In-Situ Air Sparging

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STEP
Strategies for Today's
Environmental Partnership

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Environmental Partnership

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Manufacturing, Distribution and Marketing Department

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SECTION 1—INTRODUCTION

1.1 Scope

The last decade has witnessed an evolution of remediation technologies starting with the early containment or mass reduction techniques to today's very aggressive site closure techniques, which address containment as well as residual petroleum hydrocarbon compounds. Initially, pump and treat systems were primarily used for the remediation of dissolved phase chemicals of concern. As time passed, the importance of addressing the trapped and adsorbed hydrocarbons present in the capillary fringe and saturated zone was realized due to the very slow asymptotic decline of the dissolved concentrations. Efforts were made to address trapped and adsorbed hydrocarbons, even though the dissolved plume may have stabilized.

1.2 Techniques

One of the first techniques applied to augment pump and treat systems in addressing residual hydrocarbons below the water table was in-situ bioremediation. Hydrogen peroxide or other oxygenating agents were used to increase the dissolved oxygen levels in the groundwater. But, it was soon discovered that the stability of hydrogen peroxide in soil systems was extremely low, thus resulting in inefficient oxygen delivery and escalated project costs. Air sparging, which is the injection of air into formations below the water table, was established as an alternative in-situ remediation technique, using air to effect volatization and stripping, and to enhance in-situ biodegradation.

In-situ air sparging has been used since about 1985, with varying success [1] for the remediation of volatile organic compounds (VOCs) dissolved in the groundwater and adsorbed to the saturated zone soils. Vacuum extraction systems are often used in conjunction with this technology (see Figure 1) to remove the volatilized chemical(s) of concern; this technology has broad appeal due to its projected low capital costs in relation to conventional approaches.

The difficulties encountered in modeling and monitoring the multiphase air sparging process (that is, air injection into water saturated conditions) have contributed to the current uncertainties regarding process(es) responsible for removing petroleum hydrocarbons from the saturated zone. Engineering design of these systems is largely dependent on empirical knowledge.

It is commonly perceived that the injected air travels up through the saturated zone in the form of air bubbles; however, when grain sizes are less than 2 millimeters it is more realistic that the air travels in the form of continuous air channels [2]. The air flow path will be strongly influenced by the structuring and stratification of the saturated zone soils. Significant channeling may result from relatively subtle permeability changes, and channeling will increase as the size of the pore throats decrease. Research [3, 4] shows that even minor differences in permeability due to stratification can impact the sparging effectiveness.

It should be noted that in this discussion, "air sparging" refers to the injection of air into formations below the water table and should not be confused with processes where air is injected within a well (in-well air sparging) to oxygenate and strip the well water.

SECTION 2—GOVERNING PHENOMENA

In-situ air sparging is potentially applicable when volatile and/or easily aerobically biodegradable compounds are present in water-saturated zones, under relatively permeable conditions. The in-situ air sparging process can be defined as, the injection of compressed air at controlled pressures and volumes into water-saturated soils. The phenomena that occur during the operation of air sparging systems include:

a. In-situ stripping of dissolved volatile organic compounds (VOCs).
b. Volatilization of trapped and adsorbed phase hydrocarbon compounds present below the water table and in the capillary fringe.
c. Aerobic biodegradation of both dissolved and adsorbed phase hydrocarbon compounds.

All three phenomena are dependent on the ability to get air in contact with the soil and groundwater containing petroleum hydrocarbons.

2.1 In-Situ Air Stripping

Among the above removal mechanisms, in-situ air stripping may be the dominant process for some dissolved compounds. The strippability of any compound is a function of its Henry's Law Constant (estimated for nonpolar substructures, and vapor pressure/solubility). Compounds such as benzene, toluene, xylene, ethylbenzene, trichloroethylene, and tetrachloroethylene are considered to be easily strippable. During air sparging, dissolved compounds that are

