DO uptake for abiotic processes (e.g., oxidation of iron or manganese in reduced state due to anoxic groundwater conditions). In addition, alternate biological demands (natural organics degradation) could be a sink for the injected oxygen. Running IAS tests over a period of a few days should minimize the potential for a measured false negative. Obviously, DO increases associated with IAS are a critical factor in the design of biosparging systems.

The distribution of ROI values obtained from both pilot-scale and full-scale system operations was developed from the API - IAS Database. The results are presented in Figure 4-4. At a limited number of sites ROI values greater than 40 feet were reported; however, the test method and data collected at these sites were considered to be of questionable reliability. It is clear that in general, the ROI has been determined to be between 10 and 25 feet.

In the API - IAS Database analysis, a number of parameters were graphically analyzed to determine the impact, if any, on the ROI. Several of the graphical analyses are presented in the Appendix. The parameters investigated included: depth of IAS well screen below grade; depth of IAS well screen below the water table; soil hydraulic conductivity; IAS flow rate; IAS well pressure and IAS well over-pressure. Over-pressure is defined as the pressure in excess of that required to overcome the hydrostatic head. No distinguishable relationship was observed between ROI and the aforementioned parameters. At several sites when IAS system pressures and flows were doubled, only slight increases in ROI resulted. Numerical models and field observations at a flooded site reveal that increased system pressures and flows will generally not significantly increase the ROI (Marley *et al.,* 1992b, 1994). At the flooded site it was observed that a denser distribution of air filled channels occurred within the ROI. However, other numerical multiphase flow modeling of IAS under homogenous conditions suggested that increased injection pressure would lead to an increased region of air flow (Lundegard and Anderson, 1993).

Figure 4-4. Reported *In situ* Air Sparging Radius of Influence vs. Number of Sites

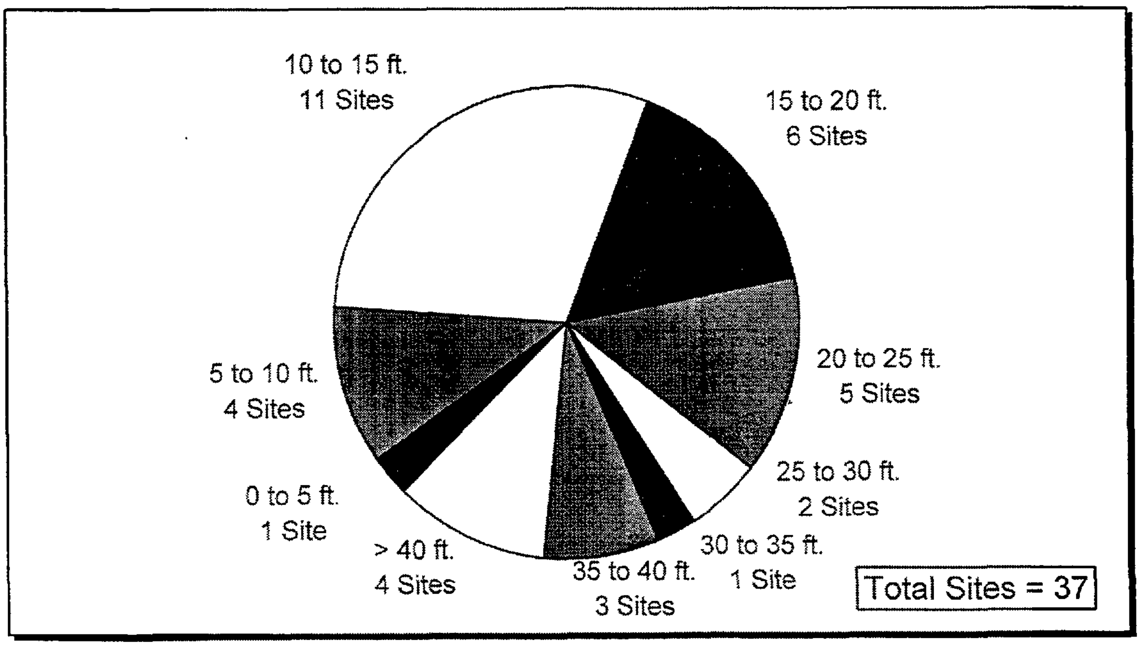
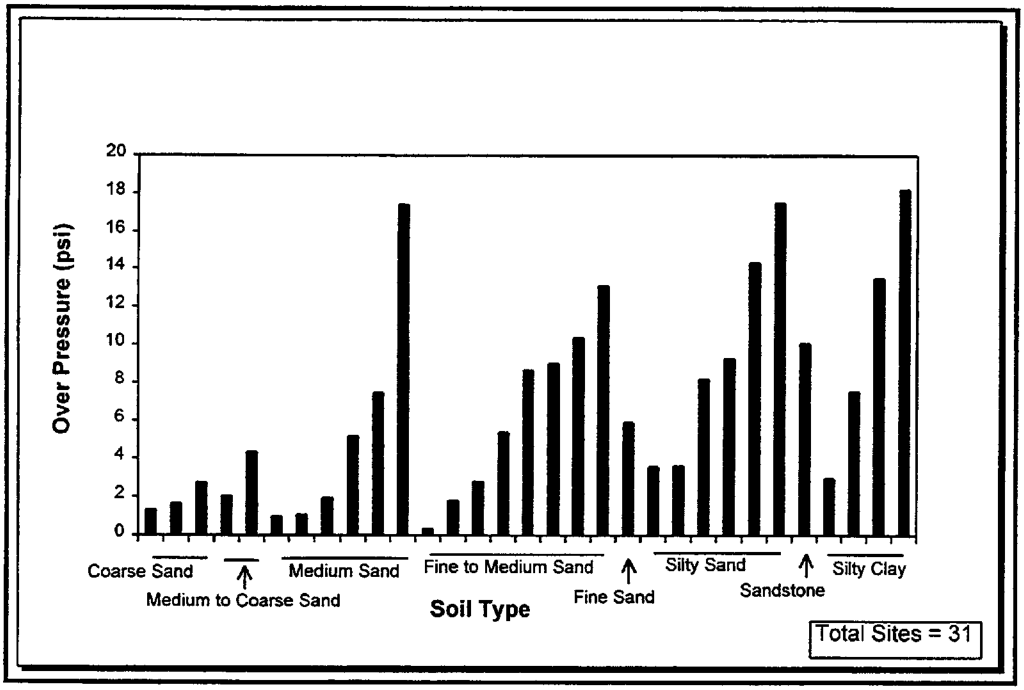



Figure 4-5 shows the relationship between over-pressure applied and soil type. Generally, when finer, tighter soils were present, as expected, larger values of over-pressures were applied. In the field, the selection of operating over-pressure must be done with great care. Excessive over-pressures may result in soil fracturing.

Figure 4-5. Soil Type vs. Over-Pressure




The unusually low over-pressure observed in tight soils at some sites may be as a result of soil fracturing. A graphical analysis of over-pressure vs. air injection flow rate revealed no correlations.

In summary, there are a number of parameters that have been measured in the field to determine the IAS ROI. Each method has potential shortcomings. The most potentially reliable methodologies appear to be the appropriate use of tracer gases or DO. However, these methods also have potential shortcomings. In essence, additional research needs to be done and additional experience needs to be gained in order for the ROI of an IAS system to be more definitively determined.

<u>Pilot Test Reporting</u>

The results of a pilot test should be presented clearly in report format. The following sections are generally included in a pilot test report (additional state specific regulatory requirements may exist):

*Discussion*

- Objectives of the testing and the regulatory criteria by which the project is managed.

- Background information on the site including geologic and hydrogeologic descriptions, historical release data, etc.

- Data from the installation of the IAS well(s), piezometers, vapor probes and SVE well(s). Include geologic observations, field jar headspace results, results of laboratory analyses of split spoon soil samples, results of sieve analyses, and well and piezometer installation specifications (installation depths, screen length, screen size, filter pack and seals, borehole diameter, drilling methods).

- General description of test protocols and equipment used.

- Presentation of physical and chemical measurements obtained prior to, during and after the test. Include results of groundwater level measurements; DO measurements; visual observations; results of VOC, $CH_4$, $CO_2$, tracer gases and $O_2$ analyses, if performed (Graphical presentations are preferred, where applicable).

- Discussion of the air flow rates that were injected and extracted during the test and how SVE discharge concentrations (if appropriate) changed as a function of IAS air injection rates. Also include the ratio of extracted to injected air flow rates utilized.

- If ROI is estimated, discuss how the estimate was determined and provide a discussion of the field data that was used to make the estimate.

- Results of air flow and/or sparging modeling and conclusions derived thereof (if performed/appropriate).

- Statement regarding the feasibility of the application of IAS technology for the remediation of contaminants from the site.

- Full-scale conceptual design (if appropriate). Include well placement and spacing, number of wells, identification of air compressor and qualification of the pressure and air flow requirements of the air compressor, SVE flow rates and vacuums (if appropriate), recommended emission control equipment (if appropriate), estimations of the timetable to achieve the objectives of the remedial project, and any other pertinent details.

*Figures*

- A site plan.

- Geologic cross section(s) with installation detail of the test well network.

- Schematic of the IAS Pilot Test Configuration.

- A detailed site plan of the remediation area (to scale, if possible), including:

  - Locations of previously existing IAS, SVE, groundwater monitoring wells, vapor probes, piezometers and/or recovery wells;

  - suspected and/or known source location(s) (if differing contaminant types are present at a site, identify the contaminant type at each source location),

  - zone of soil contamination;

  - zone of groundwater contamination;
  - direction of groundwater flow across the site;

- locations of existing underground or overhead utilities;
- scale, north arrow, title block, site name, and key or legend; and
- any other pertinent site information.

- A graph indicating the pressure and air flow characteristics of the air sparging well(s) that was tested.

- If groundwater elevation changes (upwelling, depression) are measured in monitoring wells, the designer should include a graph indicating elevation (y-axis) versus time (x-axis) and elevation versus distance from the IAS well. Data from multiple wells can be included in a single graph.

- A water table map showing data prior to, during and after the pilot test.

- A series of iso-concentration map with groundwater DO levels.

*Tables*

- Results of field and/or laboratory analyses performed on soil samples collected from soil borings for the installation of the IAS wells, piezometers, etc.

- Results of pre-test (background) analyses: groundwater level measurements; DO measurements; visual observations; results of VOC, $CH_4$, $CO_2$, and $O_2$ analyses.

- Results of physical and chemical measurements obtained during the performance of the test: groundwater level measurements; DO measurements; visual observations; results of VOC, $CH_4$, $CO_2$, tracer gas and $O_2$ analyses; and IAS wellhead injection pressures and flowrates. Results should include the time each sample/measurement was collected/performed and the total run time of the IAS pilot system.

- Results of post-test analyses: groundwater level measurements; DO measurements; visual observations; results of VOC, $CH_4$, $CO_2$, and $O_2$ analyses.

- Results of laboratory analyses (if appropriate).

*Appendices*

- Boring Logs and well/probe construction specifications.

- Standard Operating Procedures (if appropriate).

- Laboratory reports, if applicable.

- Calculations.

- Raw data tables.

# Section 5

# DETAILED DESIGN AND INSTALLATION OF AN AIR SPARGING SYSTEM

An air sparging system design consists of a number of components, including the IAS well field and well design, the IAS system manifold and associated equipment, and an air source and associated equipment. Each of these design components are described in this section.

## DESIGN OF *IN SITU* AIR SPARGING WELLS

Typical design and operating parameters from the API - IAS Database are presented in Table 5-1. Data in this table is derived from the analysis of 59 sites from the API - IAS Database. Both pilot-scale and full-scale sites were included within the analysis. A discussion of each of these parameters follows.

## WELL FIELD DESIGN

A detailed discussion on estimating IAS-ROI was presented in Section 4. The typical well field design entails coverage of the delineated source area with adjacent wells having a ROI as determined from a pilot test. This approach is sometimes used over the dissolved plume area also.

Other approaches use a line of wells oriented perpendicular to the direction of groundwater flow (sparging curtain). Care must be taken in the design and operation of sparging curtains to ensure that sufficient contact is achieved between the sparging air and the dissolved contaminant to ensure remediation. In addition, due to sparging potentially reducing the local soil conductivity, the potential exists for regional groundwater flow to move *around* as opposed to *through* the sparging curtain. In general if site logistics allow, a sparging trench is likely to provide a better dissolved contaminant plume containment system than a sparging curtain. Economics will generally dictate which is the most appropriate strategy for dissolved contaminant plume treatment. On a site-specific basis, the economics of an IAS system should be compared to other remediation strategies (e.g. pump and treat).

Table 5-1. Typical Design and Operation Parameters for *In situ* Air Sparging Wells

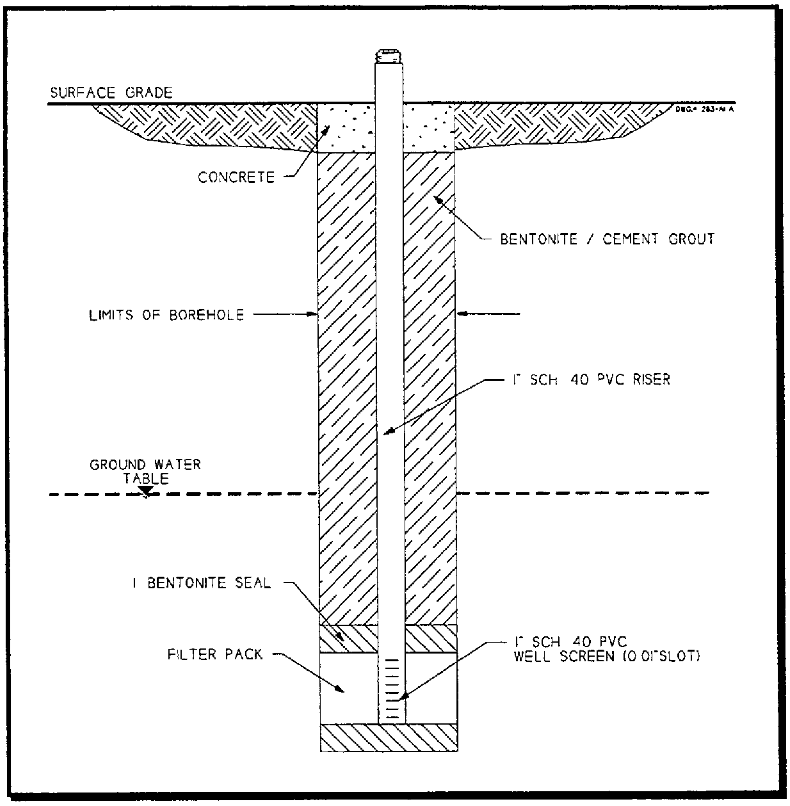
| Parameter and Range | | Most often used value *(No. of sites)* | Second-most often used value *(No. of sites)* | Third-most often used value *(No. of sites)* | Total number of sites | Ranges from Johnson *et al.*, 1993 |
|---|---|---|---|---|---|---|
| Screen length | 0.5 - 10 (feet) | 2 feet *16 sites* | 3 feet *8 sites* | 5 feet *7 sites* | 40 | 2 - 300 feet |
| Well diameter | 1 - 4 (inches) | 2 inch *17 sites* | 4 inch *7 sites* | 1 inch *5 sites* | 37 | 1 - 4 inch |
| Over-pressure | 0.35 - 18.24 (psi) | 0.35 - 5 psi *14 sites* | 5 - 10 psi *9 sites* | 10 - 15 psi *5 sites* | 31 | NA |
| Well screen depth below water table | 2 - 26.5 (feet) | 5 - 10 feet *10 sites* | 10-15 feet *8 sites* | 2 - 5 feet *6 sites* | 31 | 3 - 40 feet |
| In-situ sparging flow-rate | 1.3 - 40 (cfm) | 1.3 - 5 cfm *16 sites* | 5 - 10 cfm *9 sites* | 15 - 20 cfm *5 sites* | 39 | 2 - 270 cfm |
| In-situ sparging pressure | 3.5 - 25 (psi) | 5 - 10 psi *17 sites* | 10 - 15 psi *8 sites* | 20 - 25 psi *6 sites* | 40 | 1 - 8 psi |
| $\frac{\text{SVE ROI}}{\text{IAS ROI}}$ (ratio) | 0.16 - 7.42 (ft/ft) | 1 - 2 *12 sites* | 0.16 - 1 *6 sites* | 3 - 4 *3 sites* | 26 | NA |

During IAS system operation, the lateral distribution of contaminants in the saturated zone may increase due to induced groundwater flow during IAS system start-up or shut-down. Therefore, additional groundwater monitoring wells and air sparging wells may be necessary near the perimeter of the contaminated zone.

# IAS WELL DESIGN/CONSTRUCTION

A diagram of a typical IAS well is shown in Figure 5-1.

Figure 5-1. Typical IAS Well




## Drilling Methods

Hollow stem auger is the most commonly used drilling method for IAS wells. Wells should be two inches in diameter or larger for ease of conventional well development and monitoring equipment installation. However, the use of smaller diameter wells is sometimes advantageous when considering the spacial requirements associated with nesting additional wells and monitoring points in the same borehole.

The presence of running or heaving sands during well installation may require the use of drilling fluids or an excess hydrostatic head within the auger to maintain borehole integrity during installation. An experienced driller should be able to overcome this potential installation problem. Deformities in the soil formation as a result of installation associated problems can result in significant preferential channeling and therefore a reduction in system performance.

In some cases, due to potential installation cost savings, sparging wells can be driven, hydraulically advanced or pushed by CPT. Limited experience indicates that the performance of a driven point is as good as the performance of a drilled well (Droste *et al.,* 1994). Special drive point techniques may be needed in fine grained soils (clays), due to the potential for well screen smearing.

Filter Pack

The average grain size of the filter pack should be as close to the native soils as practical. If the filterpack's average grain size is larger than the native geologic materials, the filter pack may be more permeable than the native soil. While a highly permeable filter pack is an advantage in constructing wells for other uses (monitoring or extraction), a filter pack that has a higher permeability than the surrounding formation will be a conduit for short circuiting of air up through the borehole in the depth interval between the bentonite seal and the top of the well screen (Schima *et al.,*. 1994). If the filter pack is significantly smaller than the native soils, too much restriction to air flow results. Natural filter packs may be used in caving formations provided that the native materials do not have significant levels of fines that could accumulate within the well screens. The filter pack should extend from the base of the well screen to approximately one foot above the screen.

Seals

A bentonite seal is generally placed from approximately one foot above the IAS well screen filter pack to approximately one foot above the seasonally high water table level and hydrated. The annular space above the bentonite seal is then filled with a five percent by weight bentonite/ cement grout mix. A tremie tube is often used for placing the grout when installing a seal below the water table.

Well Screen Slot Size

Well screen slot size should complement the filter pack design. Since air readily passes through well screens, a small slot size usually is sufficient; underestimating the slot size (by a small margin), relative to the filter pack, is usually acceptable. In most cases, a 0.020 inch or 0.010 inch slot size is used. Larger slot sizes may be used to decrease head losses, however the potential for washing fines into the well should be evaluated. Diffusers have been suggested as an alternate to a well screen, however, for most soils, it is recognized that the air bubbles that evolve from the diffusers will quickly coalesce into air channels in the natural formation (Ji *et al.,* 1993).

Well Screen Length and Construction

A relatively short length of screen, such as one to three feet is sufficient as it is likely that the air will emanate from the top of the filter pack. Shorter screen lengths may be used, but are more susceptible to becoming clogged with silts and/or precipitates. The well screen typically is a slotted pipe constructed of PVC or chlorinated PVC (CPVC). Generally, the screen is flush threaded with schedule 40 or 80 pipe. However, the designer should evaluate the need for alternative construction materials if chemical compatibility is of concern or if projected injection pressures or injection temperatures are in excess of manufacturer's specifications (typically 40 psig and 100°F). Frequently, a length of galvanized steel is connected to the compressed air source outlet to dissipate heat prior to connection to a PVC manifold.

For the IAS wells, a bottom plug is commonly utilized. Designers should not use glue below the groundwater table in the construction of the IAS wells as the glue may adversely affect any groundwater samples from the wells. The well casing schedule should be the same as the well screen. "O" rings or other seals are usually installed to limit air leakage from the joints.

The pressure that is needed to inject air into the aquifer is related to the pressure that is required to overcome the static water level to the top of the screen and to overcome the air entry pressure. Wells are generally screened several feet below the delineated vertical extent of contamination. If the top of a well screen in one well on a common manifold header is not as deep beneath the water table as the other wells, then a disproportionate air flow will likely pass through this shallower well. This happens because less pressure is needed to inject air to the top of the screen in that well. Therefore, designers often estimate the depth at which each well will be installed by drawing an accurate water table map, surveying the elevations of proposed air sparging well locations, and calculating the estimated depth of the water table for each well to determine the screened interval placement. Since it is more important to place the well screen below the vertical extent of contamination at any location, discrepancies in air flow due to non-uniform IAS well depths may exist but can be compensated for by balancing the system using individual well throttle valves or regulators.

While limited data are available, the practical minimum depth from the water table to the top of the sparge well filter pack is probably 5 feet. Lesser depths in uniform soils may result in a limited ROI.

IAS Well Head

Designers may wish to connect the well head to the manifold with a tee, which allows a threaded top cap to be attached. This configuration allows access to the well for sampling or measurement of water levels or water quality data.

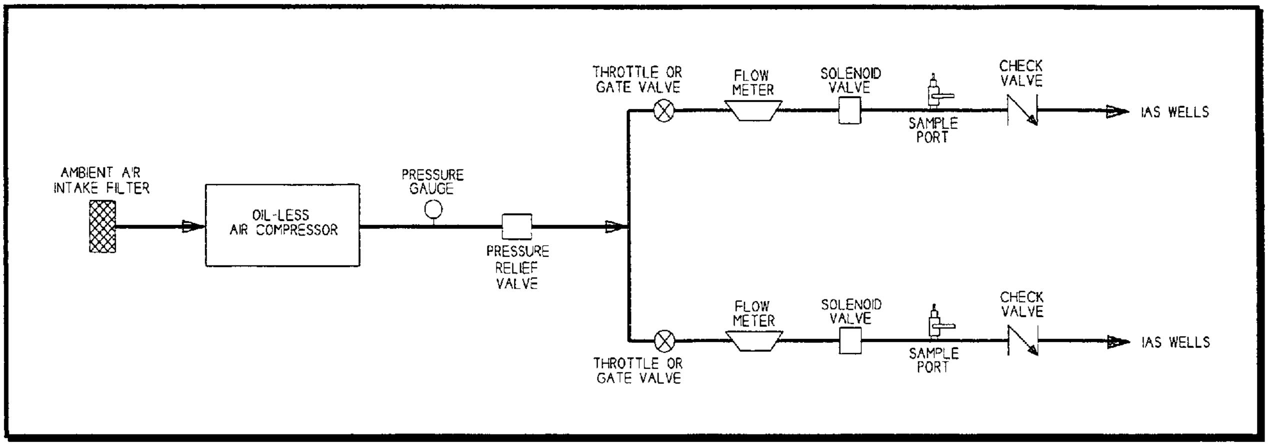
IAS Well Development

Wells are developed to minimize accumulation of fines in the screened section and/or filter pack. The reason for developing air sparging wells prior to operation is that pulse operation of an air sparging well produces an effect essentially the same as the development of a well, without the removal of accumulated fines. The reverse gradient created between pulses is sufficient, in some cases, to cause the migration of fines into the well and the filter pack and cause clogging. Therefore, IAS wells installed in soils which contain significant fines and/or silts are especially susceptible to fines accumulation. Surging and bailing the air sparging wells may be periodically necessary in order to remove accumulated fines. In some cases, fines removal is accomplished by air lifting through a drop tube in the well that is connected to the air supply.

