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CONCEPTUAL AIR SPARGING DECISION TOOL IN SUPPORT OF THE DEVELOPMENT OF AN AIR SPARGING OPTIMIZATION DECISION TOOL

FINAL

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EXECUTIVE SUMMARY

The enclosed document describes a conceptual decision tool (hereinafter, Tool) for determining applicability of and for optimizing air sparging systems. The Tool was developed by a multi-disciplinary team of internationally recognized experts in air sparging technology, lead by a group of project and task managers at Parsons Engineering Science, Inc. (Parsons ES). The team included Mr. Douglas Downey and Dr. Robert Hinchee of Parsons ES, Dr. Paul Johnson of Arizona State University, Dr. Richard Johnson of Oregon Graduate Institute, and Mr. Michael Marley of Envirogen, Inc. User Community Panel Review was coordinated by Dr. Robert Siegrist of Colorado School of Mines (also of Oak Ridge National Laboratory) and Dr. Thomas Brouns of Battelle/Pacific Northwest Laboratory.

The objectives of the Tool are to provide:

1. Guidance to field-based practitioners and environmental managers for evaluating the applicability of air sparging to a wide range of sites and for optimizing the operation of air sparging systems;
2. A straight-forward, easy-to-follow decision-making process for assessing air sparging applicability and optimization; and
3. The tools for practitioners to develop the conceptual design for an air sparging system suitable for the identified site. As indicated above, the Tool provides a model of the decision-making process, not for detailed design of air sparging systems. The Tool will quickly and cost-effectively assist the practitioner in screening for applicability of the technology at a proposed site. This is accomplished in three distinct steps or tiers.

The three (3) tiers include the Scenario Approach, Conceptual Feasibility and Pilot Studies. In the first tier, the practitioner is asked to develop a conceptual geologic model for the identified site and compare the model with eleven conceptualized scenarios. Having identified a scenario which most closely approximates the practitioner's site, an initial screening value for applicability is provided. If the initial screening value is favorable, the practitioner is encouraged to proceed further with the Tool; if not, alternative technologies are suggested for further consideration.

In the second tier, removal rates due to volatilization and biodegradation are calculated, an effective area of remediation is determined, the number of sparging points and other air sparging system operating parameters are determined, and costs for conceptual system designs are estimated. Look-up tables, nomographs and other guidances are provided to facilitate the practitioner's completion of these calculations and determinations.

In the last tier, guidance is provided for conducting field-based pilot-scale testing of the previously completed conceptual air sparging system design. Results of the pilot tests can be used to "fine-tune" the conceptual design, optimize systems operations or demonstrate the infeasibility of air sparging for the identified site.

To assist the field practitioner, a complete, cross-referenced (to appropriate tables and figures) decision tree, upon which the Tool is based, is provided in Appendix A. In Appendix B, the conceptualized scenarios are presented, including conceptual visualizations, general descriptions and examples of previous air sparging experience for the three categories of remedial objectives: source area, plume remediation, or containment. A complete example of Tool usage is provided in Appendix C, providing the prospective user with sample calculations and decisions made in applying the Tool. Finally in Appendix D, a complete bibliography is presented, including the many references cited throughout this document.

The prospective user is advised to consult a companion document, entitled "Existing Air Sparging Model and Literature Review for the Development of An Air Sparging Optimization Decision Tool" (revised August 1995), for a detailed description of the development of air sparging technology, previous modeling efforts and the background for the Tool's development. For more detailed information regarding the interpretation of Tool results or application of the Tool in complex geological or contaminant settings, contact one of the Project Team members listed above or another expert in air sparging technology.

SECTION 1.0

INTRODUCTION

1.1 WELCOME TO THE CONCEPTUAL AIR SPARGING DECISION TOOL

Welcome to the Conceptual Air Sparging Decision Tool! The intent of this Tool is to assist you, as a field practitioner and environmental manager, in evaluating the potential application of air sparging for use in the remediation of your particular site. The Tool will allow you to determine air sparging applicability through completion of a series of progressively more detailed steps or tiers. If your site or remediation situation is not very likely to support application of air sparging, other technologies will be recommended early in the decision-making process. If, on the other hand, air sparging seems likely to be applicable, you will be asked to perform additional steps leading to a conceptual design.

1.2 INTRODUCTION TO THE CONCEPTUAL DECISION TOOL

The Conceptual Decision Tool has been developed to provide U.S. Department of Energy (DOE), other government agencies, and industrial practitioners with a simple yet comprehensive process for accurate and expedited decision-making with respect to the applicability of air sparging at a particular site. Use of the Tool is not intended for detailed design applications or for fate and transport modelling of specific sites. The Tool is not intended to model physical systems; instead it provides a "model" of the decision-making process, focused on determining the applicability of air sparging and on the optimization of air sparging systems.

The Decision Tool utilizes a three-tiered approach to educate the prospective user and evaluate the applicability of air sparging at a given site. The logic for developing a three-tiered approach is to allow progressive screening for applicability, "disqualifying" least applicable sites early in the process and thus, minimizing wasted effort and expense. A decision tree depicting the logical progression of the Tool is included as Appendix A. The three tiers (with a brief discussion of each) are:

> Tier 1 - Scenario Approach. This tier presents a number of generalized geologic/contaminant scenarios (realizing that not all possible scenarios can be included) which are used to quickly determine whether sparging may (or may not) be

applicable to a particular site. This tier also aids the user in classifying his/her site and assessing whether air sparging might be used to address the source area or the dissolved contaminant plume in the saturated zone or if air sparging could be used to help limit contaminant migration at a site (e.g., through containment).