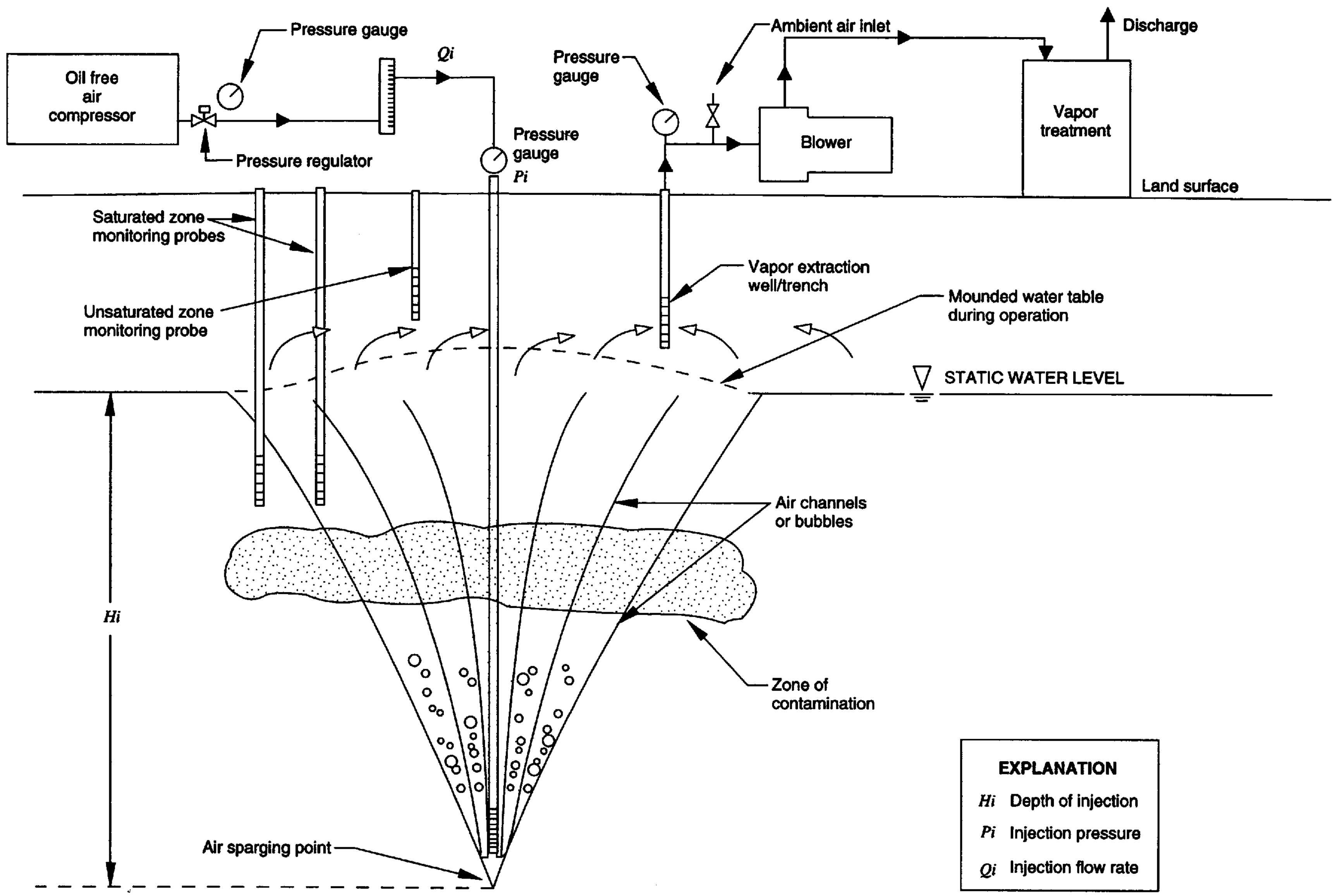

Figure 1—Air Sparging Process Schematic

transferred into the vapor phase and may be captured by a vapor extraction system (VES) once they migrate into the vadose zone.

It has been proposed that in-situ air sparging also helps to increase the rate of dissolution of the adsorbed phase compounds below the water table. This enhancement dissolution is caused by increased mixing and the higher concentration gradient between the adsorbed and dissolved phases under sparging conditions.

2.2 Direct Volatilization

During in-situ air sparging, direct volatilization of the adsorbed and trapped compounds (residual hydrocarbons) is enhanced in the zones where air flow takes place. Direct volatilization of any compound is governed by its vapor pressure, and most volatile organic compounds are easily removed through volatilization.

In areas where air is brought into contact with significant concentrations of residual VOCs in the saturated zone, direct volatilization into the vapor phase may become the dominant mechanism for mass removal.

2.3 Biodegradation

In most natural situations, aerobic biodegradation of hydrocarbons in the saturated zone is limited by the availability of oxygen. Biodegradability of any compound under aerobic conditions is dependent on its chemical structure and environmental parameters such as pH and temperature. Some VOCs are considered to be easily biodegradable under aerobic conditions (for example, benzene, toluene, acetone, and so on,) and some are not (for example, trichloroethylene and tetrachloroethylene).

Typically the dissolved oxygen (DO) concentration in groundwater is less than 4.0 milligrams per liter (mg/L), and under anaerobic conditions induced by the natural degradation of petroleum hydrocarbons, is often less than 1.0 mg/L. DO can be raised to 6 to 10 mg/L by air sparging under equilibrium conditions. This potential increase in the DO levels will contribute to enhanced rates of aerobic biodegradation in the saturated zone.

SECTION 3—APPLICABILITY

3.1 Examples of Compound Applicability

Based on the previous discussion, Table 1 describes the applicability of a few selected compounds.

In practice, the criterion for defining strippability is based on Henry's Law Constant being greater than 1×10^{-5} atm-m^3/mole. In general, compounds with a vapor pressure greater than 0.5 to 1.0 mm Hg can be volatilized easily; however, the degree of volatilization is also limited by the flow rate of air in contact with sorbed or dissolved compounds. The half lives presented in Table 1 are estimates in groundwater under natural conditions without any enhancements to improve the rate of degradation.

The compounds present in heavier petroleum products such as No. 6 fuel oil will not be amenable to either stripping or volatilization (see Figure 2). Hence, the primary mode of remediation, if successful, will be due to aerobic biodegradation. Required air injection rates under such conditions will be influenced only by the requirement to introduce sufficient oxygen into the saturated zone. Enhancing DO concentrations in the target area is dependent upon:

Table 1—Examples of Compound Applicability for In-Situ Air Sparging [5, 6]

Compound	Strippability	Volatility	Aerobic[a] Biodegradability
Benzene	High ($H = 5.5 \times 10^{-3}$)	High ($V_P = 95.2$)	High ($t_{1/2} = 240$)
Toluene	High ($H = 6.6 \times 10^{-3}$)	High ($V_P = 28.4$)	High ($t_{1/2} = 168$)
Xylenes	High ($H = 5.1 \times 10^{-3}$)	High ($V_P = 6.6$)	High ($t_{1/2} = 336$)
Ethylbenzene	High ($H = 8.7 \times 10^{-3}$)	High ($V_P = 9.5$)	High ($t_{1/2} = 144$)
TCE	High ($H = 10.0 \times 10^{-3}$)	High ($V_P = 60$)	Very low ($t_{1/2} = 7{,}704$)
PCE	High ($H = 8.3 \times 10^{-3}$)	High ($V_P = 14.3$)	Very low ($t_{1/2} = 8{,}640$)
Gasoline compounds	High	High	High
Fuel oil compounds	Low	Very low	Moderate

Note:

Where:

H = Henry's Law Constant (atm-m^3/mol).