## MANIFOLD, VALVES, AND INSTRUMENTATION

A schematic illustrating a typical manifold construction detail is shown in Figure 5-2.

Figure 5-2. Typical Manifold Construction Details




The construction of an IAS manifold typically includes the following components: check valve, throttle valve, manifold piping or hose, quick-connect couplers and plugs as needed, and sampling port(s) at the wellhead. These components and their construction are explained in more detail below.

<u>Installation and Construction of the IAS Manifold Line</u>

The manifold is typically buried underground below the frost level. If it is within the frost zone, it may need to be protected from frost with insulation and/or heat tape, and flexible connections may be needed to prevent damage from frost heaving. However, if land use and traffic patterns allow, the manifold may be installed above ground. If PVC manifold is installed above ground, the potential for shock load and photo oxidation damage should be considered. Once the main manifold run has been installed in the vicinity of a group of wells, hard piping or a high pressure air hose equipped with couplers and plugs can be used for attachment to the well. If a buried manifold constructed of plastic pipe is used, designers may wish to install a steel wire or some other material that can be detected by a metal detector above the manifold piping.

IAS System Valving

Check valves are used at the well (between each well and the manifold) to prevent temporary high pressure in the screened interval of the aquifer from forcing air and water back into the manifold system after the IAS system is shut down. Throttle valves are generally installed at each well. Gate valves and globe valves are effective throttle valves. The throttle valve allows for the isolation of the well from the system or for adjustments to the well air flow rate.

Due to cost, manifold instrumentation installations are generally constructed for periodic use. Well/manifolds equipped with quick-connect couplers and plugs allow for the temporary placement of flow meters. Sampling ports should be installed for temporary attachment of a pressure gauge and/or temperature gauge to the well, well cap, or manifold near each well.

Pulsed operation of an IAS system may provide more effective remediation due to groundwater mixing and is also expected to result in energy and capital cost savings (smaller pump sizes are required). Automatic motorized or solenoid valves may be used to activate and deactivate wells or well groups. Simple analog or programmable logic control (PLC) timers can be used to actuate the valves based upon a pre-determined time interval for operation of a well(s) or well group(s). The use of automatic valves and timers allows a great deal of control over pulse-mode operation. A permanent pressure gauge, flow meter and temperature gauge installed in the manifold line between the solenoid valves and the air compressor allows measurement of total system pressure, flow and temperature. Designers should follow manufacturer's recommendations for length of unobstructed flow—both upstream and downstream of installed instrumentation.

A manual or automatic pressure relief valve is installed immediately downstream of the air compressor outlet. This valve exhausts excess air from the manifold to either the atmosphere or the compressor air inlet and acts to prevent excessive pressure from damaging the manifold or fracturing the aquifer in the event of a system blockage.

AIR COMPRESSOR SELECTION

The selection of a suitable air compressor is typically based on the results of a pilot test. The results of the pilot study are used to determine the optimal pressure and flow for a well installed within a specific geologic domain. From the API - IAS Database, typical air flow rates and injection over-pressures are 2 to 10 scfm per sparge point at up to 5 psig over-pressure. The pressure capacity and flow rate of the air compressor should be designed based upon the maximum expected pressure and flow for any one or group of wells, and should consider manifold system head losses.

Compression of air can generate a significant amount of heat and noise. As part of the design, the system designer should calculate the air compressor exhaust temperature based on manufacturer's data. Piping and manifold materials must be compatible with compression discharge temperature and pressure. A sensor located at the air compressor exhaust may be used for automatic shutdown if the pressure and/or temperature exceeds design criteria. Dependent on the compressed air source and sensitivity to noise of the adjacent property owners, noise controls may have to be included in the system design. Noise can usually be reduced to acceptable levels through the proper application of standard noise reduction materials in equipment housing areas.

The process of air compression can also cause precipitation of moisture in the air compressor and/or manifold line. In the winter months, precipitation in the manifold can freeze, restricting or blocking the flow from the compressor. Heat tracing can be used to winterize the piping/manifold. A receiver (air tank) with a manual or automatic drain to remove condensate from the receiver is suggested. For larger systems moisture removal equipment may be installed upstream of the air inlet to the compressed air source.

Estimation of Maximum Air Pressure

Excessive air injection pressures may cause equipment failures and/or the creation of secondary permeability in the aquifer.

To estimate the maximum pressure that can safely be used without creating secondary permeability, designers usually assume that the pressure must not exceed the weight of the soil column above the IAS well screen. For example, assume:

- a soil particle density of 2.7;
- water table depth at 18 feet;
- sparging system screened interval from 30 to 35 feet,
- porosity of 30 percent or 0.3, and
- soils are unconsolidated.

To estimate the overlying pressure exerted by the weight of the soil column:
Weight of soil = 30 ft * 2.7 * (1-0.3) * 62.4 lbs/ft$^3$ = 3,538 lbs/ft$^2$
Weight of water = (30-18) ft * 0.3 * 62.4 lbs/ft$^3$ = 224 lbs/ft$^2$
Total = 3,538 + 224 = 3,762 lbs/ft$^2$ = 26 psig at 30 feet of depth (the top of screen).

In this case, injection pressures higher than 26 psi could cause secondary permeability channels to develop. To provide a design factor of safety, a rule of thumb utilized by some designers for the maximum allowable injection pressure is 60% to 80% of the overlying pressure (i.e. 0.6 x 26 psig - 0.8 x 26 psig). This example is based on simplistic assumptions and designers should evaluate additional geotechnical information if it is available.

Air Compressors

System designers should only use air compressors that are rated for continuous duty. Common air compressor types are as follows:

- *Reciprocating air compressors* are used when high pressure is required and a low flow rate is acceptable. Only oil-less air compressors are generally utilized because of the potential to inject oils into the aquifer if a seal (piston ring) fails. Since these air compressors may produce sufficient pressure to burst PVC and CPVC pipe and fittings, an automatic pressure relief valve is usually installed on the air compressor outlet.

- *Rotary lobe blowers* are positive pressure blowers capable of pressurizing air up to 15 psig. Blowers may have an oil-filled gear case, but may not use any other lubricants or fluids that could enter the air stream and reach the groundwater.

- *Regenerative blowers or rotary vane pumps* are relatively simple and have low maintenance requirements relative to other blower types. Because of their low pressure capability, (up to 10 psig) these blowers/pumps can only be used at sites that can be operated under conditions of low pressure injection. A multi-stage blower may be used for higher pressure requirements.

- Designers may use other compressor types, such as a *rotary screw compressor*. If designers use an alternative compressor that could inject oil, a filter is used to remove the oil. An air filter is installed to prevent particulate matter from damaging the air compressor. A silencer on the air inlet may also be required. The air inlet should be installed in a contaminant-free environment. The air inlet should be located outside of the building if the air compressor is installed inside a building that may have airborne contaminants—such as a service garage. If the air inlet is located near the stack of a soil venting system, a minimum of ten feet of vertical separation is usually warranted.

Liquid ring vacuum pumps/blowers may also be used as air compressors. However, liquid ring pumps require a supply of water (water/metal as opposed to metal/metal contact provides the seal for the air compression) and some practitioners have found these type pumps to require a relatively high level of maintenance.

# Section 6

# OPERATION, MONITORING AND PERFORMANCE OF IAS SYSTEMS

## OVERVIEW

Operation of an air sparging system requires ongoing monitoring and system adjustment for optimal system performance. The following section briefly presents the basic operation of IAS systems. IAS systems monitoring and performance data developed from the API - IAS Database are also presented.

## IAS SYSTEM START-UP OPERATIONS

It is useful to develop a brief workplan on the IAS system start-up. The workplan typically defines typically the objectives of the IAS system and the proposed strategy and procedures for start-up.

### Baseline Measurements

Prior to startup of a full scale IAS system, baseline measurements should be collected from monitoring locations at the site. Details on the following measurement parameters are presented in Section 4:

- groundwater levels;
- SVE discharge VOC concentrations;
- Water quality measurements (e.g., DO concentrations);
- SVE parameters, including total SVE system flow rate, and vacuum distribution; and
- Soil gas VOC, $O_2$ and $CO_2$ concentrations.

### Start-up

Establishment of baseline conditions will facilitate interpretation of changing conditions after IAS startup. In the remainder of this section, it is assumed that pulsed sparging will be the chosen mode of operation and that one or more groups of wells will be run off separate manifold lines.

If any chemical adhesives were used in constructing the system, purge the volatiles from the manifold system by opening IAS wellheads and injecting air into the manifold lines. Run the air compressor for a minimum of 10 minutes up to two hours. Use an OVA to determine when the lines have been purged. Following purging of the manifold lines (if appropriate):

- Turn on the air source, regulate from a lower pressure to the necessary pressure to attain the design air flow rate for the chosen well group. DO NOT EXCEED THE MAXIMUM RECOMMENDED AIR PRESSURE.
- Balance the flow to each well, since each well may behave differently.
- Develop a flow vs. pressure (F/P) curve for each well. The generated F/P curve allows determination of well flow rate based upon wellhead pressure measurements. This approach reduces the effort required during routine site measurements.
- Verify the air compressor and manifold line pressure and total injection flow rate, following the balancing of the wells. Any design deficiencies will be apparent at this time. A quick check to determine an agreement between total air compressor flow and the cumulative flow as measured at each of the wells is useful.
- Sample the SVE system inlet and exhaust streams and analyze over the startup period.
- Check for bubbling in piezometers at the site. If bubbling is observed, operators should install air-tight caps on these wells. If these wells are uncapped, fugitive VOC emissions can result.
- Record periodic groundwater table measurements to document the site-specific impacts, of operating the IAS well group, on the groundwater mounding/mixing.
- IF ANY POSITIVE SUBSURFACE AIR PRESSURE READINGS AND/OR HIGH LEVELS OF VAPOR PHASE CONTAMINANTS ARE MEASURED IN VADOSE ZONE MONITORING POINTS ADJACENT TO BUILDINGS OR OTHER STRUCTURES THAT MAY ACCUMULATE POTENTIALLY HAZARDOUS VAPORS, SYSTEM OPERATORS SHOULD IMMEDIATELY RE-EVALUATE THE OPERATIONAL PARAMETERS OF THE SPARGING SYSTEM. DISCONTINUE OPERATION OF THE AIR SPARGING SYSTEM IF CONDITIONS ARE DEEMED UNSAFE.
- Repeat the previous steps for each of the IAS well groups.

As-Built Submittal

After completing a successful IAS system start-up, as-built drawings and records are typically developed. The as-built submittal may include the following information:

- Results of start-up testing to document and verify start-up conditions and assumptions.
- Deviations from specifications as presented in the design report.
- Map of actual well locations drawn to scale, including:
  - Location of existing sparging wells;
  - Location of the manifold, instrumentation, and sample ports;
  - Location of air compressor and other equipment;
  - Suspected and/or known source location(s) (if differing contaminant types are present at a site, identify the contaminant type at each location);
  - Zone of soil contamination;
  - Zone of groundwater contamination; and
  - Other pertinent site information.
- Table of air sparging well screen depths and static water levels prior to start-up.
- Well construction diagrams.
- Boring logs.
- Other pertinent information.

MONITORING OF IAS SYSTEMS

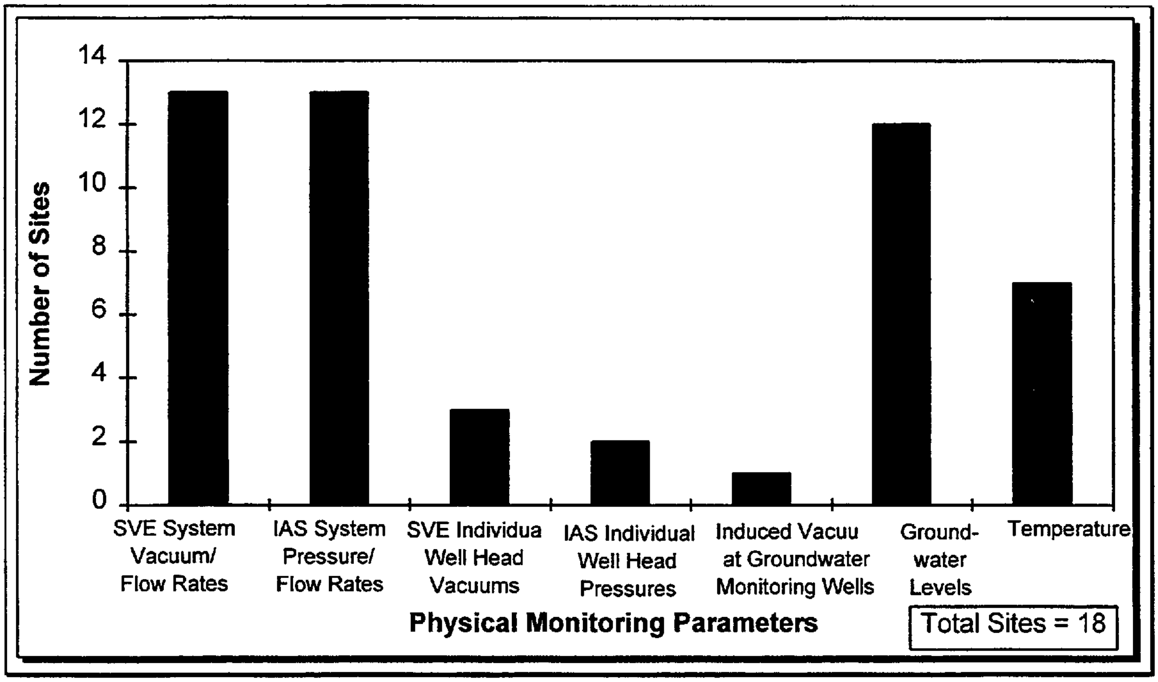
Over the first few months of operation, it is necessary to monitor the performance of the IAS system to optimize the system and to ensure uncontrolled migration of VOCs, in any phase, is not occurring. Optimization of the system is most important over the first several months of operation as the remediation of VOCs from saturated soils should essentially proceed in the same inverse logarithmic manner which characterizes SVE performance. Additionally, it will be important to detect, qualify and if necessary, correct flaws in the system which may have arisen due to unforeseen environmental factors, limited historical/background information, etc.

Detailed discussions on many of the monitoring techniques used in determining the IAS well Radius of Influence (ROI) from pilot test data are presented in Section 4. A description of the typical monitoring activities performed at full-scale IAS sites, as determined from the API - IAS Database, is presented in the following sections.

Physical Monitoring Parameters at Full-Scale Sites

Physical monitoring parameters employed at full-scale IAS sites in the API - IAS Database and their frequency of use are presented in Figure 6-1. Measurements of both IAS and SVE system and individual well pressures and flows are necessary to balance the system and to optimize system operation. Measurements of groundwater levels should be monitored to insure that SVE well screens are not submerged and that the regional groundwater flow is not being negatively impacted by the IAS system operation.

Figure 6-1. Physical Monitoring Parameters At Full-Scale Sites

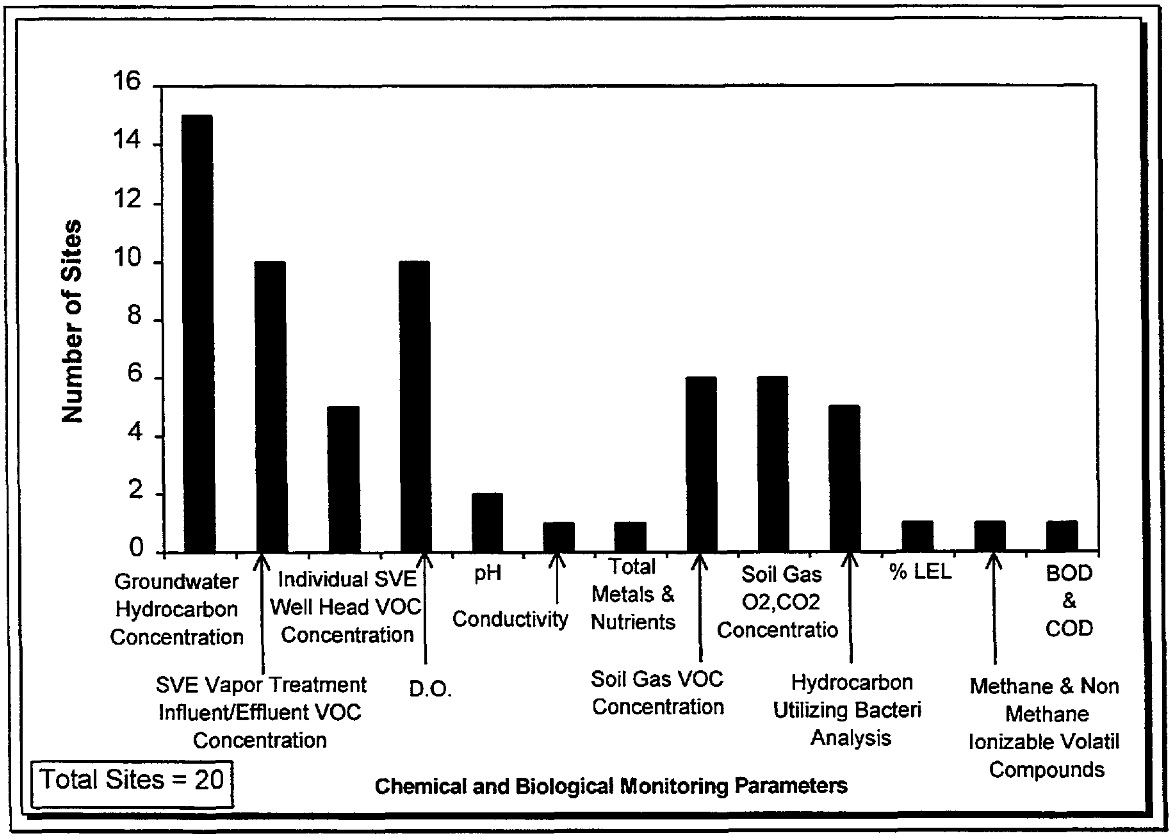



Chemical and Biological Monitoring Parameters At Sites with Fully Operational IAS Systems

The frequency of use of various chemical and biological monitoring parameters is shown in Figure 6-2. Sustained groundwater quality changes are one of the few definitive indicators of the effectiveness of IAS systems. The required extent of monitoring of hydrocarbon content in groundwaters is highly dependent upon local regulatory requirements. Typically, quarterly monitoring is required. More frequent (bi-monthly) sampling is beneficial for select wells over the first 6 months of IAS system operation. The frequent initial sampling will provide data that will better assist in the system optimization. Groundwater sampling should be conducted following an IAS system shut-down and in a manner to obtain a representative aquifer sample.

BTEX is the most popular measure of water quality at all sites that reported groundwater hydrocarbon content. Additional types of hydrocarbon analyses or specific hydrocarbon constituents analyzed for are total petroleum hydrocarbons (TPH) or methyl-tertiary-butyl ether (MTBE). Groundwater monitoring is often timed to coincide with activities on site, or at seasonal high and low groundwater levels.

Figure 6-2. Chemical and Biological Monitoring Parameters at Full-Scale Sites



Qualitative and quantitative monitoring of SVE system effluent-gas is often used to provide a real-time indication of system performance. Monitoring of the individual SVE well-head discharges and the total system stack-effluent provide another definitive measure of the impact of the IAS system on the overall site remediation.

Extensive chemical analysis of nutrients and metals were conducted at one full-scale demonstration project. No discernible trends resulting from operation of the IAS system were observed.

Total Plate Count (TPC) is a non-specific microbial analysis to track numbers of bacteria as an indicator of relative biological activity in groundwater. Generally, bacterial numbers initially increase in response to the elevated dissolved oxygen resulting from IAS and subsequently decrease as the hydrocarbon supply (food source) is exhausted from the system.

Measurements of groundwater pH may exhibit a decrease with time while IAS is in progress. This is due to the increased microbial activity which can produce carbon dioxide that may be converted to carbonic acid.

## PERFORMANCE OF IAS SYSTEMS

In comparison to SVE technology, the determination of IAS system performance in the short term is more qualitative. Generally, definitive quantitative measurements of IAS system performance presently require longer term (months) monitoring. However, one good indication of IAS system effectiveness that does not require long term monitoring is the pre- and post-remediation analysis of soil samples collected from contaminated areas of the site.

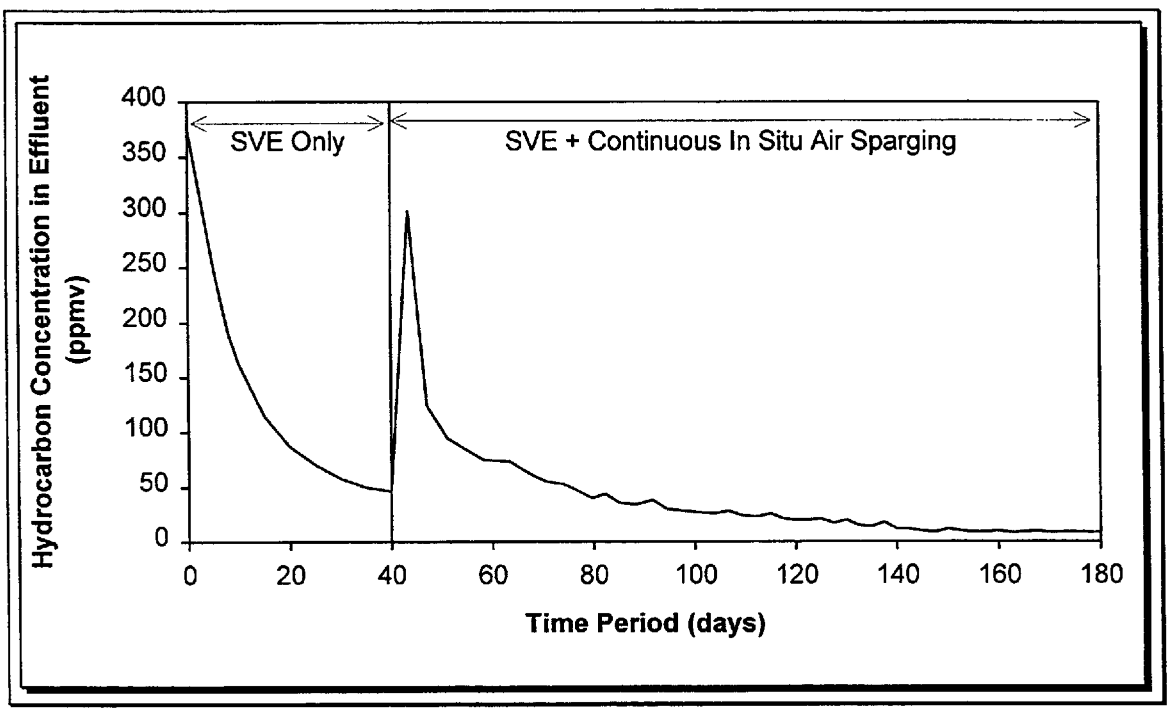
### Pulsed vs. Continuous IAS System Operation

When remediating sites, SVE is often operated prior to and then in conjunction with the IAS system operation. The SVE system is designed to remove any residual or mobile NAPL above the water table level. IAS activities are normally initiated after any mobile NAPL has been removed from the site soils.