V_p = vapor pressure (mm Hg) at 20°C.

$t_{1/2}$ = half life during aerobic biodegradation, in hours.

[a] = the estimated half lives could vary depending on site specific environmental conditions.

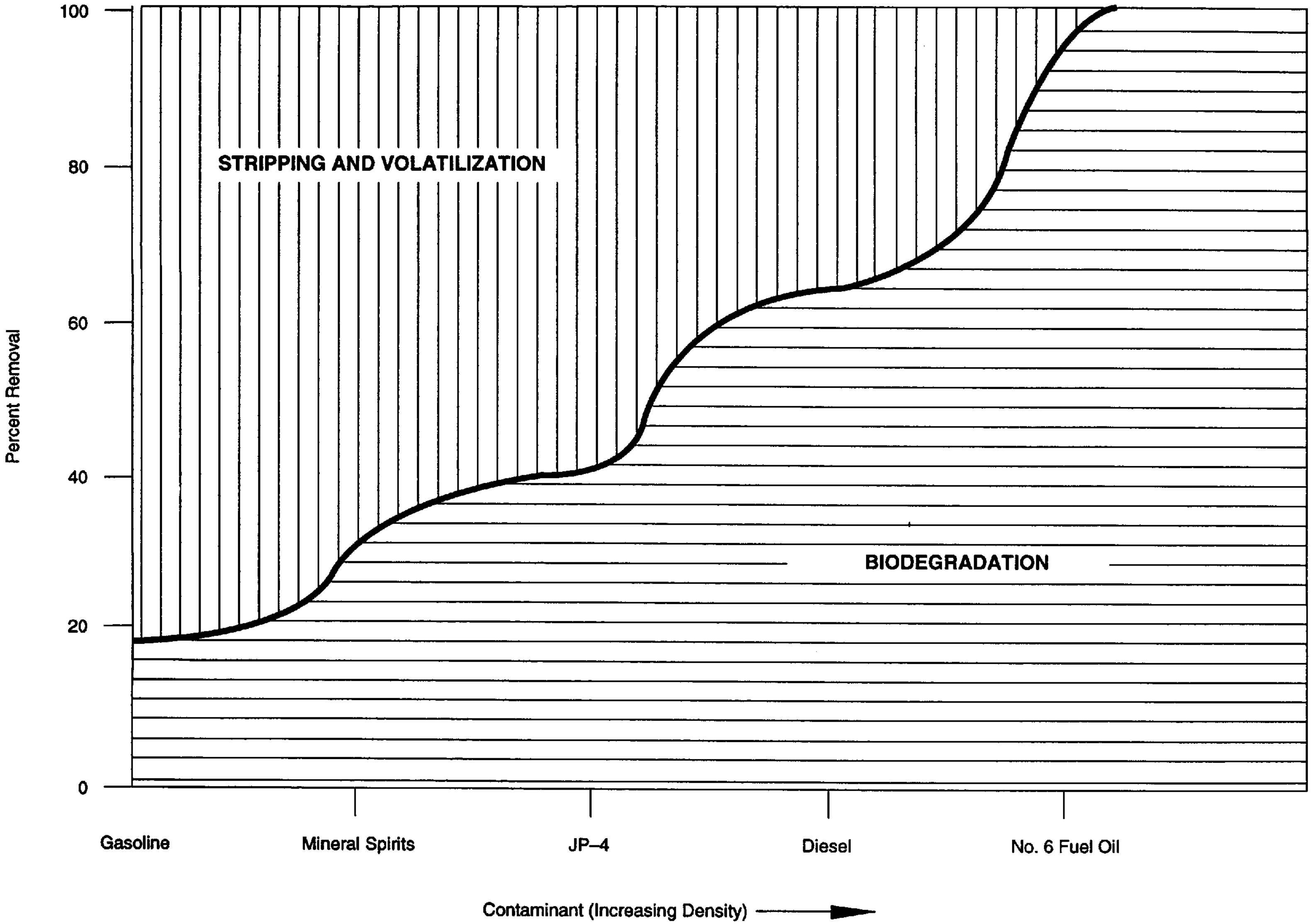

Figure 2—Qualitative Presentation of Potential Air Sparging Mass Removal for Petroleum Compounds

a. The distribution of air as a source of oxygen.
b. Oxygen diffusion rates.
c. Movement of dissolved oxygen through the saturated zone.

Air distribution is achieved by gaining sufficient air saturation within the target zone. Oxygen diffusion rates can be slow and without movement of dissolved oxygen in the saturated zone, then may not provide sufficient availability to many areas within the target zone. It is important to distribute DO throughout the target zone. Movement of DO can result from:

a. Groundwater flow.
b. Mixing during on and off cycling of air sparging.
c. Diffusion.

Determining DO distribution is achieved empirically by measuring DO concentrations at various depths and locations of the saturated zone within the target zone.

Figure 2 qualitatively describes different mass removal phenomena in a simplified version under optimum field conditions. The amount of mass removed by stripping and volatilization has been grouped together, due to the difficulty in separating it in a meaningful manner. However, emphasis should be placed on reaching site target cleanup levels resulting from total mass removal, particularly of mobile volatile compounds, and closure of the site regardless of the mass transfer mechanisms.

3.2 Geological Considerations

Physical implementation of in-situ air sparging is greatly influenced by the ability to achieve significant air distribution within the target zone. Good vertical pneumatic conductivity is essential to avoid bypassing or channeling of injected air horizontally, away from the sparge point. It is not an easy task to evaluate the pneumatic conductivities in the horizontal and vertical direction for every site considered for in-situ air sparging.

Geological characteristics of a site are very important when considering the applicability of in-situ air sparging. The most important geological characteristic is stratigraphic homogeneity. The presence of lower permeability layers over/under stratified geological conditions will impede the vertical passage of injected air. Under such conditions, injected air may accumulate below the lower permeability layers and will travel in a horizontal direction, thus potentially enlarging the compound plume. Any obvious high permeability layers will also cause the air to preferentially travel laterally, thus causing an enlargement of the plume. Horizontal migration of injected air limits the volume of soils that can be treated by direct volatilization and can cause concerns if hydrocarbon vapors migrate into confined spaces such as basements and utilities. Vapor monitoring points can be installed at or near property lines (near utilities) and/or near similar receptors to monitor for potential migration of petroleum hydrocarbon compounds in the vapor phase.

Both vertical pneumatic conductivity and the ratio of horizontal to vertical permeability increase with decreasing average particle size of the sediments in the saturated zone. The reduction of vertical permeability is directly proportional to the effective porosity and average grain size of the sediments [7]. Hence, based on the empirical information available, it is recommended that application of in-situ air sparging be limited to saturated zone conditions where the hydraulic conductivities are greater than 10^{-3} cm/sec [1].

It may not be possible to encounter nearly homogeneous geological conditions across the entire cross section at most sites. Hence, the optimum geological conditions for air sparging may be where permeability increases with increasing elevation above the point of air injection. Decreasing permeabilities with elevation above the point of air injection will tend to enlarge the plume due to lateral movement of injected air.

SECTION 4—DESCRIPTION OF THE PROCESS

4.1 Air Injection Into Water-Saturated Soils

The ability to predict the performance of air sparging systems is limited by the current understanding of air flow in the water-saturated zone and the availability of performance data. There are two schools of thought in the literature describing this phenomenon; the most accepted one describes that the injected air travels in a vertical direction in the form of discrete air channels, while the second one suggests that the injected air travels in the form of air bubbles. Air flow mechanisms cannot be directly observed in the field; however, conclusions can be reached by circumstantial evidence collected at various sites and by laboratory-scale visualization studies.

Sandbox model studies performed tend to favor the "air channels" concept over the "air bubbles" concept [3, 4]. In laboratory studies simulating sandy aquifers (grain sizes of 0.75 mm or less), stable air channels were established in the medium at low injection rates; whereas, under conditions simulating coarse gravels (grain sizes of 4 mm or larger), the injected air rose in the form of bubbles. At high air injection rates in sandy, shallow, water-table aquifers, the possibility for fluidization (loss of soil cohesion) around the point of injection exists [2, 4, 8].

4.2 Mounding of Water Table

As the injected air enters the saturated zone, the water-table elevation adjacent to the sparge point may rise due to the displacement of pore water by injected air. Displacement of groundwater may initially form a mound around the injection well, although there is some evidence in the literature that this phenomenon is transient [2, 4, 8]. Some concerns have been raised regarding the potential for enhanced dissolved transport caused by the movement of groundwater away from the induced mound. Recent studies have shown that water table mounding is temporary and that increased migration of groundwater away from the injection point is not significant.

4.3 Distribution of Air Flow Pathways

It is often envisioned that air flow pathways developed during air sparging form an inverted cone with the point of injection at the apex. This would be true if soils were homogeneous and of larger grain size, and injected air flow rate was low. Laboratory experiments simulating mesoscale heterogeneities in soil particle sizes resulted in distorted plume shapes caused by channels expanding, coalescing, and migrating upwards [3]. Thus, it is reasonable to expect that distorted air channels will predominate in natural settings. During laboratory experiments using homogeneous media with uniform grain sizes, symmetric air flow patterns about the vertical axis were observed [3]. However, media formed with mixed grain sizes yielded non-symmetric air flow patterns. The asymmetry apparently resulted from minor variations in the permeability and capillary air entry resistance that resulted from pore-scale heterogeneity. Hence, under natural conditions, it is realistic to expect that symmetric air distribution will never occur. These same experiments also indicated that the channel density increased with increased air flow rates.

It is reported in some literature [9] that, at low sparge pressures, air travels 1 to 2 feet horizontally for every foot of vertical travel. However, it has to be noted that this correlation was not widely observed. It was also reported that as the sparge pressure is increased, the degree of horizontal travel increases [4, 8, 10].

The injected air will penetrate the aquifer only when the air pressure exceeds the sum of the water column's hydrostatic pressure and the threshold capillary pressure, or the "air entry pressure." The air entry pressure is equal to the minimum capillary entry resistance for the air to flow into the porous medium. Capillary entry resistance is inversely proportional to the average diameter of the grains and porosity [7, 8]. Thus, the air entry pressure will be higher for fine-grained media (one to ten feet of water) and lower for coarse-grained media (one to ten inches of water).

SECTION 5—SYSTEM DESIGN PARAMETERS

In the absence of any reliable models for the in-situ air sparging process, empirical approaches are used in the system design process. Significant parameters that are important in designing an in-situ air sparging system are as follows:

a. Air distribution (soil stratification).
b. Depth of air injection.
c. Air injection pressure and flow rate.
d. Number of injection wells.
e. Chemical(s) of concern and distribution.

5.1 Air Distribution

It is important to estimate the radius of influence (ROI) of an air sparging point, in order to design a full-scale air sparging system consisting of multiple points. However, there is no standard method for determining the ROI during the field testing of an in-situ air sparging system. Geological control of air distribution is the most important aspect of sparging system design. Even though the term "radius of influence" is used here, radially symmetric air flow is unlikely in air sparging operation due to heterogeneities in the subsurface [11].