Figure 6-3 shows an idealized system response to remediation by SVE followed by a combination of SVE and continuous IAS, as measured by the hydrocarbon content (i.e., VOC) in the SVE stack effluent. Over the period of only SVE operation, the hydrocarbon content declines rapidly towards an asymptotic level. The asymptotic level reached is generally a result of the removal of VOCs that partition from the contaminated groundwater and that diffuse from contaminated soils not directly contacted by the SVE air flow.

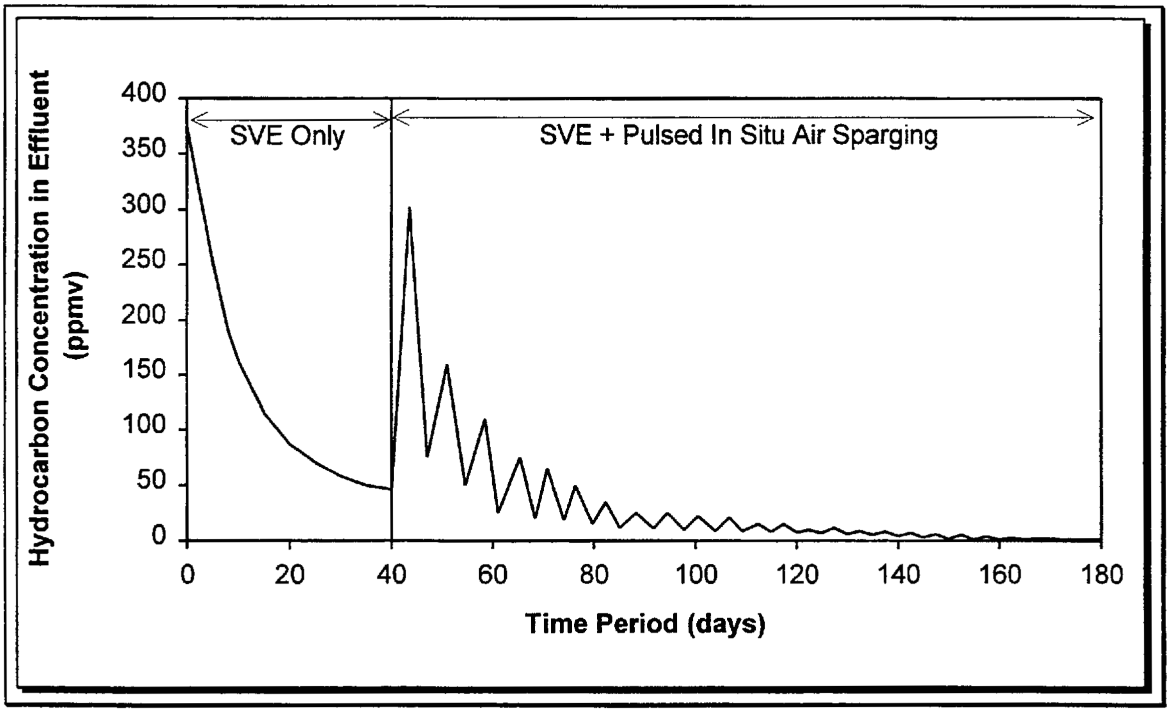
When the IAS system is started, a rapid increase in stack VOC levels is observed. VOCs trapped beneath the water table are being mobilized by the migrating air. The rapid increase in VOCs in the SVE discharge is followed by a gradual decrease in VOC levels with time. When the IAS system is in operation, the VOC levels in the SVE discharge can generally be related to groundwater VOC content. However, with a effectively operating IAS system, the rate of decline of groundwater VOC levels using combined IAS-SVE is much faster than that expected when using SVE alone.

Figure 6-3. Idealized SVE Discharge Plot Resulting From *In situ* Air Sparging Continuous Operation



Cycling an IAS system on and off for periods of time ranging from several hours to several days is known as "pulsed" operation. An idealized system response to remediation by SVE followed by a combination of SVE and pulsed IAS is shown in Figure 6-4. Pulsed operation typically results in a "saw tooth" type of response. Pulsed IAS system operation may result in a faster rate of removal of aquifer hydrocarbons than continuous IAS operation. However, there are presently no well documented data available to demonstrate the increase, if any, in hydrocarbon removal rates through pulsed IAS system operation. Pulsed operation is expected to provide project cost savings due to the requirements for smaller air compressor equipment and the related reduced energy usage (Marley *et al.,* 1993a).

Figure 6-4. Idealized SVE Discharge Plot Resulting From *In situ* Air Sparging with Pulsed Operation




When air sparging is initiated, injected air establishes selected preferential pathways within the aquifer. During continuous IAS operation, hydrocarbon removal occurs first in the immediate vicinity of the preferential pathways. Subsequent hydrocarbon removal will occur as a result of transport by diffusion and through natural groundwater advection to these preferential pathways.

As previously discussed, the groundwater mixing associated with IAS system start up and shut down is expected to enhance the mass transfer of VOCs from the groundwater and the mass transfer of oxygen into the soil matrix to promote biodegradation.

BTEX Removal at Full-Scale Sites

The long term water quality data available from full scale sites within the API - IAS Database was reviewed with respect to IAS system effectiveness. Most of the available sites had only limited long term water quality data. At full-scale sites where long term groundwater quality data is available, remediation technologies such as groundwater pump and treat or SVE were often in operation prior to IAS system operation. IAS was added to the overall remediation system to control migrating plumes or to remove hydrocarbons from selected hydrocarbon contaminated zones. Therefore, with the limited data available, it is difficult to determine what portion of the remediation can be attributed to IAS.

As previously stated, one of the few definitive measurements of IAS system effectiveness is long-term monitoring of the groundwater quality at the site, following IAS system shutdown. In the course of a site remediation, groundwater BTEX levels will generally decrease with time. However, in some cases, temporary increases in BTEX concentrations can be observed as a result of contaminated groundwater movement caused by IAS/SVE activities or seasonally elevated groundwater tables.

A comparison of total BTEX removals at three separate IAS sites from the API - IAS Database is shown in Figure 6-5.

At site A, initial total BTEX levels were relatively low and IAS was used to transport hydrocarbon contaminants from beneath the water table into the vadose zone where biodegradation occurred. Since BTEX was not volatilized to the atmosphere, a SVE system was not used. Following the shut-down of the IAS, total BTEX levels continued to drop probably as a result of continued biodegradation in the groundwater. However, no long term data was available for this site to indicate if any rebound in the water quality data occurred.

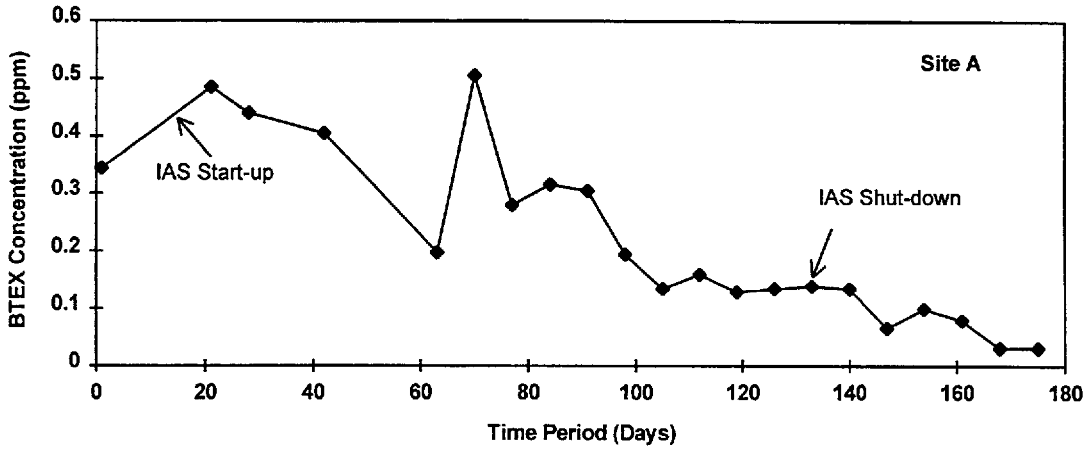
Site B had a sandy soil with gasoline contamination above and below the water table. Historic groundwater sampling indicated that substantial BTEX levels had been observed at the site for an extended period of time. Following the start-up of IAS/SVE, reductions in total BTEX were observed at all monitoring locations, especially MW-B. The peak concentration observed in MW-B prior to IAS/SVE system start-up and the two subsequent peak concentrations observed at approximately 1060 days, 1430 days, and 1790 days, respectively, all coincided with the annual high groundwater elevations observed at the site.

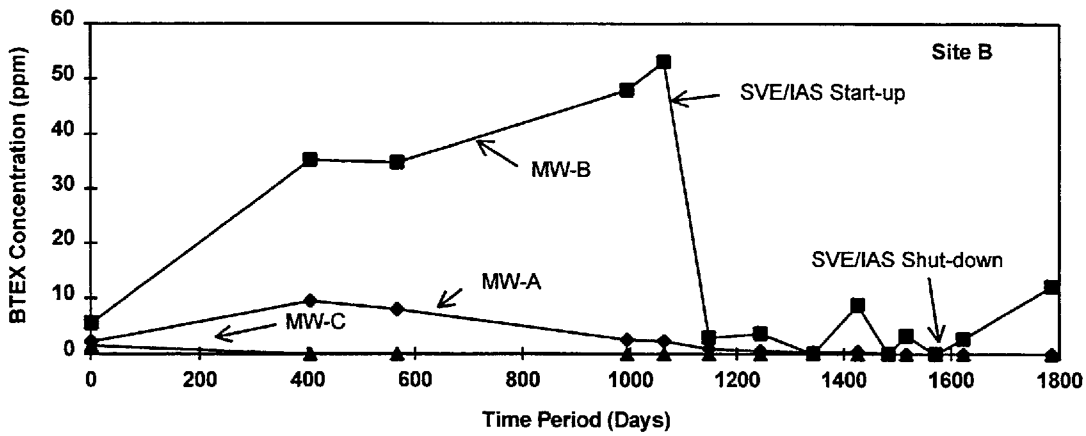
Following system shut-down, MW-A and MW-C continued to exhibit total BTEX concentrations below 40 ppb, while MW-B exhibited some rebound. It is speculated but not proven that the rebound observed in MW-B was a result of a continuous isolated source area. Again, longer term data was not available to further define the groundwater quality trends.

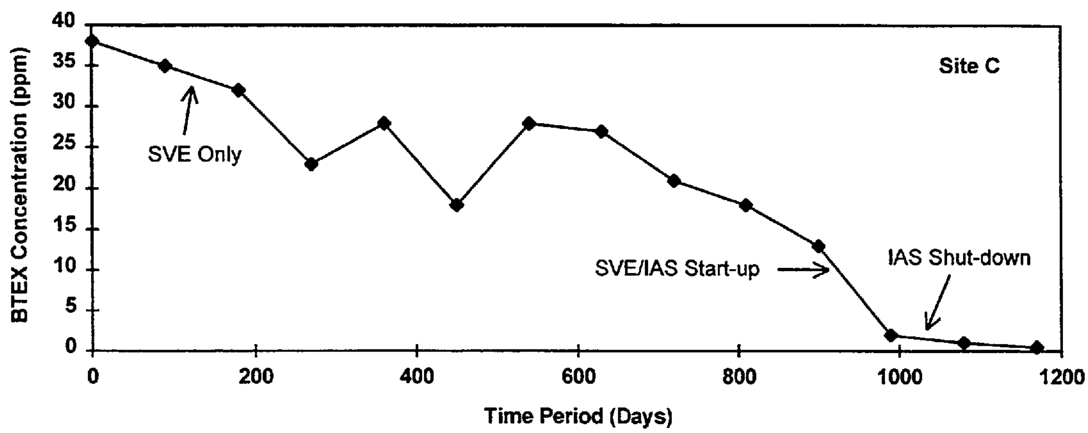
Site C had initially used a mobile NAPL recovery system, a groundwater pump and treatment system, and an SVE system for several years prior to installing a IAS/SVE system. Before using IAS/SVE, the rate of total BTEX removal was low. This was likely the result of gasoline contamination that was trapped below the water table in the relatively uniform coarse to fine sands. After 60 days of IAS/SVE operation, the system achieved the site-specific closure criteria. The site was monitored for a year following IAS system shutdown. BTEX levels reduced to and remained below the site closure criteria, likely due to a combination of dilution and biodegradation.

The lack of long term groundwater monitoring data at full-scale IAS sites is a significant limitation to a full understanding of the effectiveness of IAS technology. At most sites, extensive sampling was not conducted throughout the course of IAS. Often, no intermediate samples exist, making it difficult to determine the exact rate of hydrocarbon removal. However, to determine the approximate rate of hydrocarbon removal, groundwater total BTEX concentrations measured at the start and end of an interval of IAS treatment, are presented in Table 6-1.

Figure 6-5. Total BTEX Concentrations in Groundwater vs. Time at IAS Sites



When IAS activities resulted in a reduction in hydrocarbons to non-detectable (ND), then the interval of IAS operation until the first measurement of ND is reported. Hydrocarbon data was taken from selected wells that appeared to be directly impacted by IAS activities. It should be noted that for the majority of sites presented within Table 6-1, IAS remediation was in progress at the time of sampling. Therefore, the possibility of hydrocarbon contamination rebound, following system shut-down, existed.

PROJECT CLOSE OUT

The procedures defined by the regulatory agency within the State in which the site is located should be followed when closing out a site. Closure may entail the performance of investigatory soil gas, groundwater and/or soil boring sampling and analysis, and performance of a site-specific risk assessment to confirm the remediation of contamination to below acceptable criteria. As the limitations and effectiveness of IAS technology are not fully understood, it is likely that following shut down a period of groundwater monitoring will be required to verify the maintenance of acceptable dissolved phase VOC concentrations.

Table 6-1. Total BTEX Reduction in Groundwater Observed at Selected *In situ* Air Sparging Sites From the API - IAS Database

| Site | Distance to IAS well (ft) | Total BTEX conc. at start of interval of IAS (PPB) | Total BTEX conc. at end of interval of IAS (PPB) | Percent reduction | IAS Time interval (days) |
|---|---|---|---|---|---|
| s-10-b | 4 | 1,540 | 42 | 97% | 130 |
| s-6 | 5 | 13,125 | 1,562 | 88% | 60 |
| s-1 | 5 | 44,926 | 8,906 | 80% | 180 |
| s-2 | 8 | 2,200 | 0 | 100% | 60 |
| s-4 | 10 | 36,900 | 12,500 | 66% | 90 |
| s-9-a | 11 | 2,400 | 0 | 100% | 450 |
| s-10-a | 11 | 344 | 139 | 60% | 130 |
| s-5 | 12 | 76,900 | 1,700 | 98% | 150 |
| s-8 | 19 | 396 | 11 | 97% | 36 |
| s-7 | 20 | 43,093 | 18,413 | 57% | 120 |
| s-9-b | 22 | 53,000 | 7 | 100% | 450 |
| s-3 | 30 | 142 | 4 | 97% | 14 |
| s-9-c | 33 | 19 | 7 | 63% | 450 |

# Section 7

## POTENTIAL LIMITATIONS AND KNOWLEDGE GAPS IN IAS SYSTEM DESIGN AND EFFECTIVENESS AND RESEARCH NEEDS

Based on a review of the literature and an examination of the API -IAS Database, several limitations and knowledge gaps exist with respect to IAS technology. They are as follows:

- The vast majority of sites contained within the database were short-term pilot-scale investigations.
- Sites within the database had limited or no pre- or post-sparging groundwater quality data that could be used to evaluate system performance.
- Sites within the database generally used an alternative remediation technology, such as pump and treat or SVE, before the application of IAS. Generally, IAS was being added to deal with "hot-spots" that did not respond to SVE alone. Due to the concurrent operation of more than one remediation technology, it was difficult to assess which technology was responsible for the observed remediation and to what extent.
- Because of the limited size of the database, analysis of IAS hydrocarbon removal data could not be conducted on a statistical basis. Instead, these sites had to be examined individually.
- The movement of both air/vapor and water within the saturated zone at IAS sites is still not well understood. Factors such as contaminant and oxygen mass transfer and air channel distribution, in response to various conditions of IAS system operation, is not well understood.
- To date, modeling efforts have not been sufficiently robust to characterize air flow distribution in a manner that could aid in system design.

# Section 8

# REFERENCES

Ahlfeld, D.P., A. Dahmani and W. Ji. 1994. "A Conceptual Model of Field Behavior of Air Sparging and Its Implications for Application." *Ground Water Monitoring & Remediation.* (14)4:132-139.

Ardito, C.P. and J.F. Billings. 1990. "Alternative remediation strategies: The subsurface volatilization and ventilation system." In *Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration.* Houston, Texas, NWWA/API. pp. 281-296.

Baehr, A.L., G.E. Hoag and M.C. Marley. 1989. "Removing volatile contaminants from the unsaturated zone by inducing advective air-phase transport." *J. of Contaminant Hydrology.* 4:1-26.

Berry-Spark, K. and J.F. Barker. 1986. "Remediation of gasoline-contaminated ground-waters: a controlled field experiment." In *Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration.* Houston, Texas, NWWA/API. pp. 613-623.

Brown, R., C. Herman and E. Henry. 1991. "The use of aeration in environmental clean-ups." Presented at Haztech International Pittsburgh Waste Conference, Pittsburgh, PA, May 14-16.

Brown, R.A. and F. Jasiulewicz. 1992. "Air sparging: a new model for remediation." *Pollution Engineering*. July:52-55.

Domenico, P.A. and F.W. Schwartz. 1990. *Physical and Chemical Hydrogeology.* Wiley-Interscience, New York, NY.

Driscoll, F.G. 1986. *Groundwater and Wells.* Second edition. Johnson Division, St. Paul, Minnesota. p. 811.

Fetter, C.W. 1993. *Contaminant Hydrogeology*. Macmillan Publishing Company. New York, NY. 458 pages.

Freeze, R.A. and J.A. Cherry. 1979. *Groundwater*. Prentice Hall Inc., Englewood Cliffs, NJ. pp. 30-35.

Gudemann, H., and D. Hiller. 1988. "In situ remediation of VOC contaminated soil and ground water by vapor extraction and ground water aeration." In *Proceedings of the Third Annual Haztech International Conference*. Cleveland, OH, Sept. 20.

Gvirtzman, H., and S.M. Gorelick. 1992. "The concept of *in-situ* vapor stripping for removing VOCs from ground water." *Transport in Porous Media*. 8:71-92.

Hinchee, R.E., D.C. Downey, and E.J. Coleman. 1987. "Enhanced bioreclamation, soil venting and ground water extraction: A cost-effectiveness and feasibility comparison." In *Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection and Restoration*. Houston, TX, NWWA/API. pp. 147-164.

Ji, W., A. Dahmani, D. Ahlfeld, J. Lin and E. Hill Jr. 1993. "Laboratory study of air sparging: air flow visualization." *Ground Water Monitoring and Remediation*. 13(4), 115-125.

Johnson, R.L. 1993. "A Conceptual Model of Enhanced Biodegradation Using In Situ Air Sparging." In *Proceedings 2nd International Symposium In Situ and On Site Bioremediation*. R.E. Hinchee (ed.), Lewis Publishers. pp. 14-22.

Johnson, R.L., P.C. Johnson, D.B. McWhorter, R.E. Hinchee and I. Goodman. 1993. "An overview of in situ air sparging." *Ground Water Monitoring and Remediation*. 13(4), 127-135.

Johnson, R.L., W. Bagby, P. Matthew, and C.T Chien. 1992. "Experimental Examination of Integrated Soil Vapor Extraction Techniques." In *Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration*. Houston, TX, NGWA/API. pp. 441-452.

Loden, M.E. and C-Y Fan. 1992. "Air sparging technology evaluation." *In Proceedings of the National Conference on the Control of Hazardous Materials.* San Francisco, CA , Hazardous Material Control Research Institute. pp. 328-334.

Lundegard, P.D. and G. Andersen. 1993. "Numerical simulation of air sparging performance." In *Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration.* NGWA/API, Houston, TX. pp. 461-476.

Lundegard, P.D. 1994. "Actual Versus Apparent Radius of Influence - Air Sparging in a Sandy Aquifer." In *Proceedings of the Petroleum Hydrocarbon and Organic Chemicals in Groundwater Conference.* NGWA/API Conference, Houston, TX. pp. 191-206.

Marley, M.C. 1991. "Air Sparging in Conjunction with Vapor Extraction for Source Removal at VOC Spill Sites." In *Proceedings of the Fifth National Outdoor Action Conference.* NWWA, Las Vegas, NV. pp. 89-103.

Marley, M.C., D.J. Hazebrouck, and M.T. Walsh. 1992a. "The application of in situ air sparging as an innovative soils and ground water remediation technology." *Ground Water Monitoring Review.* Spring:137-145.

Marley, M.C., F. Li, and S. Magee. 1992b. "The application of models in the design of air sparging systems." In *Proceedings of HMC Superfund 92, HMCRI's 13th Annual Conference & Exhibition SARA-RCRA-HSWA-CAA-CWA.* December 1-3, Washington, D.C. pp. 853-858.

Marley, M.C., E.X. Droste,. and R.J. Cody. 1993a. "Mechanisms that Govern the Successful Application of Sparging Technologies." In *Proceedings of the 87th Annual Meeting of the Air and Waste Management Association.* Cincinnati, Ohio.

Marley, M.C., E.X. Droste, and C. Lizotte. 1993b. "Air Sparging Technology as a Ground Water Remediation Strategy." In *Proceedings of New England Exposition.* Boston, MA.

Marley, M.C. 1994. "The State of the Art in Air Sparging." In *Proceedings of the HMCRI's Superfund 15th Annual Conference and Exhibition.* Washington, DC.

Marley, M.C., E.X. Droste, F. Li, and R.J. Cody. 1994. "Design of an *In Situ* Sparging Trench." In *Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Groundwater: Prevention, Detection and Restoration.* Houston, TX. NGWA/API.

Martin, L.M., R.J. Sarnelli, and M.T. Walsh. 1992. "Pilot Scale Evaluation of Groundwater and Air Sparging: Site Specific Advantages and Limitations." In *Proceedings of the National R&D Conference on the Control of Hazardous Materials.* San Francisco, CA. pp. 318-328

Martinson, M.M., and J.A. Linck. 1993. "Field Pilot Testing for Air Sparging of Hydrocarbon Contaminated Ground Water." In *Proceedings of the Sixteenth International Madison Waste Conference.* University of Wisconsin - Madison.

Masch, F.D. and K.J. Denny. 1966. "Grain Size Distribution and its effect on the permeability of unconsolidated sand." *Water Resources Research.* Volume 2, Number 4, pp. 665-677.

McCarty, P.L. 1987. "Removal of organic substances from water by air sparging." *Control of Organic Substances in Water and Wastewater, Pollution Technology Review No. 140.* Bernard B. Berger, Ed., Noyles Data Corp., Park Ridge, NJ. pp. 19-147.

Middleton, A.C. and D. Hiller. 1990. "*In situ* aeration of ground water: A technology overview." In *Proceedings of 1990 Environment Canada Montreal Conference.* Montreal, Quebec.

Miller, R.N., R.E. Hinchee, and C. Vogel. 1991. "A Field-Scale Investigation of Petroleum Hydrocarbon Biodegradation in the Vadose Zone Enhanced by Soil Venting at Tyndall AFB, Florida." In *In Situ and On-site Bioreclamation.* R.E. Hinchee and R.F. Olfenbuttel, (eds.) Vol. 1, Stoneham, MA.

Montgomery, J.H. 1991. *Groundwater Chemicals Desk Reference.* Volume 2. Lewis Publishers, Michigan. 640 pages.

Newman, P.A.B., F.S. Peterson, P.E. Boersma, and R.E. Huddleston. 1994. "Effects of Sparging on Ground Water Hydraulics and Ground Water Quality." In *Proceedings 87th Annual Meeting Air and Waste Management Association.* Cincinnati, Ohio.

Nyer, E.K. 1985. *Groundwater Treatment Technology.* Van Nostrand Reinhold Company, New York, NY.

Nyer, E.K. and S.S. Suthersan. 1993. "Air sparging: savior of ground water remediations or just blowing bubbles in the bath tub?" *Ground Water Monitoring and Remediation.* 13(4), 87-91.

Pankow, J.F., R.L. Johnson, J.A. Cherry. 1993. "Air sparging in gate wells in cutoff walls and trenches for control of plumes of volatile organic compounds (VOCs)." *Ground Water.* 31 (4), pp. 654-663.

Roberts, L.A, and J.D. Wilson. 1993. "Ground Water Cleanup by In-Situ Sparging. III. Modelling of Dense Nonaqueous Phase Liquid Droplet Removal." *Sep. Sci. Technol.* 27(5), pp. 1127-1143.

Schima, S., D.J LaBrecque,. and P.D. Lundegard. 1994. "Using Resistivity Tomography to Monitor Air Sparging." In *Proceedings of the Symposium on the Application of Geophysical to Engineering and Environmental Problems.* Environmental and Engineering Geophysical Society. pp. 757-774.

Schwille, F. 1988. *Dense Chlorinated Solvents in Porous and Fractured Media: Model Experiments.* J.F. Pankow, translator. Lewis Publishers, Chelsea, Michigan. 146 pages.

Sellers, K.L. and R.P. Schreiber. 1992. "Air sparging model for predicting ground water cleanup rate." In *Proceedings of the Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration.* Houston, Texas, NGWA/API. pp. 365-376.

Thibodeaux, L.J. 1979. *Chemodynamics, environmental movement of chemicals in air water and soil.* John Wiley & Sons, N.Y., NY.

Wehrle, K. 1990. "In situ cleaning of CHC contaminated sites: model-scale experiments using the air injection (In Situ Stripping) method in granular soils." F. Arenak, M. Hinsenveld, and W.J. van den Brink, eds. *Contaminated Soil '90.* Kluwer Academic Publishers, Netherlands. pp. 1061-1062.

Wilson, D.J., S. Kayano, R.D. Murch, Jr., and A.N. Clarke. 1992. "Groundwater cleanup by in-situ sparging. I. Mathematical modelling." *Sep. Sci. Technol.* 27(8&9), pp. 1023-1041.

Wilson, D.J. 1992. "Groundwater cleanup by in-situ sparging. II. modelling of dissolved VOC removal" *Sep. Sci. Technol.* 27(13), pp. 1675-1690.

Wisconsin Department of Natural Resources (DNR). 1993. "Guidance for design, installation and operation of in situ air sparging systems." *PUBL-SW186-93.* Emergency and Remedial Response Section, PO Box 7921, Madison, WI 53707.

Yaniga, P.M., C. Matson, and D.J. Demko. 1985. "Restoration of water quality in a multi-aquifer system via in situ biodegradation of the organic contaminants." In *Proceedings of the Fifth National Symposium and Exposition on Aquifer Restoration and Ground Water Monitoring*. NWWA. Dublin, Ohio.

# Appendix

## API *IN SITU* AIR SPARGING DATABASE

# Appendix

# API *IN SITU* AIR SPARGING DATABASE

## DATA COLLECTION

To assemble a database that would be representative of the petroleum industry's experience with *in situ* air sparging technology, requests were made of API member companies and several consultants to provide comprehensive engineering reports detailing their application of IAS technology. Table A-1 describes the information that was obtained.

**Table A-1. Database Site Statistics**

| **Number of Sites** | | Total |
|---|---|---|
| With Air Sparging Data | | 59 |
| Without Air Sparging Data | | 7 |
| Total Received | | 66 |
| ***In situ* Air Sparging Sites in Database** | Total | Rejected |
| Sites With Both Pilot and Full Scale Data | 13 | 1 |
| Sites With Only Pilot Scale Data | 40 | 13 |
| Sites With Only Full Scale Data | 6 | 1 |
| Total Number of Sites in Database | 59 | 15 |
| **Reason for Site Rejection** | | |
| Insufficient Data | | 8 |
| IAS Technology Failure Site | | 7 |

## SITE REJECTION

For seven of the sites, no or only very limited IAS data was available; therefore, these files were not included in the database. If a site within the database is designated as "rejected" then it was not used in the preparation of tables or figures presented within the document. It should also be noted that data from sites within the database that were designated as "IAS technology failure sites" were not used in the preparation of graphs or tables.

Generally, a site was rejected if insufficient data was present to enable an understanding of what transpired at a site. In some cases inconclusive data was presented in tabular form without any interpretation. Analysis of this data was often impossible.

Sites were also rejected for one or more deficiencies. Several files contained fragmented data. For example, a file might have been a copy of a monthly or quarterly activity report, which consisted of chemical analysis within numerous sampling wells for that period. However, if no timeline of IAS/SVE activity was reported, it was impossible to know when measurements were made in relation to IAS/SVE activities. At many sites boring logs, soil descriptions, and well construction details were not provided. Often IAS system lay-out details were not provided or were not clear. If it appeared that additional data would be available, attempts were made to contact these industry representatives and consultants and obtain any missing data.

## DATABASE

The information within the database describes contaminant type; site conditions; monitoring system design and operation; and IAS design and operation. A variety of approaches were used to conduct pilot-scale evaluations of IAS systems and to analyze *in situ* air sparging data. Some studies focused on physical measurements such as soil characteristics (i.e., description, permeability, hydraulic conductivity); measurements of pressures in monitoring wells; 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 difference in these approaches may be as a result of different monitoring required in different states. The inclusion of time-dependent hydrocarbon removal data within the database was not practical. However, some of this data is presented and discussed within the document.

## DATABASE LIMITATIONS

At the onset of the project it was hoped that engineering reports detailing the use of *in situ* air sparging technology at 100 full-scale installations with plentiful long-term water-quality data describing hydrocarbon removal would be available. An analysis of groundwater hydrocarbon content vs. time under various operating conditions was to provide various system design coefficients. However, the majority of reports examined described short-term pilot scale tests, often less than eight hours in duration.

Generally, only the full-scale sites contained information describing the time-dependent removal of aqueous phase hydrocarbons from groundwater. Two sites that were originally classified as pilot-scale were reclassified as having full scale data based on the length of the study, the relative size of the site and extent of the data collection effort. Water quality data derived from short-term IAS pilot-scale testing studies is of little value. The major benefit of these short-term pilot-scale evaluations is the determination of an IAS well radius of influence.

**Alternate Attempts to Analyze Sparging Data ROI Relationships**

At a limited number of sites, ROI values greater than 40 feet were reported. These data are considered to be questionable and possibly a result of preferential flow to isolated monitoring wells. However, for completeness they were included in Figure 4-4. Attempts were made to graphically analyze data to determine the dependence of ROI on a variety of parameters. All data points including ROI values in excess of 40 feet were included in the analysis. Selected plots are presented in this Appendix.

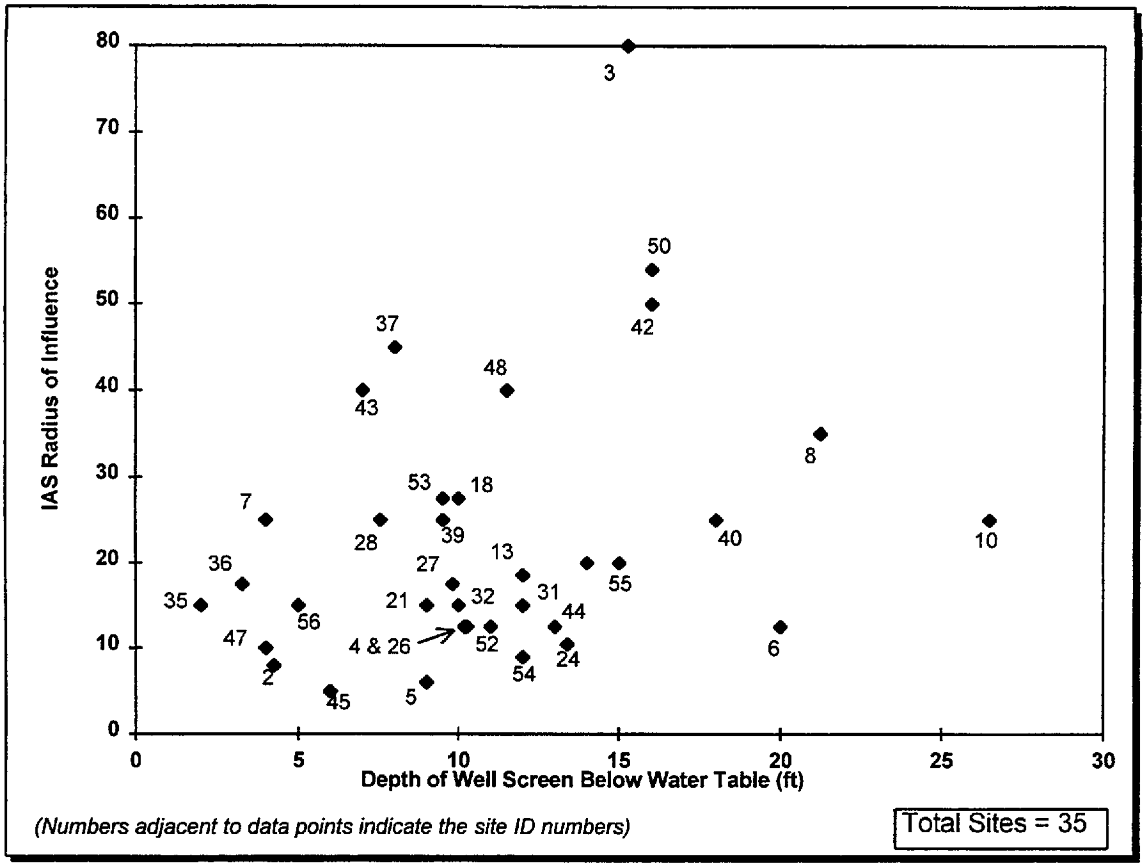
Depth of IAS Well Screen Below the Water Table

It has been postulated in the literature that deeper IAS wells would result in a larger ROI (Nyer and Suthersan, 1993). Graphical analysis of the relevant data from the API - IAS Database as presented in Figure A-1 indicates that there was no apparent relationship between ROI and depth of air injection. Depth of air injection was measured to the top of the well screen. It should be noted that a limitation of the analysis presented is that the ROIs were observed at different sites with different soils. A more appropriate method to examine this relationship would be to examine a series of nested IAS wells at different depths at a site with uniform aquifer materials. However, data was not available to permit this analysis.

Soil Hydraulic Conductivity

The relationship between ROI and soil hydraulic conductivity is examined in Figure A-2. A plot of the available data revealed no apparent relationships between soil hydraulic conductivity and ROI.

**Figure A-1. ROI vs. Depth of IAS Well Screen Below the Water Table**



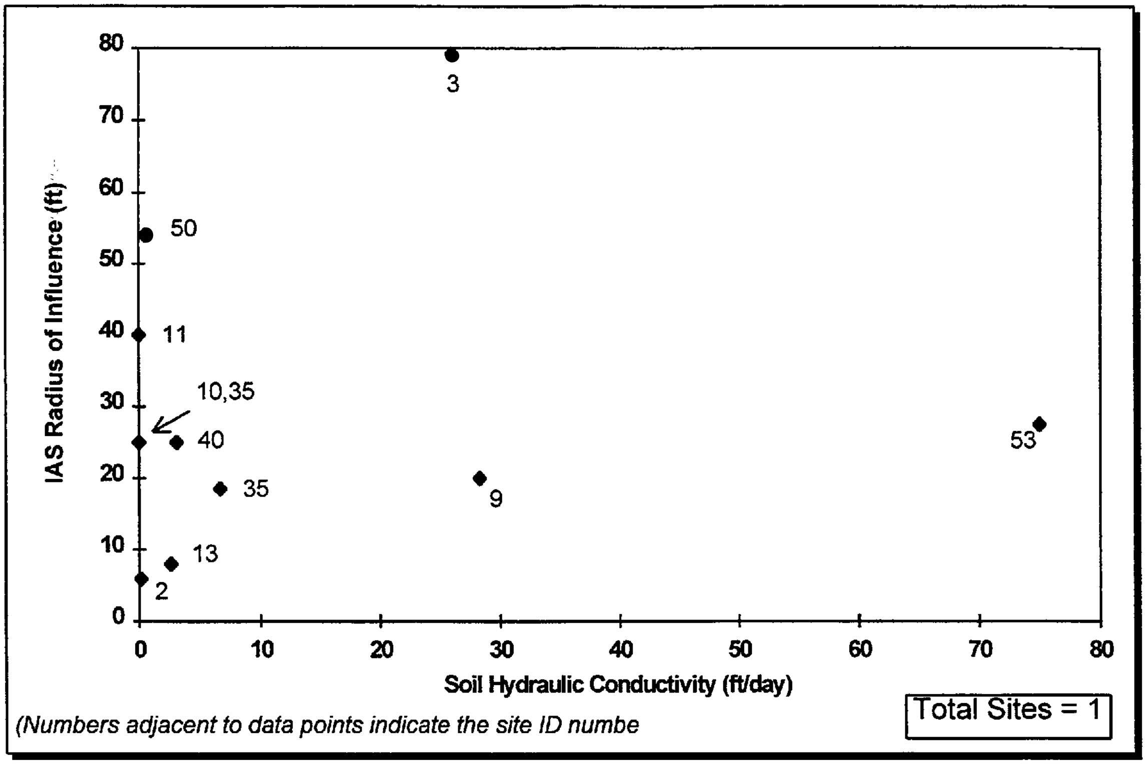

Hydraulic conductivity data was only available at a limited number of sites. Hydraulic conductivity values were obtained via pumping tests or laboratory analysis of representative soil samples. In either case the value reported is likely a good representation of the horizontal hydraulic conductivity, but does not necessarily provide information on the vertical hydraulic conductivity of the soil. Note that a relatively thin confining layer or a relatively high anisotrophy ratio may control the vertical movement of the air and therefore the ROI. If continuous split spoon sampling or alternate detailed characterization procedures were not conducted at the site, the presence of a confining layer may not have been detected.

IAS Flow Rate

A plot of IAS air flow rate vs. observed ROI, at various sites is presented in Figure A-3. No relationship between IAS flow rate and ROI was observed. Again a limitation of this analysis is that the majority of the data points plotted represent data collected at different sites.

At several sites more than one injection flow rate was utilized. At these sites when IAS system pressures were increased and flows were doubled, only slight increases in ROI were observed. Field observations at a flooded site allowed the observation of air bubbles exiting the soil surface under various flow regimes. This test revealed that increased system pressures and flows resulted in a denser distribution of air filled channels as opposed to a larger ROI.

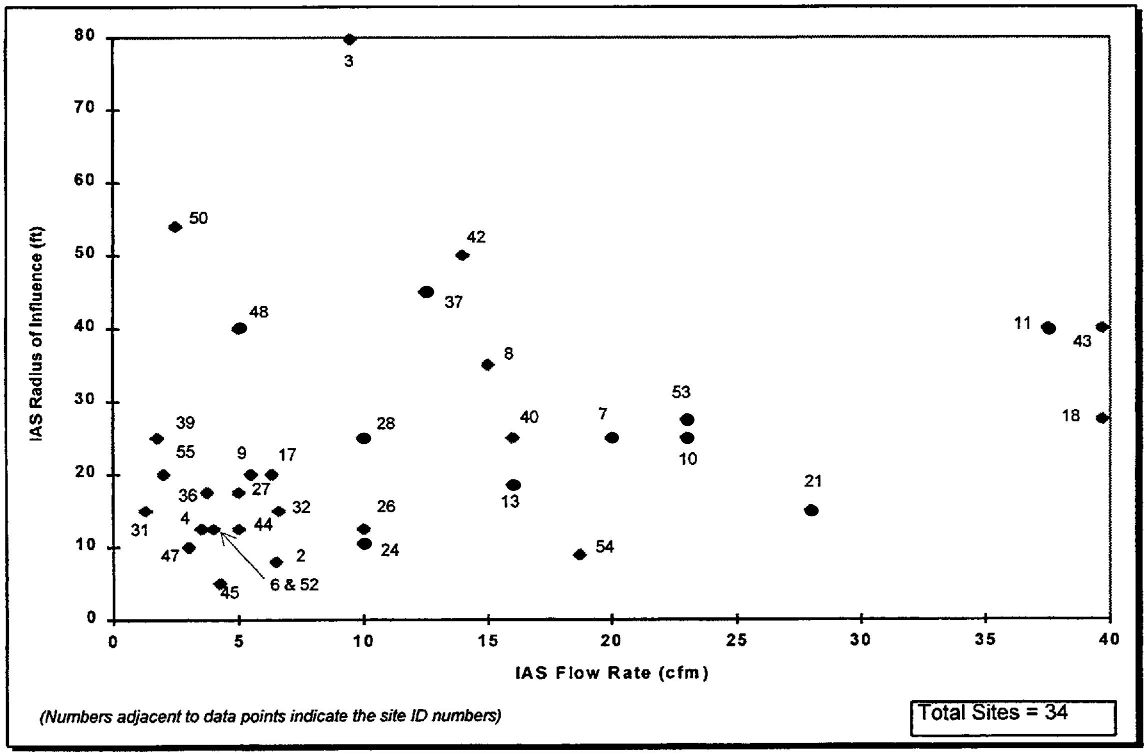
**Figure A-2. ROI vs. Soil Hydraulic Conductivity**




<u>Summary</u>

No relationship was observed between ROI and parameters such as depth of IAS well below the water table or IAS flow rate. Controlled experiments at a selected site would be necessary to clearly define this relationship. To examine the influence of soil hydraulic conductivity on ROI, in homogeneous-isotropic soils would be preferred. It would be necessary to conduct detailed soil characterization to define the site stratigraphy and to confirm that confining layers do not exist.

**Figure A-3. ROI vs. IAS Flow Rate**



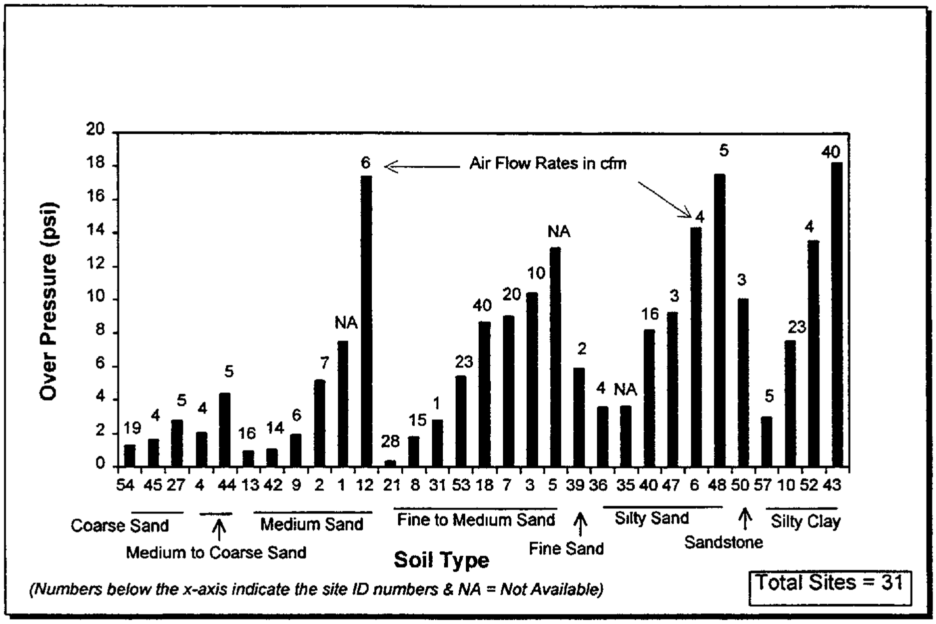

## System Pressures Related to Soil Types

<u>The Relationship Between Soil Type, Over-Pressure and Flow</u>

Over-pressure is defined as the pressure in excess of that required to overcome the hydrostatic head above the IAS well screen. The relationship between soil type and over-pressure was previously presented in Figure 4-5. Figure A-4, presented here, is a modification of Figure of 4-5 in that the sparging air flow rates are added to the tops of each bar. Generally, when finer, tighter soils were present, larger values of over-pressures were observed. However, when examining over-pressures vs. flow rate within a group of soils with the same description (e.g., Medium to Fine Sand) no correlation between over-pressures and flow rates was observed.