The ROI of an air sparging point is assumed to be a cone (see 4.3); however, this assumption implies homogeneous soils of moderate to high permeability that are rarely observed in the field. During a numerical simulation study on air sparging [8], three phases of behavior were predicted following initiation of air injection. These are:

a. An expansion phase in which the vertical and lateral limits of air flow grow in a transient manner.
b. A second transient period of reduction in the lateral limits (collapse phase).
c. A steady-state phase during which the system remains static as long as injection parameters do not change. The ROI of air sparging was found to reach a roughly conical shape during the steady-state phase.

Based on the inverted cone air flow distribution model, many air sparging system designs are established on a ROI measured by performing a field design test. A properly designed test can provide valuable information. However, time and money limitations often restrict field evaluations to short duration single-well tests. A smaller ROI is expected for coarse gravels than for finer-grained sediments due to the lower horizontal to vertical permeability ratio present in coarse-grained sediments. Potential measuring parameters (see Figure 3) of the zone of influence include:

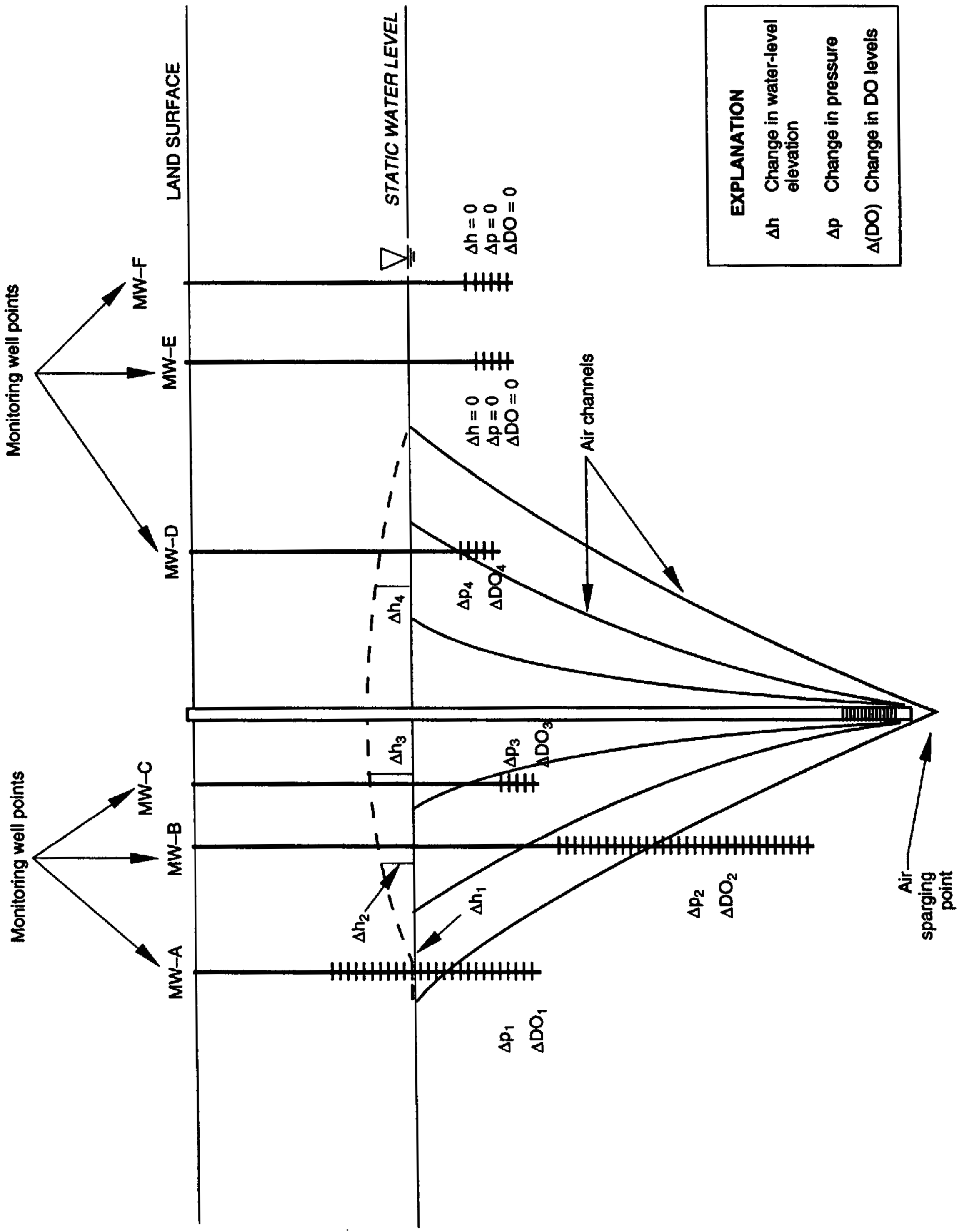

Figure 3—Air Sparging Test Measurements

a. Measurement of the lateral extent of groundwater mounding [10, 12].
b. Increase in DO levels and redox potentials in comparison to pre-sparging conditions [10, 13, 14].
c. Increase in pressure within sealed saturated zone monitoring probes that are perforated below the water table only.
d. The use and detection of insoluble tracer gases, such as helium [13] or sulfur hexafluoride (SF6) [11].
e. The actual reduction in concentrations of chemical(s) of concern following sparging.

5.2 Depth of Air Injection

Among the design parameters, depth of air injection may be the easiest to determine since the choice is very much influenced by the distribution of the chemical(s) of concern. It is prudent to choose the depth of injection at least a foot or two deeper than the extent of concentrations of chemical(s) of concern that are above site target levels. However, in reality, the depth determination is very much influenced by soil structuring and extent of layering since injection below any impermeable or very permeable zones should be avoided. The current experience in the industry is mostly based on depths less than 20 feet [1].

5.3 Air Injection Pressure and Flow Rate

The injection pressure necessary to initiate in-situ air sparging should be able to overcome the following:

a. The hydrostatic pressure of the overlying water column at the point of injection.
b. The capillary entry resistance to displace the pore water; this depends on the type of sediments in the subsurface.