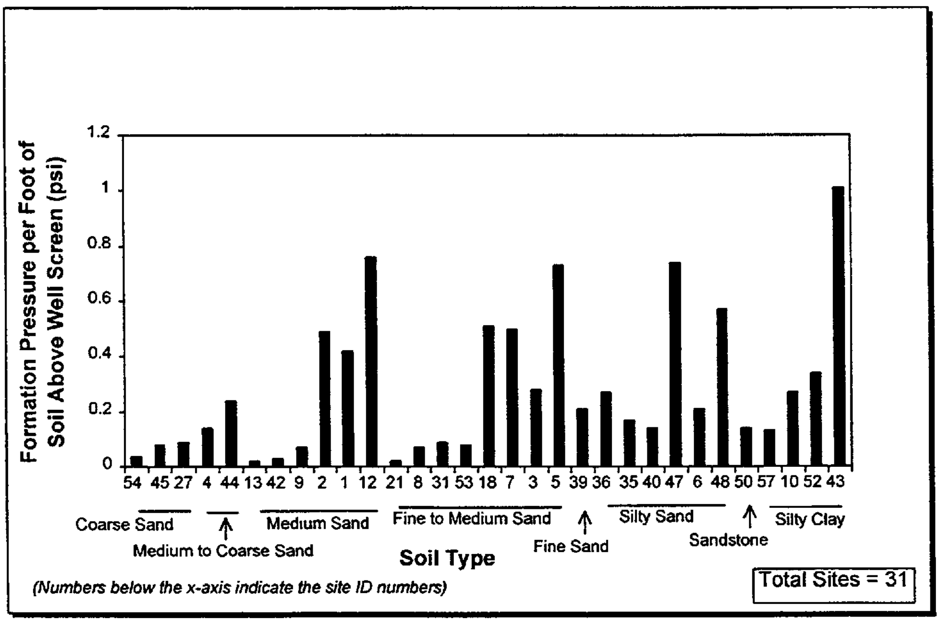
It is postulated that soil rupturing and short-circuiting may have occurred in the cases where relatively high air flow rates were observed in conjunction with relatively low over-pressures or when unusually low over-pressures were observed in tight soils.

**Figure A-4. Soil Type vs. Over-Pressure vs. IAS Flow**




When observed over-pressures are divided by the depth of soil above the top of the well screen the resulting value represents the formation pressure. Formation pressures for the various soil types are shown in Figure A-5. In general, tighter soils (as defined by typical soil hydraulic conductivities) exhibited larger formation pressures.

**Figure A-5. Soil Type vs. Formation Pressure**



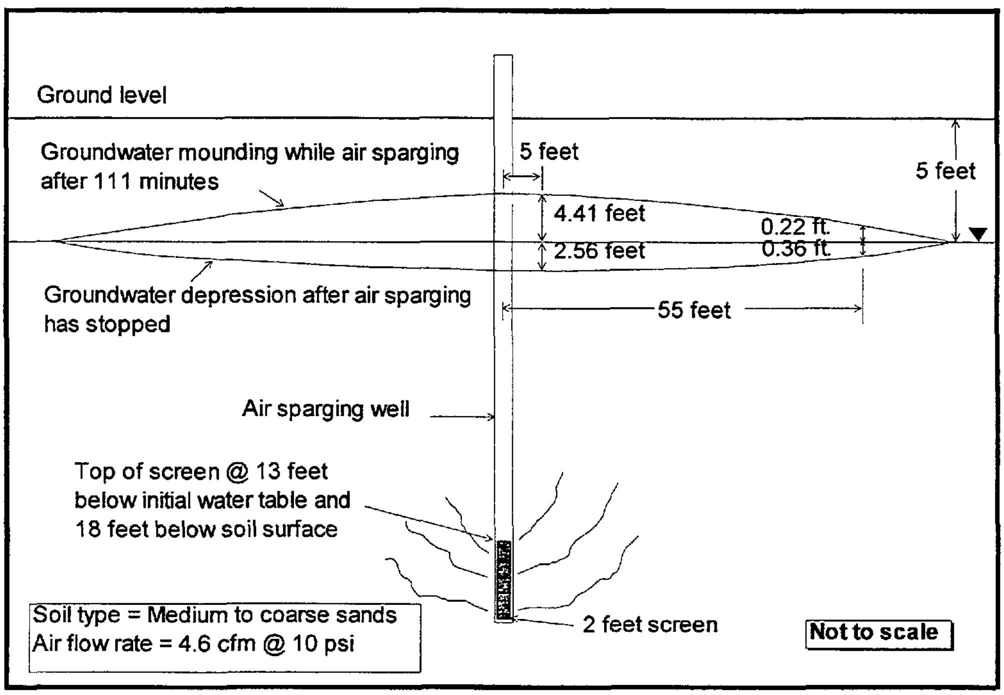
**Water Table Response to IAS Activity**

The operation of an IAS system results in the transient mounding of the groundwater in the vicinity of the well. Some practitioners use this as a measure of ROI. A representative plot (from the API - IAS Database) of groundwater elevation vs. time is shown in Figure A-6.

The mounding observed (i.e., + 4.41 feet) after 111 minutes of operation is as a result of displacing water from the overlying aquifer by air. The air enters the aquifer at a faster rate than the water can flow away from the well. Over time the mound tends to dissipate back to pre-sparging levels. The time period for the mound to dissipate appears to be dependent on the soil permeability. When the IAS system is shut-off the ground water table appears to be depressed (i.e., - 2.56 feet) since the air escapes the system faster than the displaced water can flow back.

Recognizing that this phenomenon occurs, it is speculated that pulsing the air sparging system may have some benefit resulting from groundwater mixing.

**Figure A-6. Groundwater Elevation vs. Time at a Representative IAS Site**



**Aqueous Phase BTEX Reductions**

Dissolved BTEX concentrations at a site were used as an indicator of the minimal (Min.) and maximal (Max.) effect resulting from IAS system operation. The results of the API - IAS Database analysis are presented in Table A-2. Data was taken from all sites within the database where available. Maximal effect data was selected from sample locations that initially exhibited elevated aqueous phase BTEX concentrations and then exhibited the maximum reduction in concentration (based on the percentage of initial remaining). Minimal effect data was selected from wells that initially exhibited elevated hydrocarbon levels and then were minimally reduced or actually increased in hydrocarbon concentration during IAS system operation. The same time period was examined for the min. and max. wells. Temporary increases in hydrocarbon content at selected wells is not unusual at sites that have an operating IAS system. As remediation by IAS continues these values appear to generally diminish.

Whenever possible data was selected from wells that were likely to be influenced by IAS even if they were not within the reported ROI. Generally, SVE activities were in progress for several months prior to start-up of the IAS systems. An attempt was made to use groundwater BTEX data from a time period that brackets a period of IAS system operation. The "sample span time" represents the period of time between the initial and final groundwater samples. The "period of IAS" represents the time that the IAS system was operating between the initial and final groundwater sampling events. When the "sample span time" is equal to the "period of IAS" this means that the IAS system was still in operation at the time of the final sampling event.

Generally, significant reductions in groundwater BTEX were observed. At many of the sites examined IAS system operation was ongoing and therefore elevated BTEX still remained at the time of the "Final BTEX" measurement

**Table A-2. Aqueous Phase BTEX Reductions at IAS Sites**

| Site No. | Initial BTEX (PPB) | Final BTEX (PPB) | Sample Span (days) | Period of IAS (days) | Distance to IAS well (ft) | ROI (ft) | Min. or Max. |
|---|---|---|---|---|---|---|---|
| 5 | 44,025 | 2,454 | 180 | 180 | 10 | 6 | max. |
| | 65,296 | 38,480 | | | 15 | | min. |
| 12 | 3,200 | 6 | 600 | 420 | 4 | NA | max. |
| | 2,200 | 0 | | | 20 | | min. |
| 35 | 102 | <3 | 660 | 150 | 30 | 15 - 20 | max. |
| | <2 | 3.6 | | | 50 | | min. |
| 37 | 2,400 | 14.7 | 720 | 450 | 11 | 45 | max. |
| | 53,000 | 12,200 | | | 22 | | min. |
| 38 | 36,900 | 12,500 | 90 | 90 | 10 | NA | max. |
| | 9,530 | 11,000 | | | 26 | | min. |
| 39 | 76,000 | 1,700 | 150 | 136 | 12 | 25 | max. |
| | 120,000 | 100,000 | | | 19 | | min. |
| 45 | 13,125 | 1,562 | 74 | 60 | 5 | 5 | max. |
| | NA | NA | | | NA | | min. |
| 46 | 43,093 | 28,400 | 270 | 90 | 20 | NA | max. |
| | 56 | 4,350 | | | 30 | | min. |
| 55 | 396 | 63 | 149 | 149 | 19 | 20 - 24 | max. |
| | 2.5 | 27 | | | NA | | min. |
| 56 | 704 | 4 | 420 | 280 | 11 | 15 | max. |
| | 9.7 | 562.6 | | | 11 | | min. |
| 57 | 81 | BDL | 75 | 75 | 44 | NA | max. |
| | 9,690 | 4,460 | | | 25 | | min. |
| 59 | 1,540 | 42 | 134 | 113 | 3.75 | NA | max. |
| | 1 | 2 | | | 10 | | min. |

NA = Not available BDL = Below detection limits

# API IAS Database

# Abbreviations:

| | |
|---|---|
| NA | Not available |
| GW | Ground water |
| MW | Monitoring well |
| GWMW | Ground water monitoring well |
| IAS | In-situ air sparging |
| IASW | In-situ air sparging well |
| IASMW | In-situ air sparging monitoring well |
| SVE | Soil vapor extration |
| SVEW | Soil vapor extraction well |
| SVEMW | Soil vapor extraction monitoring well |
| VMP | Vapor monitoring point |
| ROI | Radius of influence |
| IAS ROI | In-situ air sparging radius of influence |
| SVE ROI | Soil vapor extraction radius of influence |
| PSH | Phase seperated hydrocarbons |
| GAC | Granular activated carbon |
| ORP | Oxidation reduction potential |
| psi. | Pounds per square inch |
| cfm. | Cubic feet per minute |
| HP | Horse power |
| Hg. | Mercury column |
| w.c. | Water column |
| kr | Horizantal intrinsic air permeability |
| kz | Vertical intrinsic air permeability |
| kc | Equivalent vertical intrinsic permeability of the overlying lenses/boundaries |
| {p1} | Reference page 1 |
| {F1} | Reference figure 1 |
| {T1} | Reference table 1 |

# Note:

Some of the data numbers are averaged for calculations.

**For example:**

Groundwater depth = 15 to 25 feet
Averaged value = 20 feet

| ID | Site | Facility Type | Client name | Report prepared by | Scale | Soil type |
|---|---|---|---|---|---|---|
| 1 | Black River Falls, WI | Gasoline station | Holiday Company | Central Wisconsin Engineers, Inc and Vapex Environmental Tech, Inc. | Pilot | Sandy |
| 2 | Willingboro, NJ | Industrial facility | Methode Electronics, Inc. | Vapex Environmental Tech, Inc. & Harding Lawson Associates | Pilot | Medium sand |
| 3 | Charleston, WV | Gasoline station | Chevron | Groundwater Technology, Inc. | Pilot | Fine to medium sand |
| 4 | Mansfield, MA | Industrial facility | Compo Chemicals | Vapex Environmental Tech, Inc. | Pilot & Full | Medium to coarse sand |
| 5 | Moodus, CT | Lumber company | Moodus Lumber and Coal Company | Vapex Environmental Tech, Inc. | Pilot & Full | Fine to medium sand |
| 6 | Machias, NY | Waste disposal site | Motorola | Vapex Environmental Tech, Inc. | Pilot & Full | Silty sand |
| 7 | Lanham, MD | Gasoline station | Chevron | Groundwater Technology, Inc. | Pilot | Fine to medium sand |
| 8 | LaBelle, FL | Gasoline station | BP Oil Company | Cherokee Groundwater Consultants, Inc., & IRC Environmental Inc., & HSW Engineering Inc | Pilot | Fine to medium sand |
| 9 | Springdale, PA | Gasoline station | Chevron | Engineering-Science | Pilot | Medium sand |
| 10 | Derita, NC (Vertical wells) | Gasoline station | Unocal | S & ME, Inc. | Pilot | Silty clay |
| 11 | Derita, NC (Horizantal wells) | Gasoline station | Unocal | S & ME, Inc | Pilot | Silty sand |
| 12 | Mansfield, CT | Gasoline station | G. Merrit Thompson & Sons | Vapex Environmental Tech, Inc. | Pilot & Full | Sandy |

| ID | Soil description | Contaminants | Conc Range |
|---|---|---|---|
| 1 | The site consists of stratified fine to coarse sand and gravel deposits upto depths of 20 to 25 feet. Occasional silt and/or clay lenses are present. Sandstone present under these deposits. | BTEX | 211,800 ppb |
| 2 | A clay layer is present under the sandy layer at a depth that varies between 6 and 14 feet below grade. {p2} | TCE and TCA | 100 to 1,000 ug/l (EPA TO3) in H2O {p4} |
| 3 | A brown silty clay to depths of 11 to 20 feet. A fine to medium grained micaceous silty sand present below to a depth of atleast 40 feet. {Summary} | BTEX and TPH | Soil: BTEX = 24 to 1,566 ppm and TPH = 2 to 227 ppm {p25}; In H2O: BTEX = 0.3 to 20,000 ppb {p25}. Small amounts of PSHs. |
| 4 | A fine to medium sand and silt lense is present from 0 to 2 feet below grade underlain by medium to coarse sands and gravel to a depth of 17 ft. {1/93, p5} | VOCs, specifically Toluene | VOCs = 80 to 10,000 ppmv/v in vapor via OVA-108 {1/93, p9} |
| 5 | A fine to medium sand with varying percentages of fine gravel, cobbles and silt. Depth of bedrock varied from 17 to 24 feet | BTEX | 69 to 178 ppm (EPA 602/8020) {p4} |
| 6 | 0 to 25 feet below grade = fine sand, 25 to 37 feet = alternating layers of fine compact sands and silty fine sands, 37 to 47 feet = sand and gravel, 47 to 57 ft = silty fine sand, bedrock present at 90 feet. {8/93, p3} | TCE and TCA | 291 to 1,800 ug/l |
| 7 | The site is underlain by fill material alluvial deposits of kaolinitic clay and a well-sorted, medium to fine-grained quartz sand. Clay layer at 17 to 22 feet. Bedrock below 22 feet | BTEX and TPH | BTEX = 2 to 1,044 ppm, TPH = 0 to 3,100 ppm (EPA 8020/5030/8015) {p4} |
| 8 | Fine to medium sand mixed with silt, clay and shell fragments upto to depths of 12 to 16 feet. A clayey sand to sandy clay is present from 16 to 25 feet and may extend to a depth of about 48 ft. | VOAs | 1,132 to 38,000 ppb (EPA 5030/8020) |
| 9 | Fill material and tight brown clays from surface to 10 feet in depth underlain by clayey sands grading to sand with coarse gravel lenses at 14 feet | TCE and TCA | TCE max. = 5,500 ug/l and TCA max. = 270 ppb |
| 10 | Clayey silts near the surface underlain by sandy silts and hard silts to sandy silts above the bedrock. A saprolitic zone of 5 to 10 feet thick overlies bedrock. Bedrock occurs below 50 feet | BTEX | Upto 24,530 ug/L {p14} |
| 11 | Clayey silts near the surface underlain by sandy silts and hard silts to sandy silts above the bedrock. A saprolitic zone of 5 to 10 feet thick overlies bedrock. Bedrock occurs below 50 feet | BTEX | Upto 30,000 ppb |
| 12 | Sandy soils with varying percentages of gravel, cobbles upto a depths of 35 feet | BTEX | 10 to 341 ppmv/v |

| ID | Type of Phase | Depth of GW table | Gradient of GW | No of GW monitoring wells | GWMW depth | GWMW dia |
|---|---|---|---|---|---|---|
| 1 | NA | 14 to 15 feet | 0.029 | 6 | NA | NA |
| 2 | Dissolved | 3.5 to 10.5 feet {p3} North = 6.5 ft. {F5} South = 6.0 ft. {F3} Avg. = 6.25 feet | 0.0035 ft/ft {p25} | NA | NA | NA |
| 3 | Dissolved | 11 to 27 feet and averaging 22 feet. {p3}. 25.26 ft. {AH} | 0.01 ft/ft | 9 {F2} | 20 to 30 feet {F5} | NA |
| 4 | NAPLS | 3.5 to 6 feet | NA | 8 | NA | NA |
| 5 | Dissolved | 5 to 13 feet {4/91, p3} | 0.12 ft/ft | 12 | NA | NA |
| 6 | Dissolved | 47 feet {p3} | NA | 2 | 54 feet and 75 feet {p3} | 2 inch |
| 7 | Dissolved | 12 to 16 feet {p5} | NA | 7 | 17 to 22 feet | 4 inch |
| 8 | Dissolved | 5.75 feet {p2-1} | 0.00034 ft/ft | 12 {F2} | 12.5 feet {p10} | 4 inch |
| 9 | Dissolved | 15 feet {p1} | 0.0015 ft/ft | 4 {p28} | 30 feet | NA |
| 10 | Dissolved | 12 to 15 feet {p10} | NA | 15 {T2] | 23 to 50 feet {F6} | NA |
| 11 | Dissolved | 12 to 15 feet | NA | 18 {T1} | Upto 50 feet | NA |
| 12 | Dissolved | 12 to 22 feet {T1} | NA | 5 {P3, 10/12/93} | 30 feet | 2 inch |

| ID | GWMW screen length | No of IAS wells | IASW depth | IASW dia | IASW Screen length |
|---|---|---|---|---|---|
| 1 | NA | 3 | 20 feet | NA | 2 feet |
| 2 | NA | 3; North = 2 and South = 1 {p7} | North = 12 ft {F5}, South = 10 ft {F3} and Avg.=11 ft. | 2 inch | 0.5 feet |
| 3 | 10 feet to 25 feet {F6} | 1 | 39.26 ft. {p11} | 4 inch {p11} | 2 feet {p11} |
| 4 | NA | 67 | 17 feet {1/93, p18} | 1.25 inch | 2 feet |
| 5 | NA | 23 {p2} | 17 to 23 feet {p4} | 1 inch | 1.5 feet |
| 6 | 10 feet | 39 {p2} | 22 feet below GW table {p2} | 1 inch | 2 feet |
| 7 | NA | 4 | 20 feet | 2 inch {p13} | 2 feet |
| 8 | 10 feet | 1 | 30 feet {6/93, p2-3} | 4 inch | 3 feet |
| 9 | 15 feet | 1 | 34 feet {p8} | 4 inch | 5 feet |
| 10 | 10 to 25 feet | 1 | 50 feet | 2 inch | 10 feet |
| 11 | 10 feet {p6} | 1 Horizantal, 310 feet long | 40 feet | 2 inch | 130 feet {p4} |
| 12 | 2 feet {p3} | 3 | 8 feet below GW table | 2 inch | 2 feet |

| ID | IAS flow/pressure rate/well | IAS Radius of Influence/well | Method of IAS ROI | IAS Compressor size |
|---|---|---|---|---|
| 1 | 9 psi | NA | NA | 1.5 HP Elmglo air compressor |
| 2 | 5 to 8 cfm @ 5 to 9 psi. {p20} Avg. = 6.5 cfm @ 7 psi | 6 to 10 feet {p20}. Avg. = 8 ft | Helium tracer and air bubbling | NA |
| 3 | 9.5 cfm @ 17 psig {Summary, p25} | 80 feet - D.O and 162 feet - Positive pressures. {Summary} | Positive pressures, Dissolved oxygen {p16} | NA |
| 4 | 3 to 4 cfm at 5 to 8 psi | 12.5 feet @ 4 cfm {p19} | Positive pressures, Dissolved oxygen and past experience {p7} | One 100 cfm and one 50 cfm AS units Model GC-6066-100 and GC-6066-50. (2.5 HP oilless air compressor for pilot test) |
| 5 | 17 psi {p10} | 6 feet {p11} | Based on past experience on sites with similar soils | 7.5 HP Atlas Copco oil-less reciprocating air compressor rated 43 cfm @ 20 psi {p5} |
| 6 | 3 to 5 cfm @ 23 psi {p1} | 12.5 feet {p1} | D.O., Positive pressures, GW mounding and past experience | 30 HP rotary screw type, capacity = 130 cfm @ 30 psi {p4} |
| 7 | 20 cfm @ 10 to 11.5 psi {T} | 25 feet @ 20 cfm | Air bubbling | 7.5 HP, 375 cfm regenerative blower |
| 8 | 15 cfm @ 11 psi {6/93, p2-4} | 35 feet | Positive pressures | Portable, Ingersol-Rand compressor. Rating NA |
| 9 | 3 to 8 cfm @ 6 to 10 psi {p17} | > 20 feet | D.O., GW mounding, air bubbling and positive pressures | NA |
| 10 | 23 cfm @ 25 psi {p19} | 25 feet {p4} | D.O., Ground water mounding and positive pressures {p8} | 7.5 HP reciprocating air compressor, rated 125 psi @ 34 cfm |
| 11 | 20 to 55 cfm @ 16 to 25 psi | 40 feet | D.O., Ground water mounding and positive pressures {p16} | 185 cfm @ 125 psi air compressor |
| 12 | 6 cfm @ 20 psi | Not stated | NA | 1 HP, Positive displacement compressor, capacity = 2 to 4 cfm @ 15 to 20 psi {p8} |

| ID | No of IAS monitoring wells | IASMW depth | IASMW dia | IASMW screen length | No of SVE wells |
|---|---|---|---|---|---|
| 1 | NA | NA | NA | NA | 3 |
| 2 | NA | NA | NA | NA | 2 {p7} |
| 3 | NA | NA | NA | NA | 1 |
| 4 | NA | NA | NA | NA | 70 |
| 5 | NA | NA | NA | NA | 8 {p4 & F1} |
| 6 | NA | NA | NA | NA | 16 {p1} |
| 7 | NA | NA | NA | NA | 4 |
| 8 | NA | NA | NA | NA | 1 |
| 9 | 3 {35} | 33 feet {p8} | 2 inch | 15 feet {p8} | 1 |
| 10 | NA | NA | NA | NA | 1 |
| 11 | NA | NA | NA | NA | 1 Horizantal, 230 feet long |
| 12 | NA | NA | NA | NA | 3 |

| ID | SVEW depth | SVEW dia | SVEW Screen length | SVE flow/pressure rate/well | SVE radius of influence/well |
|---|---|---|---|---|---|
| 1 | 12 feet | NA | 7 feet | 23 cfm @ 3 inches of water column | 50 to 60 feet |
| 2 | 5 feet | 2 inch | 2.5 feet | 5 cfm @ 2 inch of water column 30 cfm @ 11 inch w.c. | 26 to 40 feet {p19} |
| 3 | 35 feet {BL} | 4 inch | 20 feet | 21 TO 111 cfm @ 10 to 50 inches of water column {Summary, p25, p9, T6} | 90 to 100 feet {p22} |
| 4 | 6 feet {F2} | 2 inch | 4 to 5 feet | 5 to 10 cfm at 2 to 3 inches of water column {8/16/93, p2} | 12.5 feet {1/93, p22} |
| 5 | 9 feet | 2 inch | 4 feet | 24 cfm @ 10 to 20 inches of water column {p14} | 44.5 feet |
| 6 | 5 feet above GW table {p3} | 2 inch | 10 feet | 30 cfm @ 8 inches of Hg. {p1} | 25 feet {p1} |
| 7 | 14 feet | 2 inch | 9 feet | 64 to 72 cfm @ 14 to 31 inches water column {T} | 40 feet |
| 8 | 9 feet {p2-1} | 4 inch | 7 feet | 30 to 35 cfm @ 50 inches of water column {p2-2} | 30 feet {p2-5} |
| 9 | 15 feet | 4 inch | 10 feet | 20 and 64 inches of w.c. @ 144 and 186 cfm {T9A} | 40 feet {p31} |
| 10 | 41 feet {p17} | 6 inch | 34 feet {p4} | 71 to 200 cfm @ 15 to 140 inches of water column {p17&21} | 35 feet {p23} |
| 11 | 4 to 5 feet | 2 inch | 140 feet | 171 to 235 cfm @ 6 inches of Hg. | NA |
| 12 | 17 feet | 2 inch | 5 feet {p3} | 20 to 25 cfm @ 15 to 30 inches of water column | NA |

| ID | Method of SVE ROI | SVE Vacuum pump size | No of VMPs | VMP depth | VMP dia | VMP screen length |
|---|---|---|---|---|---|---|
| 1 | Vacuum | 0.75 HP and 1.5 HP rotary vane vacuum pumps | 7 | 10 to 12 feet | NA | 1 feet |
| 2 | Vacuum | 1 HP Rotron blower | 2 | 4 feet | 0.5 inch | 0.5 feet |
| 3 | Vacuum | NA | NA | NA | NA | NA |
| 4 | Vacuum | Three 120 scfm explosion proof SVE blowers Model GB-R5-100 {8/93,p4} 1.5 HP rotary vane pump for pilot test {1/93, p6} | NA | NA | NA | NA |
| 5 | Vacuum | Two 125 cfm, 1.5 HP regenerative blower {p4} | 16 {4/91, p4) | NA | NA | NA |
| 6 | Vacuum | 25 HP rotary lobe type, capacity = 480 cfm @ 10 inches of Hg. | 4 | 35 feet | 0.5 inch | 0.5 feet |
| 7 | Vacuum | 1HP Rotron blower {p13} | NA | NA | NA | NA |
| 8 | Vacuum | Two 2 HP Gast regenerative blowers {p2-2} | 5 | 4.5 feet | 2 inch | 2 feet |
| 9 | Vacuum, D.O. and Organic vapor concentrations {p25, 31} | NA | 8 | 7 and 12 feet {p9} | 0.75 inch | NA |
| 10 | Vacuum | 7.5 HP mobile unit, rated 11 inches of Hg. @ 300 cfm {p16} | NA | 14 feet | 1 inch | 5 feet |
| 11 | NA | 15 HP vacuum blower rated 650 cfm @ 10 inches of Hg. | NA | NA | NA | NA |
| 12 | NA | NA | 3 {p2} | 10 to 12 feet | 0.5 inch | NA |

| ID | Effluent gas treatment | System operation | Other data |
|---|---|---|---|
| 1 | NA | Continuous | K = 0.01 cm/sec, GW velocity = 4.1 feet/day, T = 1060 gpd/ft, Sp. yield = 0.15 to 0.30. |
| 2 | GAC units | Continuous | North area: kr = kz = 5.67E-7 cm^2, kc = 1.29E-10 cm^2 and K = 2.6 ft/day. {p12,25}<br>South area: kr = kz = 6.11E-07 cm^2 and kc = 8.19E-10 cm^2 {p12} |
| 3 | NA | Pulsed | K = 26 ft/day. Porosity = 0.28 {p17}. Total Organic Carbon content = 55 to 96 ppm. Hydrocarbon utilizing bacteria ranging from 250,000 to 780,000 CFU/ml. |
| 4 | Three 100 cfm catalytic oxidation units.<br>Two 200 pound vapor phase canisters for pilot test. | Pulsed | kr = kz = 3.7E-07 cm^2 and kc = 2.2E-09 cm^2. Mass removal table available. {1/93, p21} |
| 5 | Two 200 pounds vapor phase activated carbon canisters | Pulsed | kr = 1.15E-6 cm^2, kz = 2.29E-7 cm^2, GW velocity = 0.072 ft/d, K = 0.18 ft/d, Porosity =0.3 {p13} |
| 6 | Two 1000 pound carbon contactors in series {p5} | Pulsed | kr = 1.7E-8 cm^2, kz = 6.4E-8 cm^2, Porosity = 0.3 |
| 7 | NA | Pulsed | Soil boring logs and manufacturer's specifications available. |
| 8 | NA | Continuous | Soil porosity = 0.35, K = 350 ft/day, Sp. Yield = 0.14, Avg. Transmissivity = 8,900 sq.ft/day, GW. Flow velocity = 0.0476 ft/day |
| 9 | NA | Continuous | K = 0.01 cm/sec |
| 10 | NA | Continuous | Transmissivity = 6 ft^2/day, Storativity = 1x10^-4, K = 3.5E-6 cm/sec {9/93, p3} |
| 11 | NA | Continuous with stepped injection pressure | Transmissivity = 6 ft^2/day, Storativity = 1x10^-4, K = 3.5E-6 cm/sec |
| 12 | NA | Pulsed | SVE/AS operating conditions table available. Boring logs data available. |

| ID | Notes | Asymptotic behavior | Site status |
|---|---|---|---|
| 1 | 600 gallons of gasoline was lost. 30 gallons of free product was removed (pumping). 460 tons of soil removed during excavation (this soil contained 100 gallons of gasoline). 80 gallons of product recovered by P & T system. This is a 2 day pilot test. | | Accepted |
| 2 | Calculations were performed that indicate that between 600 and 3,200 pounds of TCE are sorbed to the fine sand in the saturated zone in a 75 foot by 50 foot area. Proposed design available. Multi-phase extraction (MPE) also being used. | | Accepted |
| 3 | PSH detected in MW-1 at a thickness of 0.01 ft. It was estimated that 6.8 lbs/day BTEX and 160 lbs/day TPH could be removed from the subsurface at this location. {25} | | Accepted |
| 4 | Three single vapor extraction wells are 10 feet deep with 8 feet screens. In a period of 157 days, 9584 pounds (or 1327 gallons) of toluene range HCs are removed. Good VOC removal vs. time data. BTEX in GW samples are not available. | Asymptotic behavior was not attained based on soil vapor extraction data. | Accepted |
| 5 | Estimated amount of sorbed gasoline onto vadose zone soils = 1100 gallons {p23}. Estimated amount of VOCs removed = 299 gallons (1956 pounds) as benzene in a period of 404 days {T2&T4}. Good VOC removed vs. time data. {1/93, F10, T4} | Asymptotic behavior was attained based on soil vapor extraction data. | Accepted |
| 6 | In a period of 33 days, 89 pounds (the equivalent of 7 gallons of TCE) of VOCs are removed {p9}. No long-term VOC removal data for this site. | Asymptotic behavior was not attained based on soil vapor extraction data. | Accepted |
| 7 | Estimated amount of contaminant that can be removed is more than 400 lbs/day. | | Accepted |
| 8 | Proposed full scale SVE system design available. Estimated cost data available. {p8-10} | | Accepted |
| 9 | Dissolved oxygen, ORP data available. Many parameters measured to determine ROI, however some were not strong indicators (i.e., ORP, specific conductivity) and some should no change at all (i.e., pH, temp, bicarbonate, carbonate). {p29} | | Accepted |
| 10 | Proposed full scale SVE system design available. Good VOC vs. distance removal data.<br>Good D.O./ upwelling/ pressure vs. distance data {Chart 3}. | | Accepted |
| 11 | The horizontal air sparging well screen (130 ft) consists of 1/8" perforation, in 3 ft intervals, in a spiral shape around the pipe. | | Accepted |
| 12 | Perched H2O table present over part of the site. No conclusions about ROI; often vapor probe was above the sparging well. | | Accepted |

| ID | Site | Facility Type | Client name | Report prepared by | Scale | Soil type |
|---|---|---|---|---|---|---|
| 13 | Cranbury / Pars, NJ | Gasoline station | NJ Turnpike Authority | Vapex Environmental Tech, Inc. | Pilot | Medium sand |
| 14 | Milton, WV | Gasoline station | Chevron | Engineering-Science | Pilot | Sandy |
| 15 | Crystal, MN | Gasoline station | Rapid Oil Change | Delta Environmental Consultants, Inc. | Pilot | NA |
| 16 | Grantsburg, WI | Industrial facility | Parker Hannafin Corp. | Delta Environmental Consultants, Inc. | Pilot | NA |
| 17 | Walla Walla, WA | Gasoline station | Unocal | Geo Engineers, Inc. | Pilot | Silty sand |
| 18 | Willow River, MN | Industrial facility | William Pipeline Company | EPA | Pilot | Fine to medium sand |
| 19 | Boulder Jn, WI | Industrial facility | White Sands Youth Camp | Delta Environmental Consultants, Inc. | Pilot | NA |
| 20 | Plattsburgh, NY | Gasoline station | Sun Company, Inc. / Atlantic | Matrix Environmental Technologies | Pilot | Sandy |
| 21 | Mt. Vernon, WA | Gasoline station | Unocal | Geo Engineers, Inc. | Pilot | Fine to medium sand |
| 22 | Rochester, MN | Gasoline station | Holiday Station | Delta Environmental Consultants, Inc. | Pilot | NA |
| 23 | Dodgeville, WI | Gasoline station | Braaten Oil Company | Delta Environmental Consultants, Inc. | Pilot | NA |
| 24 | Mondovi, WI | Gasoline station | Superamerica Service Station | Delta Environmental Consultants, Inc. | Pilot | NA |

| ID | Soil description | Contaminants | Conc Range |
|---|---|---|---|
| 13 | A 6 to 8 inches asphalt covering and coarse to fine sand to 30 feet below grade. From 30 to 45 feet, the coarse to fine sand contains a trace of silt. A sandy silt and clay appears to a depths of 45 feet below grade | Petroleum Hydrocarbons | 42 to 470 ppm. Vapor phase of OVA 60,000 to 80,000 ppm {p7} |
| 14 | Dry clay mixed with sand and gravel to 8 feet depth. Fine grained, poorly sorted sands and silts to depths of 14 feet. Fine grained, micaceous, well compacted sand present from 13 to 16 feet | BTEX and TPH | BTEX = 0 to 5.1 ppm and TPH = 13 to 500 ppm {T4} |
| 15 | NA | BTEX and THC | Soil air OVM 210 to 767 ppm {T} |
| 16 | NA | TCA | 12 to 39 ug/l (EPA 8240/601) |
| 17 | Silty fine sands upto a depth of 10 feet. Sandy gravel present from 10 to 13 feet below grade | BTEX and TPH | BTEX = 10,560 ug/L {T5} |
| 18 | A medium to fine red brown sand upto a depth of 20 feet for the majority of the known subsurface material, (appears to be unconfined). | BTEX and TPH | BTEX = 72 ug/l and THC = 680 ug/l |
| 19 | NA | THC | NA |
| 20 | Fine sands and silty clay over a dense silty fine sand embedded with coarse sands and gravels to a depth of 7 feet. (HSA met refusal at 10 feet) | BTEX | 65 ppb to 29,000 ppb |
| 21 | Gravel, sand or silt fill with occasional organic matter to depths of between 3 and 10 feet below the grade. The surficial fill is underlain by native fine sand with varying amounts of silt, grading with depth to fine to medium sand | BTEX | Total BTEX = 5,360 ppb {T2} and Fuel hydrocarbons 0 to 4 mg/L {p2} |
| 22 | NA | Petroleum Hydrocarbons | 30,000 ug/l |
| 23 | NA | Petroleum Hydrocarbons | 5,600 ug/l |
| 24 | NA | Petroleum Hydrocarbons | Vapor sample = 750 ug/l and Sum BTEX = 29,800 ug/L in H2O |

| ID | Type of Phase | Depth of GW table | Gradient of GW | No of GW monitoring wells | GWMW depth | GWMW dia |
|---|---|---|---|---|---|---|
| 13 | Dissolved and immiscible | 31 feet {p3} | 0.01 to 0.06 ft/ft | 5 {F2} | 25 to 43 feet {F3} | NA |
| 14 | Dissolved | 10 feet | NA | NA | NA | NA |
| 15 | NA | 17.8 feet | NA | 3 | 27 feet | NA |
| 16 | NA | NA | NA | 2 | 34 feet | 2 inch |
| 17 | NA | NA | NA | 13 {F2} | NA | NA |
| 18 | NA | 7 feet most of the time. Site was "ponded" at the time of IAS pilot study. | NA | 12 {F1} | NA | NA |
| 19 | Dissolved | 8.2 feet | NA | 8 | NA | 2 inches |
| 20 | Dissolved | 4 to 5 feet | NA | 5 | NA | NA |
| 21 | Dissolved | 10.5 feet {F4} | NA | 14 | NA | NA |
| 22 | NA | 12 to 18 feet | NA | 7 | 23 feet | 2 inches |
| 23 | Dissolved | 12 to 15 feet | NA | NA | NA | NA |
| 24 | Dissolved | 20.63 feet | NA | 9 | NA | NA |

| ID | GWMW screen length | No of IAS wells | IASW depth | IASW dia | IASW Screen length |
|---|---|---|---|---|---|
| 13 | 3 feet | 1 | 45 feet {p4} | 2 inch | 2 feet |
| 14 | NA | 1 | 14 feet {4-1} | NA | NA |
| 15 | 10 feet | 1 | 35.8 feet | 1.25 inch | 3 feet |
| 16 | 5 feet | 1 | NA | NA | NA |
| 17 | NA | 1 | 29 feet | 2 inch | NA |
| 18 | NA | 1 | 20 feet | 1.5 inch | 3 feet |
| 19 | 10 feet | 1 | 35 feet | NA | NA |
| 20 | NA | 1 | 8 to 10 feet | 2 inch {F5} | 2 feet |
| 21 | NA | 1 | 20.5 feet {FA-5} | 1.5 inch {p3} | 1 feet |
| 22 | 0.5 to 1.5 feet | 1 | 13.7 feet below water table | NA | 2 feet |
| 23 | 10 feet | 1 | 6 feet below water table | NA | 10 feet |
| 24 | NA | 1 | 39 feet | 2 inch | 5 feet |

| ID | IAS flow/pressure rate/well | IAS Radius of Influence/well | Method of IAS ROI | IAS Compressor size |
|---|---|---|---|---|
| 13 | 11.9 to 20 cfm @ 5.3 psi to 7 psi {p6} | 17 to 20 feet {p10} | Helium tracer, Ground water mounding and air bubbling {p6} | NA |
| 14 | 10 psi {4-1} | 0 feet | D.O. | 1.5 HP air compressor |
| 15 | 30 cfm @ 10 psi | 13.4 feet | D.O. | 185 cfm gas powered air compressor |
| 16 | NA | NA | NA | 10 to 100 cfm @ 0 to 50 psi |
| 17 | 6.3 cfm @ 7.9 psi | < 20 feet | D.O. | NA |
| 18 | 40 cfm @ 12 to 14 psi | 25 to 30 feet | Bubbling, Visualization | NA |
| 19 | 5 to 20 cfm @ 10 to 10.5 psi | NA | D.O., Bubbling | NA |
| 20 | NA | NA | NA | 2 HP Rotron blower |
| 21 | 28 cfm @ 4.25 psi {p9} | 15 feet | D.O., Bubbling | NA |
| 22 | 10 cfm @ 17 psi | 45 feet | D.O. | NA |
| 23 | NA | NA | NA | NA |
| 24 | 10 cfm @ 16 psi | 7 to 14 feet | Positive pressures and D.O. | NA |

| ID | No of IAS monitoring wells | IASMW depth | IASMW dia | IASMW screen length | No of SVE wells |
|---|---|---|---|---|---|
| 13 | NA | NA | NA | NA | 1 |
| 14 | 5 | 11 to 15 feet {p3.3} | 2 inch | 10 feet | 1 |
| 15 | NA | NA | NA | NA | NA |
| 16 | NA | NA | NA | NA | 1 |
| 17 | NA | NA | NA | NA | 1 |
| 18 | NA | NA | NA | NA | 1 |
| 19 | NA | NA | NA | NA | 1 |
| 20 | NA | NA | NA | NA | 1 |
| 21 | NA | NA | NA | NA | 2 |
| 22 | 1 | 9.7 feet above water table | NA | 15 feet | NA |
| 23 | NA | NA | NA | NA | 1 |
| 24 | 1 | 6 feet above water table | NA | 10 feet | NA |

| ID | SVEW depth | SVEW dia | SVEW Screen length | SVE flow/pressure rate/well | SVE radius of influence/well |
|---|---|---|---|---|---|
| 13 | 28 feet {p4&F3} | 2 inch | 5 feet | 10 to 20 cfm @ 2.5 to 4.4 inches of water column (air injected) | 20 feet {F5} |
| 14 | 9 feet | 4 inch | NA | NA | NA |
| 15 | NA | NA | NA | NA | NA |
| 16 | NA | NA | NA | 60 cfm @ 24 inches of water column | 56 feet |
| 17 | NA | NA | NA | 127 cfm @ 9.5 inches of w.c. and 116 cfm @ 18.2 inches of water column {p8} | 30 to 40 feet {p10} (1 well = 60 feet) |
| 18 | 8 feet | NA | 5 feet | NA | NA |
| 19 | NA | NA | 10 feet | 65 cfm @ 25 inches of water column | NA |
| 20 | Na | 2 inch | NA | NA | NA |
| 21 | 19.5 feet | NA | NA | NA | NA |
| 22 | NA | NA | 9.7 feet | 30 cfm @ 46 inches of water column | 8 feet |
| 23 | NA | NA | NA | 25 cfm @ 44 inches of water column | NA |
| 24 | NA | NA | NA | 15 cfm @ 44 inches of water column | 35 feet |

| ID | Method of SVE ROI | SVE Vacuum pump size | No of VMPs | VMP depth | VMP dia | VMP screen length |
|---|---|---|---|---|---|---|
| 13 | Air injection | NA | 7 {F3} | 28 feet {F3} and various depths | 0.5 inch | 0.5 feet |
| 14 | NA | NA | 5 {T6} | NA | NA | NA |
| 15 | NA | NA | NA | NA | NA | NA |
| 16 | Vacuum | Regenerative type vacuum blower rated 12 cfm @ 60 inches of water column | NA | NA | NA | NA |
| 17 | Vacuum | NA | NA | NA | NA | NA |
| 18 | NA | NA | NA | NA | NA | NA |
| 19 | Vacuum | NA | NA | NA | NA | 0.5 feet |
| 20 | NA | NA | NA | NA | NA | NA |
| 21 | NA | NA | NA | NA | NA | NA |
| 22 | NA | NA | NA | NA | NA | NA |
| 23 | NA | NA | NA | NA | NA | NA |
| 24 | 1% Vacuum | NA | NA | NA | NA | NA |

| ID | Effluent gas treatment | System operation | Other data |
|---|---|---|---|
| 13 | NA | Continuous | kr = 4.83E-7 cm^2, kz = 2.04E-7 cm^2, kc = 8.98E-11 cm^2, GW. velocity = 0.05 ft/d, K = 5 to 8.3 ft/d {p9} |
| 14 | NA | Continuous | K = 1.19E-4 to 7.6E-4 cm/sec, Porosity = 0.37 to 0.44 {T2}, T = 130 to 138 gpd/ft, Storativity = 0.005 to 0.01. Boring logs data available. |
| 15 | NA | Continuous | Air sparging well & monitoring well data, Air sparging field test data, Monitoring well soil & water biodata |
| 16 | NA | Continuous | Well data, Air sparging data, Pressure measurement data, Water level measurement data |
| 17 | NA | NA | Summary of Air sparge pilot test data and Summary of Vapor extraction pilot test data |
| 18 | NA | NA | Boring logs data available. Site was flooded at time of IAS ROI pilot study. |
| 19 | NA | NA | Total volume of air sparged vs. total volume of contaminant removed data available |
| 20 | Two vapor phase GAC vessels | NA | Sparge/SVE monitoring data available |
| 21 | NA | Continuous | Soil hydraulic conductivity = 790 ft/day {p7} |
| 22 | NA | NA | D.O., Vacuum and Pressure measurement data available |
| 23 | NA | NA | D.O., Vacuum and Pressure measurement data available |
| 24 | NA | NA | D.O., Vacuum and Pressure measurement data available |

| ID | Notes | Asymptotic behavior | Site status |
|---|---|---|---|
| 13 | Proposed full scale SVE system design available | | Accepted |
| 14 | Vapor extraction in the saturated sand and overlying soil is not feasible for this site. No vacuum was observed in response to an applied vacuum on the saturated layer. Groundwater extraction and IAS not feasible at this site. | | Rejected. IAS technology failure site. |
| 15 | Incomplete file. Conflicting information in the file. Insufficient data | | Rejected. No additional data available. |
| 16 | Incomplete file. Insufficient data. | | Rejected. No additional data available. |
| 17 | Incomplete file. However, data probably O.K. | | Accepted |
| 18 | The contaminate removal from the air sparge system between June 21, 93 and August 19, 93 is estimated at 86 pounds of THC as gasoline. NO SVE DATA. Video tape available. Visualization used for ROI. Site went to full scale but no data available. | | Accepted. |
| 19 | Preferential air flow pathways in the saturated zone was found because oxygenated water was detected in one monitoring well which was 19 feet from sparge point and not detected in other monitoring well which was 3 feet from sparge point. | | Rejected. IAS technology failure site |
| 20 | No data to indicate IAS ROI. Very incomplete file. Insufficient data. | | Rejected. No additional data available. |
| 21 | IAS/SVE test system parameters available. Incomplete file. Groundwater pumping/SVE | | Accepted |
| 22 | Removal rate estimated is 80 pounds of petroleum hydrocarbons per day during the polot study. Insufficient data. | | Rejected. No additional data available. |
| 23 | Conclusion was that SVE and IAS is not a feasible technology for this site. Preferential flow observed to 130 feet away. Figures missing. No wells closer than 42 feet of SVE | | Rejected. IAS technology failure site. |
| 24 | Removal rate estimated = 1 pound of petroleum hydrocarbons per day | | Accepted |