Hence, the pressure of injection (P_i) in feet of water could be defined as:

$$P_i = (\rho_w H_i\ g)/g_c + P_a + P_d$$

Where:

P_i = pressure of injection (lb_f/ft^2).
H_i = saturated zone thickness above the sparge point (ft).
P_a = air entry pressure of formation (lb_f/ft^2).
P_d = air entry pressure for the well, if a diffuser is used (lb_f/ft^2)
ρ_w = density of water (lb_m/ft^3).
g = acceleration of gravity (ft/s^2).
g_c = proportionality constant, 32.174 ($ft\ lb_m$)/($lb_f\ s^2$).

The air entry pressure is heavily dependent on the type of geology. Comparatively, the air entry pressure will be higher for finer sediments than for coarser sediments.

The notion that higher pressures correspond to better air sparging performance is not true. The typical values of injected air flow rates reported in the literature [1, 2, 11] range from 2 cfm to 10 cfm. Increasing the injection rate to achieve a greater flow and wider ROI must be implemented with caution [2, 8]. This is especially true during the start-up phase due to the low relative permeability to air because of the low initial air saturation. The danger of pneumatically fracturing the formation under excessive pressures should also be considered when determining injection pressures. Hence, it is very important to gradually increase the pressure during system start-up.

5.4 Injection Wells

Injection wells must be designed to accomplish the desired distribution of air flow in the formation. Conventional design of an air sparging well under shallow "sparge depth" conditions (less than 20 feet) and deeper sparger depth conditions (greater than 20 feet) are shown in Figures 4 and 5. Schedule 40 or 80 PVC (polyvinyl chloride) piping and screens in various diameters can be used for the well construction. Sparge points are typically completed as 1- to 4-inch diameter wells with 0.5 to 2 feet of screened interval [11]. In both configurations, the sparge point can be installed by drilling a well to ensure an adequate seal to prevent short-circuiting of the injected air. Hence, at large sites, the cost of installing multiple sparge points may prohibit the consideration of air sparging as a potential technology.

Installation of air sparging points, with driven well points made out of small diameter (3/4 inch to 1-1/2 inch) 8 to 10 feet cast iron, flush-jointed sections will help to make this technology more cost-effective.

5.5 Chemical(s) of Concern and Distribution

Volatile and strippable compounds will be more amenable to air sparging. It is anticipated that non-volatile, biodegradable compounds can also be addressed by this technique. In contrast, for more dispersed concentrations of chemical(s) of concern above site target levels, air sparging may not be attractive due to inefficiencies of removal of chemical(s) of concern. Due to irregularities in the distribution of air channels, the path of air travel may miss a significant portion of the dissolved or adsorbed mass.

Since the latest design of an in-situ air sparging system has not progressed beyond the "empirical stage," a pilot study should be considered only to prove its effectiveness. The pilot study could be more appropriately termed a field design study, since the primary objective would be to obtain site-specific design information. However, due to the unknown nature of the mechanics of the process, the data collected from a pilot test should be treated with caution. The collected data should be valued as a means of overcoming any prior concerns, if any, regarding the implementation of this technology. Since vapor extraction is a complimentary technology to in-situ air sparging, pilot testing of the integrated system at the same time is highly recommended.

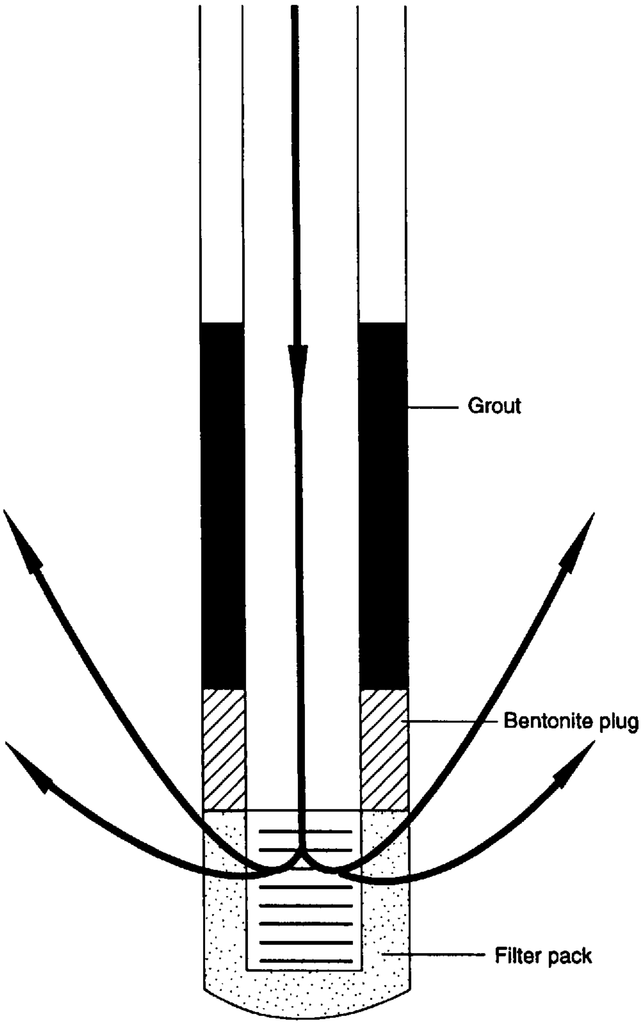

Figure 4—Schematic Showing the Conventional Design of an Air Sparging Point for Shallower Applications