| ID | Site | Facility Type | Client name | Report prepared by | Scale | Soil type |
|---|---|---|---|---|---|---|
| 25 | Richfield, MN | Gasoline station | Amoco | Delta Environmental Consultants, Inc. | Pilot | NA |
| 26 | Orrock, MN | Garage | Lambert Garage | Delta Environmental Consultants, Inc. | Pilot | NA |
| 27 | St. Paul, MN | Gasoline station | Savemore Station | Delta Environmental Consultants, Inc. | Pilot | Coarse sand |
| 28 | Spring Green, WI | Gasoline station | Koller Petroleum | Delta Environmental Consultants, Inc. | Pilot | NA |
| 29 | Elmira Heights, NY | Former gasoline station | A Plus Mini Market | Matrix Environmental Technologies | Pilot & Full | Sandy |
| 30 | Holbrook | Gasoline station | Sun Company, Inc. | Groundwater & Environmental Services, Inc. | Full only (No pilot) | Coarse to fine sands |
| 31 | Blaine, MN | Gasoline station | Kunz Oil Company | Dahl & Associates, Inc. | Pilot & Full | Fine to medium sand |
| 32 | Margate, FL | Gasoline station | Mobil | H2O Environmental, Inc. | Pilot | Fine to medium sand |
| 33 | Isle, MN | Gasoline station | NA | Delta Environmental Consultants, Inc. | Pilot | NA |
| 34 | Chillicothe, OH | Gasoline station | BP Oil Company | Hull & Associates, Inc | Pilot | Sand and gravel |
| 35 | West 65th street, Cleveland, OH | Gasoline station | BP Oil Company | Engineering-Science | Full only (No pilot) | Silty sand |
| 36 | Clifton Boulevard, Cleveland, OH | Gasoline station | BP Oil Company | Engineering-Science | Pilot | Silty sand |

| ID | Soil description | Contaminants | Conc Range |
|---|---|---|---|
| 25 | NA | Petroleum Hydrocarbons, BTEX | Vapor sample = 38,000 to 54,000 ug/l and Sum BTEX = 53,400 ug/L in H2O |
| 26 | NA | Petroleum Hydrocarbons, BTEX | 480 to 36,000 ug/l and Sum BTEX = 14,070 in H2O |
| 27 | Cement pavement covering sandy peat to 14 feet, silty sand 14 to 21 feet, coarse sand 21 to 30 feet | Benzene and THC | Benzene = 21 ug/l and THC = 2100 ug/l (vapor samples) |
| 28 | NA | Petroleum Hydrocarbons | 49,000 ug/l |
| 29 | The underlying bedrock consists of shales and siltstones. The surficial deposits are outwash sand and gravels. | BTEX | 2 to 3600 ug/l (EPA 602) |
| 30 | Site consists of brown to tan, coarse to fine-sands mixed with trace amounts of gravel and silt. | BTEX | BTEX max. = 466 ppm (EPA 602) |
| 31 | Brown, damp to moist, medium dense, medium to fine sand upto depths of 21 feet | BTEX | 1700 ppb {T1} |
| 32 | The site is underlain by fine to medium grained quartz sand | BTEX and MTBE | BTEX max. = 14,900 ppb and MTBE max. = 1,100 ppb (EPA 602,610) |
| 33 | NA | THCs | THC = 2100 ug/L |
| 34 | The surficial material in the area of the site consists of glacial outwash composed of unconsolidated sand and gravel typically 100-125 feet in thickness. | BTEX and TPH | BTEX max. = 231.6 mg/kg (EPA 8020) and TPH = 220 mg/kg (EPA 418.1) {p6} |
| 35 | Subsurface soils range from sand, to silt, to clay. Intermittent sand and silt lenses are characteristic of the material firm surface to 20 to 25 feet below grade. A most consistent clay layer present at 25 feet below grade. {p3} | BTEX and TPH | BTEX = 0.013 ppm to 1,100 ppm (EPA 8020) and TPH = 21 to 550 ppm in soils (EPA 418.1) {p14} |
| 36 | A brown sand extends from beneath pavement to 10 to 12 feet below grade. The sand is generally fine grain, well sorted, but silty on occasion and damp to moist. Beneath the sand lies an unknown thickness of moist, gray, sandy silt. | BTEX and TPH | BTEX max. = 97 ppm and TPH max. = 870 ppm (EPA 8020) |

| ID | Type of Phase | Depth of GW table | Gradient of GW | No of GW monitoring wells | GWMW depth | GWMW dia |
|---|---|---|---|---|---|---|
| 25 | Dissolved | 39.18 feet | NA | 9 | NA | NA |
| 26 | Dissolved | 14.62 feet | NA | 4 | NA | NA |
| 27 | Dissolved | 19.8 feet | NA | NA | NA | NA |
| 28 | NA | 9.35 feet | NA | NA | NA | NA |
| 29 | NA | 12 to 14 feet | NA | 11 | NA | NA |
| 30 | Dissolved and immiscible | 20 to 34 feet | 0.002 ft/ft | 44 | NA | NA |
| 31 | NA | 15 to 21 feet | 2.11E-03 | 6 | 23 feet | NA |
| 32 | NA | 5 to 7 feet | NA | 11 | NA | NA |
| 33 | NA | NA | NA | NA | NA | NA |
| 34 | NA | 30 feet {p5, F2-5} | 0.0026 ft/ft | 9 {p4} | 30 to 60 feet {F2-6} | NA |
| 35 | Dissolved | 19 feet {p24} | 0.02 ft/ft | 8 {F5} | 25 feet {F11} | 4 inch |
| 36 | NA | 9.15 to 11.3 feet | 0.025 ft/ft | 4 | NA | NA |

| ID | GWMW screen length | No of IAS wells | IASW depth | IASW dia | IASW Screen length |
|---|---|---|---|---|---|
| 25 | NA | 1 | 56.1 feet | 2 inch | 3 feet |
| 26 | NA | 1 | 27.8 feet | 1 inch | 3 feet |
| 27 | NA | 1 | 32.6 feet | 1.25 inch | 3 feet |
| 28 | NA | 1 | 19.9 feet | 2 inch | 3 feet |
| 29 | NA | 1 | 25 feet | 1 inch | NA |
| 30 | NA | 3 | 43 feet | 4 inch | 5 feet |
| 31 | NA | 19 {T4} | 33 feet | 2 inch | 3 feet |
| 32 | NA | 1 | 19 feet | 4 inch | 3 feet |
| 33 | NA | 1 | 10.2 feet below GW table | NA | 3 feet |
| 34 | 10 feet | 2 | 38 feet and 43 feet {p19} | 1.25 inch {p27} | 3 feet |
| 35 | 10 to 15 feet {F11} | 6 {p5, F2} | 26 feet {F10} | 4 inch | 5 feet {F13} |
| 36 | NA | 1 | 16 feet | 2 inch | 2.5 feet |

| ID | IAS flow/pressure rate/well | IAS Radius of Influence/well | Method of IAS ROI | IAS Compressor size |
|---|---|---|---|---|
| 25 | 10 cfm @ 7.5 psi | NA | D.O, Bubbling | NA |
| 26 | 10 cfm @ 6 psi | 10 to 15 feet | Positive pressures and D.O. | NA |
| 27 | 5 cfm @ 7 psi | 15 to 20 feet | D.O., Ground water mounding | NA |
| 28 | 10 cfm @ 3.5 psi | 20 to 30 feet | D.O. | NA |
| 29 | 17 cfm @ 12.5 psi | NA | Bubbling, Helium tracer | 2 HP regenerative blower |
| 30 | 30 cfm @ 9.25 psi {p3} | NA | NA | NA |
| 31 | 1.3 cfm @ 8 psi {T5} | 15 feet {p5, 4/1993} | D.O. {p5, 4/1993} | NA |
| 32 | 6.6 cfm | 65 feet - D.O<br>15 feet - Bubbling | D.O. and bubbling | 5 HP Spencer Lobe-Aire Blower (Model No. RBL-100) |
| 33 | NA | NA | NA | NA |
| 34 | 5 cfm | NA {p52} | NA | Electric compressor rated 5.5 cfm @ 40 psi {p21} |
| 35 | 3 to 6 psi {p18} | 15 feet (design only) {p8} (The 15 foot design value was obtained after system start-up.) | D.O. & decrease in vacuum {p13} | 15 HP, oil-less compressor rated 3 to 25 psi {p8} |
| 36 | 3.75 cfm @ 5 psi | 15 to 20 feet {p8} | Positive pressures, helium tracer, VOCs in soil vapor and bubbling | NA |

| ID | No of IAS monitoring wells | IASMW depth | IASMW dia | IASMW screen length | No of SVE wells |
|---|---|---|---|---|---|
| 25 | 1 | 5 feet above water table | NA | 10 feet | NA |
| 26 | 2 | 5.2 feet above water table | 2 inch | 10 feet | NA |
| 27 | 1 | 3.8 feet above water table | 2 inch | 10 feet | NONE |
| 28 | 1 | 5.6 feet above water table | NA | 10 feet | 1 |
| 29 | NA | NA | NA | NA | 7 |
| 30 | NA | NA | NA | NA | 5 |
| 31 | NA | NA | NA | NA | 18 |
| 32 | NA | NA | NA | NA | 1 |
| 33 | 2 | 2.6 to 3.2 feet above GW table | NA | 5 feet | 1 |
| 34 | NA | NA | NA | NA | 4 {p19} |
| 35 | 3 {F5} | 25 feet {F10} | 2 inch | 10 feet | 2 vertical and 1 horizantal |
| 36 | 3 | 14 feet | 2 inch | 2 feet | 1 |

| ID | SVEW depth | SVEW dia | SVEW Screen length | SVE flow/pressure rate/well | SVE radius of influence/well |
|---|---|---|---|---|---|
| 25 | NA | NA | NA | 17 cfm @ 40 inches of water column | 69 feet |
| 26 | NA | NA | NA | 50 cfm @ 38 inches of water column | 43 feet |
| 27 | NA | NA | NA | NA | NA |
| 28 | 15.4 feet | 2 inch | 10 feet | 70 cfm @ 24 inches of water column | 32 feet |
| 29 | 17.5 feet | 2 inch | 10 feet | 18 cfm | NA |
| 30 | 17 feet | NA | NA | 70 cfm | NA |
| 31 | 19 to 22 feet | 2 inch | 10 feet | 9 cfm @ 40 inches of water column {T3} | 34 feet {p4, 4/1993} |
| 32 | 6.5 feet | 4 inch | 5.5 feet | 47 cfm | 20 feet |
| 33 | 6.5 feet | NA | 5 feet | 30 cfm @ 20 inches of water column | NA |
| 34 | 30 feet {F2.4} | 4 inch | 10 feet | 50 cfm | 20 to 60 feet {p40-45} |
| 35 | 21.5 feet {F12} and 3.5 feet for horizantal well {F16} | 4 inch | 10 feet | 40 to 50 cfm @ 35 inches of water column {p22} | 30 feet {p8} |
| 36 | 21 feet | 4 inch | 15 feet | 30 inches of water column | >30 feet |

| ID | Method of SVE ROI | SVE Vacuum pump size | No of VMPs | VMP depth | VMP dia | VMP screen length |
|---|---|---|---|---|---|---|
| 25 | 1% Vacuum | NA | NA | NA | NA | NA |
| 26 | 1% Vacuum | NA | NA | NA | NA | NA |
| 27 | NA | NA | NA | NA | NA | NA |
| 28 | 1% Vacuum | NA | NA | NA | NA | NA |
| 29 | NA | 2 HP rotary vane compressor | NA | NA | NA | NA |
| 30 | NA | Gast rotary vane blower capable of 15 psig @ 30 cfm | NA | NA | NA | NA |
| 31 | Vacuum | NA | 5 {T3} | NA | NA | NA |
| 32 | NA | 2.3 HP Fuji ring compressor (Model No. UFC 504P-24) | 3 | 11 to 12 feet | 2 inch | 10 feet |
| 33 | NA | NA | NA | NA | NA | NA |
| 34 | Vacuum | 5 HP positive displacement blower rated 230 cfm @ 6 inches of Hg. {p21} | 12 {p19} | NA | 2 inch | 10 feet {p19} |
| 35 | Vacuum & % O2 in vapor measurements {p13} | 5 HP regenerative blower rated 225 cfm @ 85 inches of water column {p7} | 25 {p6} | 15.5 feet | 1 inch | NA |
| 36 | Vacuum | 5 HP regenerative blower | 21 | 5 to 8 feet | 0.75 inch | NA |

| ID | Effluent gas treatment | System operation | Other data |
|---|---|---|---|
| 25 | NA | NA | D.O., Vacuum and Pressure measurement data available |
| 26 | NA | NA | D.O., Vacuum and Pressure measurement data available |
| 27 | NA | NA | D.O., Vacuum and Pressure measurement data and cost estimate available |
| 28 | NA | NA | D.O., Vacuum and Pressure measurement data available |
| 29 | NA | NA | D.O. and well construction details available |
| 30 | NA | Pulsed | Transmissivity = 171,991 gal/day/ft. SVE system monitoring data available. |
| 31 | NA | NA | Boring logs data |
| 32 | NA | Continuous | Summaries of GW quality, D.O., negative pressures and Air sparging and VES effectiveness table available. |
| 33 | NA | NA | NA |
| 34 | Two 200 pound carbon canisters {p21} | Continuous | K = 0.001 to 0.1 cm/s. {p5} |
| 35 | NA | Initially continuous and then pulsed {p13,14} | Oxygen and carbon dioxide in soil vapor, data available. |
| 36 | NA | NA | Boring logs data available |

| ID | Notes | Asymptotic behavior | Site status |
|---|---|---|---|
| 25 | Removal rate estimated = 82 pounds of petroleum hydrocarbons per day. Preferential flow observed because of clay/silt layer. Conclusion was that site was not conductive to IAS technology. ROI not observed. | | Rejected. IAS technology failure site. |
| 26 | Removal rate estimated = 2.2 pounds of petroleum hydrocarbons per day | | Accepted |
| 27 | Removal rates: Benzene = 0.06 lb/day and Total hydrocarbons = 5.7 lbs/day | | Accepted |
| 28 | Removal rate estimated = 34 pounds of petroleum hydrocarbons in a period of 160 minutes | | Accepted |
| 29 | Estimated gasoline recovery via vapor extraction system is 37.9 gallons in a period of 14 months. The site is currently operating. | Data not available | Accepted |
| 30 | GW recovery system also implemented at this site. No evaluation of ROI was conducted. No pilot data. However it does have full scale performance data. Only limited use of IAS to intercept hydrocarbon plume. Insufficient data. | Asymptotic behavior was attained based on soil vapor extraction data. | Rejected. No additional data available. |
| 31 | Estimated removal rate = 11.92 gal/day. Full scale operating length = 15 days. Therefore, no BTEX removal data was present in file, following IAS start-up. | Data not available | Accepted |
| 32 | The site has been undergoing remediation by "pump and treat" technology which consists of a recovery well pumping at an average of 16.9 gpm | | Accepted |
| 33 | Estimated removal rate for benzene = 0.06 lbs/day and THC = 5.7 lbs/day during the pilot study. Insufficient data. | | Rejected. No additional data available. |
| 34 | VOCs removal rate data available. ROI could not be determined for this site. Insufficient data. | | Rejected. No additional data available |
| 35 | After clean up concentration data available. Pilot scale studies not conducted {p8}. VOC vs. time data available. | Asymptotic behavior was attained based on soil vapor extraction data. | Accepted |
| 36 | PSH detected in MW-3 at a thickness of 0.07 ft. This site is presently undergoing full scale. Extensive data was collected, therefore, sites were considered full-scale for plots in section 6 of report. | | Accepted |

| ID | Site | Facility Type | Client name | Report prepared by | Scale | Soil type |
|---|---|---|---|---|---|---|
| 37 | Batavia, NY | Gasoline station | Mobil | Groundwater Technology, Inc. | Full only (No pilot) | Silty sand |
| 38 | Yuba City, CA | Gasoline station | Shell | Weiss Associates | Full only (No pilot) | NA |
| 39 | Bristol, CT | Gasoline station | Shell | Groundwater Technology, Inc | Pilot & Full | Fine sand |
| 40 | Raleigh, NC | Gasoline station | Shell | Groundwater Technology, Inc | Pilot | Silty sand |
| 41 | Beaverton, OR | Gasoline station | Shell | Hart Crowser, Inc. | Pilot | Very silty clays |
| 42 | Hayden Island, OR | Gasoline station | Shell | Hart Crowser, Inc. | Pilot | Medium sand |
| 43 | Huntington Beach, CA | Gasoline station | Shell | Environmental Science & Engineering, Inc | Pilot | Silty clay |
| 44 | Sayreville, NJ | Industrial facility | Enprotec | Vapex Environmental Tech, Inc. | Pilot & Full | Medium to coarse sand |
| 45 | Pawtucket, RI | Service station | NA | Vapex Environmental Tech, Inc. | Pilot & Full | Coarse sand |
| 46 | Dennisport, MA | Service station | Taft's Service Station | Vapex Environmental Tech, Inc. | Full only (No pilot) | NA |
| 47 | Framingham, MA | Maintenance facility | Homart, Shopper's World | Vapex Environmental Tech, Inc. | Full only (No pilot) | Silty sand |
| 48 | Stamford, CT | Industrial facility | NA | Linda Martin, Richard Sarnelli and Matthew Walsh (paper) | Pilot | Silty sand |

| ID | Soil description | Contaminants | Conc Range |
|---|---|---|---|
| 37 | Brown, silt and sand containing course to fine gravel upto depths of 22 feet. Grey saturated sands below 22 feet. | BTEX | BTEX max. = 53,000 ppb |
| 38 | NA | BTEX & TPH | BTEX max. = 3682 ppb and TPH = 10,000 ppb {T2} |
| 39 | Sand and gravel fill overlying fine sand with trace fine gravel and trace silt upto depths of 20 feet below grade. | BTEX | BTEX = 120,000 ppb {T10} BTEX = 97 ppmv in vapor {T2} |
| 40 | Site consists of red-brown, sandy to silty clay overlying micaceous, silty sand. The soils are saprolitic and bedrock was encountered at approximately 70 feet below grade. {p3} | BTEX | BTEX max. = 10,460 ppb {T2} |
| 41 | The soils at the site are sandy, very silty clays. Bedrock present below 25 feet. | TPH | TPH max. = 240 mg/kg |
| 42 | The site consists of a layered system of sands, silts, and clays down to about 35 feet below grade, overlying a medium sand down to about 100 feet below grade where the regional sand and gravel aquifer is encountered. | BTEX and TPH | BTEX max. = 37 mg/m^3 and TPH max. = 500 mg/m^3 {T1} |
| 43 | The site consists of a 10 foot thick silty sand, 5 to 10 foot thick silty clay and a 1 to 2 foot thick silty clay layer below grade respectivily. | BTEX and TPH | BTEX = 730 mg/kg (EPA 8020) and TPH = 2500 mg/kg (EPA 8015) {T2} |
| 44 | Mediun to coarse sand to a depth of approxi ately 55 feet below grade where it changes to a silty sand. | Toluene | 560 ppm in soil sample and 2600 ppm u\ in water sample {p2} |
| 45 | Fine to coarse brown sand with no silt and 5 to 15 percent fine to medium gravel extending from grade to 19 to 20 feet below grade. The coarse, highly permeable material is underlain by a much less permeable dense fine sand. {p94} | BTEX | 835 ug/kg (EPA 8020) {p94} |
| 46 | NA | BTEX | 69,100 ug/L {T2} |
| 47 | Fine, gray, narrowly graded sand and fine sands with 20% silts are present upto depths of 28 feet. | BTEX | 17,600 ug/L (EPA 8020) {T2} |
| 48 | Site consists of stratified sands and gravel in the unsaturated zone grading into very fine sands and silts within the saturated zone. | TCE | 7.20 ppm {F9} |

| ID | Type of Phase | Depth of GW table | Gradient of GW | No of GW monitoring wells | GWMW depth | GWMW dia |
|---|---|---|---|---|---|---|
| 37 | NA | 25 feet | NA | 4 | NA | NA |
| 38 | Vapor | 15 to 23 feet | NA | 10 | NA | NA |
| 39 | Dissolved | 19 feet {p2} | 0.062 ft/ft | 9 {F2} | NA | NA |
| 40 | Dissolved | 37 to 47 feet {p4} | 0.0046 ft/ft {p4} | 11 {T2} | 50 to 70 feet {BL} | 4 inch |
| 41 | Dissolved | 12 to 15 feet | NA | NA | NA | NA |
| 42 | Dissolved | 17 to 27 feet {p2} | NA | 11 {F2} | 30 to 35 feet {F3&4} | NA |
| 43 | Dissolved | 16 feet {p3} | NA | 25 {T2} | NA | NA |
| 44 | Dissolved | 5 feet {p3} | NA | 6 {p4} | 12 feet {F2} | NA |
| 45 | Dissolved | 16 feet {p94} | NA | 2 {F4} | NA | NA |
| 46 | Dissolved | 8 to 10 feet {p3} | NA | 7 {F1} | NA | NA |
| 47 | Dissolved | 5 to 14 feet {BL} | NA | 14 {T2} | 12 to 20 feet {BL} | 2 inch |
| 48 | Dissolved | 19 feet {P3} | 0.0001 to 0.005 ft/ft {P3} | 6 {f3} | 30 feet {F4} | NA |

| ID | GWMW screen length | No of IAS wells | IASW depth | IASW dia | IASW Screen length |
|---|---|---|---|---|---|
| 37 | NA | 4 | 35 feet | 2 inch | 2 feet |
| 38 | NA | 11 {T6} | NA | NA | NA |
| 39 | NA | 2 | 29 & 32 feet {p4} | 1.25 inch | 2 feet |
| 40 | 20 to 30 feet | 1 | 65 feet {BL} | 2 inch | 5 feet |
| 41 | NA | NA | NA | NA | NA |
| 42 | NA | 1 | 40 feet | 2 inch | 2 feet |
| 43 | NA | 2 {p6} | 25 feet {F4} | 2 inch | 2 feet |
| 44 | NA | 4 {p4} | 20 feet {p16} | NA | 2 feet |
| 45 | NA | 7 shallow and 6 deep {p98} | Deep = 27 ft. and Shallow = 21 feet {p96&p98} | NA | 2 feet |
| 46 | NA | 9 {p2} | 15 to 19 feet {p2} | 1 inch | 1feet |
| 47 | 10 to 12 feet {BL} | 22 {p1} | 9 to 18 feet {BL} | NA | 1 feet |
| 48 | NA | 6 {P2} | 25 to 40 feet {P2} | 1.5 inch {P5} | 2 feet {P5} |

| ID | IAS flow/pressure rate/well | IAS Radius of Influence/well | Method of IAS ROI | IAS Compressor size |
|---|---|---|---|---|
| 37 | 12.5 cfm | 45 feet | NA | 7 HP positive displacement pump |
| 38 | 1.9 cfm @ 6.6 psi {T6} | NA | NA | NA |
| 39 | 1.75 cfm @ 10 psi {p11} | 25 ft - Positive pressures {T5} and BTEX removal {p12, F10}<br>52 ft - D.O. {T6}<br>49 ft - GW mounding {p10, | Positive pressures, D.O. and decrease in BTEX concentration | 3 HP non-explosion proof compressor rated 11 cfm @ 100 psi {p5} |
| 40 | 8 to 24 cfm @ 14 to 18 psi {T6} | 25 feet {p23} | Positive pressures, D.O., GW mounding | NA |
| 41 | NA | NA | NA | NA |
| 42 | 14 cfm @ 8 psi {p8} | 50 feet {p8} | D.O., positive pressures, Helium tracer and Sulfur Hexafluoride tracers {p8} | NA |
| 43 | 40 cfm @ 6 psi {p7} | 40 feet {p9} | Helium tracer, VOC content and GW mounding | NA |
| 44 | 5 cfm @ 10 psi {p26} | 12.5 feet - Past experience {p16}, 55 feet - GW mounding {p13} and 15 feet - Air bubbling {p14} | Bubbling and Groundwater mounding | 2.5 HP Ingersoll Rand oilless air compressor {p7} |
| 45 | Deep = 2 to 6 cfm @ 6 to 8 psi and Shallow = 3 to 6 cfm @ 1 to 2 psi {p98} | 5 feet {p96} | Positive pressures and Groundwater mounding {p96} | Two, 2.5 HP Ingersoll-Rand compressors {p98} |
| 46 | 4 to 6 psi {p3}<br>Flow data not available | NA | NA | 2.5 HP oil-less air compressor (Ingersoll-Rand model) {p2} |
| 47 | 2.5 to 3.5 cfm @ 11 psi {T2} | 10 feet | NA | NA |
| 48 | 5 cfm @ 15 to 30 psi {P7} | 40 feet {P8} | Bubbling, D.O., GW mounding and trapped vapors {P8} | 10 HP, two stage reciprocating oil-less air compressor with a maximum pressure of 175 psi. {P6} |

| ID | No of IAS monitoring wells | IASMW depth | IASMW dia | IASMW screen length | No of SVE wells |
|---|---|---|---|---|---|
| 37 | NA | NA | NA | NA | 4 |
| 38 | NA | NA | NA | NA | 8 {T5} |
| 39 | NA | NA | NA | NA | 2 |
| 40 | NA | NA | NA | NA | 3 {p6} |
| 41 | NA | NA | NA | NA | NA |
| 42 | NA | NA | NA | NA | 4 {F2} |
| 43 | NA | NA | NA | NA | 4 {p6} |
| 44 | NA | NA | NA | NA | 3 {p4} |
| 45 | NA | NA | NA | NA | 2 {F4} |
| 46 | NA | NA | NA | NA | 2 {F1} |
| 47 | NA | NA | NA | NA | 22 {p1} |
| 48 | NA | NA | NA | NA | 2 {P2} |

| ID | SVEW depth | SVEW dia | SVEW Screen length | SVE flow/pressure rate/well | SVE radius of influence/well |
|---|---|---|---|---|---|
| 37 | 24 feet | 2 inch | 22 feet | 50 cfm | 45 feet |
| 38 | NA | NA | NA | 19 cfm {T5} | NA |
| 39 | 18.5 & 24 feet {p4} | 4 inch | 5 & 10.5 feet {p4} | 45 cfm @ 44 inches of water column {p11} | 100 feet {9/92, p9} |
| 40 | 55 feet {BL} | 4 inch | 20 to 35 feet | 21 to 23 cfm @ 50 to 60 inches of water column {T6} | 20 feet {p24} |
| 41 | NA | NA | NA | NA | NA |
| 42 | 25 feet {F3} | NA | NA | 60 cfm @ 46 inches of water column | NA |
| 43 | 12 & 20 feet | 2 inch | 5 feet | NA | NA |
| 44 | 6 feet {F2} | NA | 3 feet | 30 cfm @ 21 inches of water column {p23} | 25 feet {p20} |
| 45 | NA | NA | NA | 100 cfm (Pilot) {p96} | NA |
| 46 | NA | NA | NA | NA | NA |
| 47 | 5 to 13 feet {BL} | NA | 3 to 5 feet {BL} | 20 cfm @ 15 inches of w.c. {T2} | 17 feet |
| 48 | 15 to 17 feet {P2} | 2 inch {P5} | 5 feet {P5} | 35 cfm @ 15 to 20 inches of water column {p9} | NA |

| ID | Method of SVE ROI | SVE Vacuum pump size | No of VMPs | VMP depth | VMP dia | VMP screen length |
|---|---|---|---|---|---|---|
| 37 | NA | 5 HP ORS system | NA | NA | NA | NA |
| 38 | NA | NA | NA | NA | NA | NA |
| 39 | Vacuum | 2 HP regenerative blower rated 105 cfm @ 30 inches of water column vacuum {p5} | NA | NA | NA | NA |
| 40 | Vacuum (0.1 inch) {p9} | NA | NA | NA | NA | NA |
| 41 | NA | NA | NA | NA | NA | NA |
| 42 | NA | NA | NA | NA | NA | NA |
| 43 | NA | NA | NA | NA | NA | NA |
| 44 | Vacuum | 0.5 HP regenerative blower rated 55 cfm {p6} | 16 {p4} | 20 feet {F2} | NA | 2 feet |
| 45 | NA | NA | 3 {F4} | NA | NA | NA |
| 46 | NA | 1 HP regenerative blower rated 98 cfm maximum capacity {p2} | 6 {F1} | NA | NA | NA |
| 47 | NA | NA | 4 {T2} | NA | NA | NA |
| 48 | NA | 1 HP, 98 cfm regenerative blower {p6} | 10 {p2} | 22 to 27 feet {p6} | NA | 2 feet |

| ID | Effluent gas treatment | System operation | Other data |
|---|---|---|---|
| 37 | Two carbtrol G-2 GAC units in series | NA | D.O. vs. Time data available |
| 38 | NA | Pulsed | Hydrocarbon removal rate data available |
| 39 | NA | Pulsed | K = 0.002 ft/day {p3}, Transmissivity = 0.15 gpd/ft, GW flow velocity = 0.00014 ft/day. SVE concentrations/mass removal (Table 2) available. |
| 40 | NA | Continuous | K = 3.1 ft/day, Transmissivity = 35.22 ft^2/day, Porosity = 0.1, GW flow velocity = 0.09 ft/day {p5} |
| 41 | NA | NA | K = 0.03 to 2 feet/day, TOC concentration = 770 mg/kg |
| 42 | NA | NA | D.O. data available {T2} |
| 43 | NA | Continuous | Contaminant conc. vs. time data available |
| 44 | NA | Continuous | kr = 2.16E-07 cm^2, kz = 1.60E-07 cm^2 and kc = 1.60E-08 cm^2 |
| 45 | NA | Pulsed | BTEX conc. sampling prior to and after air injection data available {F5} |
| 46 | Catalytic oxidation unit {p2} | Pulsed | Contaminant removal vs. system running time graph available. {F3} |
| 47 | Catalytic oxidation unit | Pulsed | Cost data available |
| 48 | 1,000 pound vapor phase activated carbon bed {p6} | Pulsed | Total VOC conc. vs. elapsed time data available {F8} |

| ID | Notes | Asymptotic behavior | Site status |
|---|---|---|---|
| 37 | Full data to "no further action" is available. Wells were combination vapor extraction/air sparging. Incomplete file. | Asymptotic behavior was attained based on soil vapor extraction data. | Accepted |
| 38 | 5,573 pounds of hydrocarbons removed in a period of 2,352 total operation hours. Limited data. This is only a monthly status report. Insufficient data. | Data not available | Accepted |
| 39 | During 264 days of system operation 1911 pounds of hydrocarbons have been removed. VOC vs. time data available. Reported problems of IAS plugging from iron precipitation {p6}. Combination SVE/IAS wells used. BTEX removal data available in file. | Asymptotic behavior was attained based on soil vapor extraction data. | Accepted |
| 40 | Ground water sampling data available | | Accepted |
| 41 | Aiir sparging test did not show any influence in observation wells as close as 5 feet from the test well, with air pressure as high as 20 psi. IAS is not feasible at this site. Good example of soils where IAS would not work. IAS technology failure site | | Rejected. IAS technology failure site. |
| 42 | Data collected during this short term test did not indicate if air sparging would significantly enhance the mass removal rate of gasoline constituents from the saturated zone. {p1} | | Accepted |
| 43 | Sparging test field data available | | Accepted |
| 44 | The site went to full scale but no data available. | | Accepted |
| 45 | 5 to 10 pounds of gasoline range hydrocarbons were removed in a period of 60 days {p100}. Site achieved regulatory closure. | Asymptotic behavior was attained based on BTEX concentrations | Accepted |
| 46 | 438 to 484 pounds of gasoline range hydrocarbons were removed in a period of 119 days {p4}. No ROI data. However, data from design sizing might be useful. | Asymptotic behavior was attained based on soil vapor extraction data. | Accepted |
| 47 | 366 pounds (56 gallons) of total VOCs as benzene were removed in a period of 95 days {F2}. Very little performance data available. | Asymptotic behavior was not attained based on soil vapor extraction data. | Accepted |
| 48 | The mass of VOCs removed over the four week operation is estimated at approximately 4 pounds {p9} | | Accepted |

| ID | Site | Facility Type | Client name | Report prepared by | Scale | Soil type |
|---|---|---|---|---|---|---|
| 49 | Woburn, MA | Distribution facility | Maggiore Companies | Vapex Environmental Tech, Inc. | Pilot & Full | Fine to coarse sands |
| 50 | Grants(N), NM | Oil refinery | Prewitt Refinery | Vapex Environmental Tech, Inc. | Pilot | Sandstone |
| 51 | Grants(S), NM | Oil refinery | Prewitt Refinery | Vapex Environmental Tech, Inc. | Pilot | Sandstone |
| 52 | Sartomer, PA | NA | NA | Vapex Environmental Tech, Inc. | Pilot | Silty clay |
| 53 | Windsor Locks, CT | NA | Hamilton Standard | ERI, University of Connecticut | Pilot | Fine to medium sand |
| 54 | Florence, OR | Former gasoline station | NA | Susan Schima, Douglas J. Labrecque and Paul Lundegard (Paper) | Pilot | Coarse sand |
| 55 | Missoula, Montana | Gasoline station | Conoco | Huntingdon Chen-Northern, Inc. | Pilot & Full | NA |
| 56 | Wood Village, OR | Gasoline station | BP Oil Company | RZA AGRA, Inc. | Pilot & Full | Silty clay |
| 57 | Newark, DE | Gasoline station | Sun Refining and Marketing | Environmental Alliance, Inc. | Pilot & Full | Silty clay |
| 58 | Southington, CN | Industrial facility | SRSNE PRP group | ENSR Consulting and Engineering | Pilot | NA |
| 59 | Kalkaska, MI | Gasoline station | Amoco | Amoco members | Pilot | Sandy |

| ID | Soil description | Contaminants | Conc Range |
|---|---|---|---|
| 49 | NA | BTEX | Upto 5,000 ppmv unsaturated zone soil gas |
| 50 | Site consists of a fine to medium grained moderately fractured sandstone. The sandstone is split by a one to two foot thick siltstone lens across all but the westernmost 50 feet of the north area plume. {p8-2} | BTEX | 700 to 12,000 ppmv {p5-34} |
| 51 | Site consists of a fine to medium grained moderately fractured sandstone. The sandstone is bound above by the F parting, and below by the upper confining bed. {p8-17} | BTEX | 80,000 ppm {p7-17} |
| 52 | Site consists of clayey silts upto depths of 5 feet, clayey silty sands upto 10 feet depth and weathered bedrock crumbles to silty sand upto depths of 20 feet. {4/6/93, BL} | Benzene | Vapor = 27,000 to 65,000 ppmv {p2} |
| 53 | Medium sand to depths of 8 feet. Fine to very fine sand with traces of silt from 8 to 23 feet. Medium coarse sand occurs below 23 feet. | TCE & PCE | TCE = 200 to 55oo ppb and PCE = 15 to 400 ppb |
| 54 | The site is underlain by sand and gravel fill down to a depth of 2.5 ft, and Quaternary dune sand down to depths of 100 to 200 feet | Petrolium hydrocarbons | NA |
| 55 | NA | BTEX | NA |
| 56 | The site consists of variable thicknesses of imported (Italian) fill at depths of 1 to 15 feet, underlain by unconsolidated alluvial materials consisting of interbedded clayey silts and sandy gravels and cobbles. | BTEX and TPH | BTEX = ND to 5.6 ppm (EPA 8020) and TPH = ND to 260 ppm (EPA 418.1) |
| 57 | Site consists of primarily of clays, silts and interbedded sands. | BTEX and TPH | BTEX = 14,900 ppb and TPH = 8.8 ppm |
| 58 | NA | VOCs | ND to 2500 ppm |
| 59 | Fine to coarse sands are laterally continuous to the depths of 60 feet | BTEX | BTEX max. = 27,000 ppb and benzene max. = 4,951 ppb |

| ID | Type of Phase | Depth of GW table | Gradient of GW | No of GW monitoring wells | GWMW depth | GWMW dia |
|---|---|---|---|---|---|---|
| 49 | Dissolved and residually saturated | 4 to 5 feet {p2} | NA | 12 | 12 to 15 feet | NA |
| 50 | Dissolved | 53 to 55 feet {p3-1} | 0.009 ft/ft {F3-5} | 3 {F3} | NA | NA |
| 51 | Dissolved | 20 to 23 feet {p3-10} | NA | 2 {F4} | NA | NA |
| 52 | NA | 6 to 8 feet | NA | 11 {4/6/93, T1} | 13 to 20.5 feet {4/6/93, T1} | NA |
| 53 | Dissolved and gaseous phase | 55 feet | NA | 6 | 48 to 65 feet | NA |
| 54 | Dissolved | 18 feet | NA | 5 | 25 feet | NA |
| 55 | NA | 35 to 45 feet | NA | 5 {p4} | NA | NA |
| 56 | Dissolved | 4 feet | 0.04 ft/ft | 9 | NA | NA |
| 57 | 90% adsorbed and 10% dissolved | 20 feet | NA | NA | NA | NA |
| 58 | NA | 4 to 7 feet | NA | 4 | NA | 2 inch |
| 59 | Dissolved | 18 to 35 feet | 0.004 ft/ft | 16 | NA | NA |

| ID | GWMW screen length | No of IAS wells | IASW depth | IASW dia | IASW Screen length |
|---|---|---|---|---|---|
| 49 | 10 feet | 15 | 15 feet | 2 inch | 1 feet |
| 50 | NA | 2 {F3} | 75 feet {F3-2} | 4 inch | 5 feet |
| 51 | NA | 2 {F4} | 40 to 44 feet {F3-5} | 4 inch | 5 feet |
| 52 | Upto 10 feet | 1 {3/18/93, p1} | 20 feet {4/6/93, F1} | 1.5 inch | 2 feet |
| 53 | 1 feet | 1 | 65 feet | 2.5 inch | 0.5 feet |
| 54 | 4 feet | 1 | 33 feet | 2 inch | 3 feet |
| 55 | NA | 6 {p1} | 60 feet {F3} | 4 inch | 5 feet |
| 56 | NA | 2 | 14 feet | 2 inch | 5 feet |
| 57 | NA | 3 | 30 feet | NA | 2 feet |
| 58 | 5 feet | 1 | 13 feet | 2 inch | 1 feet |
| 59 | 10 feet | 9 | 50 feet | NA | 0.5 feet |

| ID | IAS flow/pressure rate/well | IAS Radius of Influence/well | Method of IAS ROI | IAS Compressor size |
|---|---|---|---|---|
| 49 | 5.2 scfm @ 13 psi {10/14/93} | 15 to 17 feet | NA | NA |
| 50 | 1 to 4 cfm @ 17 psi {T5-4} | 54 feet {p5-30} | Bubbling {p5-30} | NA |
| 51 | 2 to 6 cfm @ 11 to 15 inches Hg. {T7-4} | 25 to 50 feet {p7-19} | NA | NA |
| 52 | 2.4 to 5.5 cfm @ 13.75 to 32 psi | 10 to 15 feet {4/6/93, F2} | Bubbling and positive pressures {4/6/93, F2 & T1} | NA |
| 53 | 23 cfm @ 9.5 psi | 25 to 30 feet {p3, 7/24/92} | Positive pressures | Air compressor rated 10 to 25 cfm @ 10 to 20 psi |
| 54 | 18.7 cfm @ 6.5 psi | 9 feet | Resistivity tomography | NA |
| 55 | 2.0 cfm @ 8 to 5 psi {T1} | 24 feet {p8} | GW mounding, D.O. | Positive displacement, rotary lobe blower |
| 56 | NA | 15 feet | D.O. | NA |
| 57 | 5 cfm @ 11 psi | NA | Positive pressures | 3 HP, Utile D26 oil free rotary blower |
| 58 | 5 to 24 cfm 7 to 30 inch w.c. | 44 feet | Positive pressures | NA |
| 59 | 2.5 cfm | NA | NA | NA |

| ID | No of IAS monitoring wells | IASMW depth | IASMW dia | IASMW screen length | No of SVE wells |
|---|---|---|---|---|---|
| 49 | NA | NA | NA | NA | 11 |
| 50 | NA | NA | NA | NA | 2 {F3} |
| 51 | NA | NA | NA | NA | 1 {F4} |
| 52 | NA | NA | NA | NA | 3 {p2} |
| 53 | 32 | NA | NA | NA | None |
| 54 | NA | NA | NA | NA | None |
| 55 | NA | NA | NA | NA | 2 {p1} |
| 56 | NA | NA | NA | NA | 1 |
| 57 | NA | NA | NA | NA | 3 |
| 58 | NA | NA | NA | NA | 2 Horizantal, 40 feet long |
| 59 | 8 | NA | NA | NA | NA |

| ID | SVEW depth | SVEW dia | SVEW Screen length | SVE flow/pressure rate/well | SVE radius of influence/well |
|---|---|---|---|---|---|
| 49 | 8 to 10 feet {p3} | 2 inch | 5 feet | 3 to 12 cfm | NA |
| 50 | 60 feet{F3-2} | 4 inch | 20 feet {F3-2} | 5 to 9 cfm @ 12 inches of Hg. {p5-22} | 20 feet {p8-13} |
| 51 | 45 feet {F3.5} | 5 inch | 30 feet {F3-5} | 3 to 4 cfm @ 1 to 6 inches Hg. {T5-4} | 20 feet {p8-23} |
| 52 | NA | NA | NA | 16 to 24 cfm @ 56 inches of water column {p2} | 23 to 48 feet {p5} |
| 53 | NA | NA | NA | NA | NA |
| 54 | NA | NA | NA | NA | NA |
| 55 | 55 feet {F3} | 4 inch | 40 feet | 86 to 116 cfm @ 20 inches of w.c. | NA |
| 56 | 4 feet | NA | 3 feet | 20 cfm @ 52 inch w.c. | 100 feet |
| 57 | 22 feet | 2 inch | 15 feet | 1 to 2 cfm @ 36 to 47 inch w.c. | NA |
| 58 | 10 inch | 4 inch | 40 feet | NA | 20 feet |
| 59 | NA | NA | NA | NA | NA |

| ID | Method of SVE ROI | SVE Vacuum pump size | No of VMPs | VMP depth | VMP dia | VMP screen length |
|---|---|---|---|---|---|---|
| 49 | NA | 1.5 HP, 145 cfm regenerative blower {p3} | NA | NA | NA | NA |
| 50 | Vacuum | NA | NA | NA | NA | NA |
| 51 | Vacuum | NA | NA | NA | NA | NA |
| 52 | NA | NA | 2 {4/6/93, F1} | 8 feet | 1.5 inch | 0.5 feet |
| 53 | NA | NA | NA | NA | NA | NA |
| 54 | NA | NA | NA | NA | NA | NA |
| 55 | NA | NA | NA | NA | NA | NA |
| 56 | Vacuum | NA | NA | NA | NA | NA |
| 57 | Vacuum | 3 HP, Rotron EN 523 blower | NA | NA | NA | NA |
| 58 | Vacuum | 3 HP, Rotron explosion-proof regenerative blower rated 200 cfm @ 75 inch w.c. | 9 | 4 to 6 feet | 3/8 inch | NA |
| 59 | NA | NA | NA | NA | NA | NA |

| ID | Effluent gas treatment | System operation | Other data |
|---|---|---|---|
| 49 | Catalytic oxydation unit {p3} | NA | kr = 5.0E-07 cm^2, kz = 6.39E-07 cm^2 and kc = 7.08E-12 cm^2 {p3} |
| 50 | NA | Continuous | K = 0.531 ft/day {p5-4} |
| 51 | NA | Continuous | K = 0.1 gpd/ ft^2 {p7-4} |
| 52 | 180 pound vapor phase carbon canister {3/18/93, p2} | Continuous | Intrinsic permeability = 8.0E-08 cm^2. Equivalent permeability of the surface boundary for the wells = 2E-11 to 2E-12 cm^2 {p5} |
| 53 | NA | Continuous | K = 50 to 100 feet/day and GW flow velocity = 1 feet/day |
| 54 | NA | Pulsed | Porosity = 0.4 and Permeability = 270 to 600 gal/day/ft^2 |
| 55 | NA | NA | Pilot test data not available. |
| 56 | NA | NA | T = 300 gpd/ft, GW flow velocity = 0.4 ft/day. Boring logs data available. Monitored parameters: Positive parameters, D.O., temperature, pH, CO2, VOCs, GW depths, COD, BOD and plate counts. |
| 57 | 1000 lb. and 180 lb vapor phase GAC adsorbers | NA | NA |
| 58 | 2500 lb. GAC canister | NA | Tensiometer and air piezometer readings available |
| 59 | NA | NA | Transmissivity = 4300 ft^2/day, Hyd. conductivity = 51 to 154 ft/day, GW velocity = 0.7 ft/day, Porosity = 0.3 |

| ID | Notes | Asymptotic behavior | Site status |
|---|---|---|---|
| 49 | Project costs data available. Insufficient data. | Data not available | Rejected. No additional data available. |
| 50 | The volume of North area NAPL plume was determined to be 11,411 gallons {p1-1} | | Accepted |
| 51 | The volume of South area NAPL plume was determined to be 29,640 gallons {p1-1}. Air sparging is not feasible at this site. {p1-3} | | Rejected. IAS technology failure site. |
| 52 | Will go full scale | | Accepted |
| 53 | | | Accepted |
| 54 | This paper examines the use of Resistivity Tomography to characterise the presence of air in soil: before; during and following in situ air sparging | | Accepted |
| 55 | Average mass extraction rate is 10 gallons of gasoline per day. Good discussion on oxygen content and carbon dioxide content. Pilot data not available. Full scale operating length = 153 days | Data not available | Accepted |
| 56 | "No Further Action" status for the site because the BTEX concentrations are below action levels. Site achieved regulatory closure. Air sparging system in operation for 288 days. | Asymptotic behavior was attained based on BTEX concentrations | Accepted. |
| 57 | No free product detected. 870 pounds of hydrocarbons were removed in a period of approximately 8 months. | Asymptotic behavior was attained based on soil vapor extraction data. | Accepted. |
| 58 | Pilot test results indicate a high potential for preferential flow and lateral migration of contamination during air sparging | | Rejected. IAS technology failure site. |
| 59 | Much microbial information, but no info on ROI and only limited info on physical behavior of the system. Extensive data was collected, therefore, sites were considered full-scale for plots in section 6 of report. | | Accepted. |

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