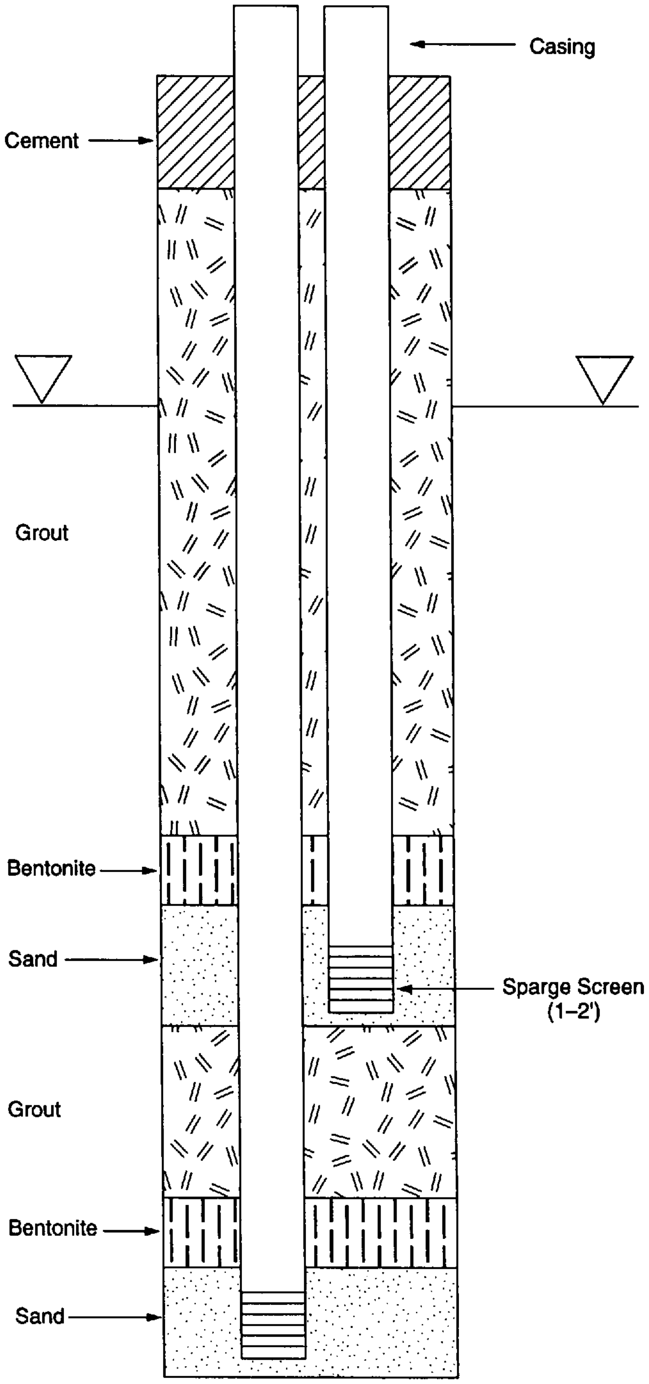

Figure 5—Diagram of a Nested Sparge Well for Deeper Applications

SECTION 6—PILOT TESTING

6.1 Preliminary Evaluation

It is very important to perform a preliminary evaluation of the geological and hydrogeological conditions for the applicability of in-situ air sparging prior to the pilot study. Particular emphasis should be placed on the potential effects of geological stratification on air propagation. Field pilot tests can help determine the distribution of air in relation to the area to be treated. A thorough characterization of the nature and extent of chemical(s) of concern should be performed.

Table 2 illustrates consideration for evaluation prior to designing a pilot test that will enhance the quality of data that would be collected.

Table 2—Considerations for Evaluation Prior to Designing a Pilot Test

Condition	Impact
Saturated zone soil permeability	Applicability—flow rate vs. pressure
Geological stratification	Applicability—air distribution
Depth of concentrations of chemical(s) of concern below the water table	Sparging depth
Type of Chemical(s) of concern	Applicability—volatilization/ biodegradability
Size of Area to be treated	Applicability
Soil conditions above the water table	Ability to capture the vapor phase chemical(s) of concern by vapor extraction

6.2 Data Collection

The data that should be collected during the pilot study, to be used later for the design of a full-scale system, include the following:

6.2.1 ZONE OF AIR DISTRIBUTION

As for any subsurface remediation system, the zone of air distribution is a key design parameter since this would determine the required number of injection points. ROI under various pressure and flow combinations should be measured. The methods to infer the ROI were described in Section 5.1 and Figure 3.

6.2.2 INJECTION AIR PRESSURE

This parameter is very much influenced by the depth of injection and subsurface geology. The required baseline pressure during the test should be equal to or just above the value necessary to overcome the sparging depth. The impact of any additional required pressure should be evaluated carefully in incremental steps.

6.2.3 INJECTION FLOW RATE

Evaluation of the injection flow rate should be governed more by the ability to capture the stripped contaminant vapors and the net pressure gradient in the vadose zone. At a minimum, the air flow rate should be sufficient to promote volatilization rates and/or maintain DO levels greater than 2 mg/L.

6.2.4 MASS REMOVAL EFFICIENCY

Another key objective during the pilot test should be to demonstrate the mass removal efficiency of the in-situ air sparging process and estimate if enough residual mass can be removed by this technology to reduce concentrations to the site target levels. It should be kept in mind, however, that pilot unit removal efficiencies may be misleading since overall remediation will be dependent on air distribution throughout impacted zone. Pilot tests may indicate what happens in the short term and only along preferential pathways. This can be determined by measuring the net increase in chemical(s) of concern concentrations in the effluent of the vapor extraction system after the initiation of the air sparging system. However, this will indicate the mass of chemical(s) of concern that have been volatized, but not the mass that has been degraded.

The first phase of the pilot test should be to perform the vapor extraction test and monitor the effluent air levels under "steady" state conditions. Then, initiate the air sparging during the second phase and monitor the concentrations of chemical(s) of concern in the vapor extraction system air stream. An increase in the concentrations and the duration of this spike would indicate the mass removal efficiency due to air sparging. Soil gas monitoring can also be used to determine increased mass removal due to air sparging and containment of the removed chemical(s) of concern by the vapor extraction system.

Determination of the increase in concentrations of chemical(s) of concern, due to air sparging, is important to evaluate the safety considerations of implementing this technology. Continuous removal of the volatile compounds transferred into the vadose zone is very important. Buildup of these compounds to explosive levels that could impact subsurface structures must be avoided. Hence, the air injection rate must be controlled in order to maintain a net negative pressure above the target area.

SECTION 7—LIMITATIONS

Previous discussions in this document have included the applicability of the in-situ air sparging process. This section summarizes the conditions under which application of this technology is *not* recommended:

a. Low hydraulic conductivity saturated zone soils, generally less than 10^{-3} cm/sec. The vertical passage of the air may be hampered and the potential for the lateral movement will be increased, as well as the potential for inefficient removal of chemical(s) of concern.

b. Heterogeneous geological conditions, with the presence of low permeability layers overlying zones with higher permeabilities. The potential for the enlargement of the plume exists again due to the inability of the injected air to reach the vadose zone.

c. Chemical(s) of concern that are non-strippable and non-biodegradable.

d. LNAPL has not been removed or completely controlled. Air injection may enhance the movement of the LNAPL away from the air injection area.

e. Air sparging system cannot be integrated with a vapor extraction system to capture all of the volatilized chemical(s) of concern. Sometimes the vapor phase chemical(s) of concern could be biodegraded in the vadose zone if optimum conditions are available. Thicker vadose zones and very low injection rates are more appropriate to implement this than shallower depths.

f. The structural stability of nearby foundations and buildings may be in jeopardy.

g. Potential for uncontrolled migration of vapors into nearby basements, buildings, or other conduits.

h. Air pressure building in confined zones or even in unconfined zones resulting in formation of a large "bubble."

SECTION 8—REMEDIATION RATES

To date, there are no reliable methods for estimating groundwater remediation rates due to air sparging. A mass removal model for in-situ air sparging has been reported [13] using air stripping as the only mass transfer mechanism. However, this model was based on the premise that injected air travels in the form of bubbles; thus, the reliability of this model may be questionable.

Remediation times of less than 12 months to 3 years have been achieved in some instances. Reports in the literature indicate sites that have implemented air sparging have often met groundwater target levels in less than 1 year [1, 10, 14, 15, 16]. However, it should be noted that, at most of these sites, the target level was around 1 mg/L for total BTEX. The required remediation time for a site will depend on the following:

a. Site specific target levels for soil and groundwater.

b. Extent and nature of chemical(s) of concern:
  1. Petroleum hydrocarbons present in the saturated zone and the capillary fringe.
  2. Extent of dissolved and adsorbed phase petroleum hydrocarbons.
  3. The presence and absence of a DNAPL (dense non-aqueous phase liquid).

c. Strippability, volatility, and biodegradability of compounds present.

d. Solubility and partitioning of the compounds present.

e. System Design:
  1. Well locations/placement.
  2. Well construction.
  3. Injection pressures.
  4. Injection flow rates.

f. Air deliverability to the area to be treated.

SECTION 9—DATA GAPS

The following recommendations are provided to promote further understanding of this technology.

a. Clear understanding of the mode and behavior of air travel. Influence of saturated zone soil structuring on the mode of air travel.

b. The optimum pressure, flow, and distribution of air flow relationships.

c. Further understanding of mass transfer mechanisms during air sparging.

d. Modeling of the physics of the process and the mass transfer mechanisms will simplify the process of designing the system and estimating remediation times.

e. Design enhancements to overcome the geological and hydrogeological limitations.

f. Is there a need to capture all the vapor phase chemical(s) of concern if they are biodegradable? Can we enhance the biodegradation rates in the vadose zone to meet the mass removal rates due to air sparging?

SECTION 10—SUMMARY OF CASE STUDIES IN THE LITERATURE

There is limited information available in the literature regarding successful case studies [1, 11]. This section summarizes only the site conditions, chemical(s) of concern, and approaches taken to successfully implement these systems, as documented in peer-reviewed studies.

Variations exist among the sites surveyed with respect to chemical(s) of concern treated, soil type, geological features, other treatment techniques used, and many other factors [1, 11].

10.1 Chemical(s) of Concern Treated

a. Gasoline components:
  1. Benzene.
  2. Toluene.
  3. Ethylbenzene.
  4. Xylenes.
b. Industrial Solvents
  1. Trichloroethylene.
  2. Tetrachloroethylene.
  3. Strippable chlorinated solvents, such as dichloroethylene, trichloroethane and so on.

Initial concentrations of chemical(s) of concern have ranged from 300 ppm to less than 5 ppm [13]. However, in most reported case studies, the target levels reached were in the range of 1 mg/L for total BTEX. There did not appear to be an upper limit above which sparging was not expected to be effective.

10.2 Soil Types

Most of the reported successful sites have permeable soil types such as sand and gravel. Sites with highly fractured bedrocks have also achieved successful cleanups by sparging [1]. Great care should be taken in bedrock situations to ensure that sparged vapors are adequately captured by the soil vapor extraction system and not lost within the bedrock fractures.

10.3 Sparging Depth

Minimum sparging depth reported for the successful sparging sites is 8 feet [1], and the maximum depth is 40 feet [2] below water table.

10.4 Remediation Times

There are many reports in the literature claiming successful closure of sites within 12 months due to in-situ air sparging. The typical range seems to be of 9 to 30 months [1], to reach a target level of 1 mg/L as total BTEX. There is very little information concerning post sparging monitoring in these reports.

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