Tier 2 - Conceptual Feasibility. In Tier 2, limited site-specific (geologic and contaminant) information is used to determine several conceptual design parameters and to conduct a semi-quantitative evaluation of the applicability and cost of sparging.

Tier 3 - Pilot Studies. In this step, the practitioner is given guidance for determining the potential feasibility of air sparging, for identifying a number of "red flags" (symptoms of technology infeasibility), and to optimize the design of existing or proposed systems or validate concepts from Tier 2. Results provide the basis for conceptual, rather than detailed, design of an air sparging system.

By progressing through one, two or all three tiers, the user will have followed the logical decision-making process for evaluating the appropriateness of air sparging to his/her particular site.

1.3 OVERVIEW OF THE REMEDIAL TECHNOLOGY OF AIR SPARGING

Due to previous incidences of volatile and semi-volatile contamination, owners and/or operators of DOE, other governmental agencies (i.e., Department of Defense (DoD)) and industrial sites have embarked on programs to remediate impacted soil and groundwater. *In situ* air sparging is an innovative technology for addressing dissolved, residual, and limited amounts of phase-separated (e.g., non-aqueous phase liquid (NAPL)) contamination which has impacted the saturated zone.

The process of air sparging involves the injection of air into the saturated zone, ideally directly below the contaminated media. In the application of air sparging, contaminant-free air is forced into the saturated zone with the intent of facilitating volatilization and biodegradation within the surrounding soil matrix (Figure 1). The air is injected in an attempt to promote the mass transfer of the volatile fractions of contaminants dissolved in groundwater and adsorbed to saturated soils to the vapor phase by "stripping". To inject air into the saturated zone, it is necessary to overcome the sum of the hydrostatic pressure of the overlying groundwater and the air-entry pressure of the formation. The use of air sparging can also facilitate concurrent

enhancement of aerobic biodegradation of many contaminants through the addition of air (oxygen). Sparging may also be used to create a hydraulic treatment zone (containment). A more detailed description of the processes involved in air sparging may be found in the companion document entitled "Existing Air Sparging Model and Literature Review for the Development of An Air Sparging Optimization Decision Tool," issued as a revised report by the Project Team in August 1995.

1.4 GENERAL APPLICATIONS FOR THE USE OF AIR SPARGING

Air sparging may be useful for remediation of sites which have the contaminant and geologic characteristics described below.

1.4.1 Chemical Contamination Appropriate for Air Sparging

Air sparging may be useful in remediating volatile organic and semi-volatile organic compounds (VOCs and SVOCs) as well as other potentially aerobically biodegradable chemical contaminants (e.g., coal tars and other higher molecular weight constituents). These contaminants, for the purpose of this Tool, have been categorized into two general, simplified groupings: chlorinated hydrocarbons, denser than water and biodegradable (e.g., trichloroethene, dichloroethene and other potentially dense non-aqueous phase liquid (DNAPL) forming constituents; and petroleum hydrocarbon constituents, lighter than water and biodegradable (e.g., benzene, toluene, ethylbenzene, xylenes and other potentially light non-aqueous phase liquid (LNAPL) forming constituents. (Note: The prospective Tool user should be aware that these groupings have been made to simplify the early stages (or Tiers) of the decision-making process. Contaminant-specific characteristics (e.g., Henry's Constant, etc.) will be considered during subsequent stages.)

Air sparging has been employed to address these categories of contaminants in several general situations: in the aqueous phase; for immobile and residual saturation within the soil matrix; and in combinations of these two situations. For sites which have heavy metal or radionuclide contamination as the primary contaminants of concern, it may not be appropriate to consider air sparging; analysis of the probability and risks of mobilizing the metals or radionuclide contamination should be completed (e.g., in development of the conceptual geologic model for the site) prior to further consideration of air sparging. This general caveat should be applied even if the site is contaminated with petroleum or chlorinated hydrocarbons.

1.4.2 Soils Applicable for Air Sparging

It has been reported that the distribution of injected air generally is more uniform and impacts a higher percentage of the soil pores in the vicinity of the sparging well in isotropic, coarser grained soils. In clayey and other fine-grained soils, air sparging has reduced effectiveness because of the limited flow rate experienced in a low permeability soil matrix (due to relatively low permeability). For this reason, the most effective applications of sparging are usually realized in more permeable, coarse-grained soils (e.g., sands, gravels).

1.4.3 Concerns When Using Air Sparging

The injection of air into the subsurface can cause various negative effects (e.g., potential "red flags") which the prospective user should take into consideration before applying air sparging for the remediation of a site. The injection of air into the subsurface can cause adverse pressure gradients which can mobilize contaminants (e.g., petroleum hydrocarbon vapors) in the unsaturated zone. These vapors can then migrate and collect in undesirable subsurface locations (i.e., basements) and cause hazardous or explosive conditions. Also, some practitioners believe that air sparging of dense non-aqueous phase liquids (DNAPLs) can spread dissolved contamination vertically as well as laterally, adversely impacting underlying aquifer quality, especially if a migration pathway is created or accessed in the process.

The injection of air into the subsurface also has been observed in some cases to cause groundwater mounding (i.e., an elevated water table), which may be followed by water table depression within the vicinity of the air sparging well. In other cases, depression of the local water table has been observed throughout the operation of the air sparging system. Some practitioners theorize that excessive mounding or depression can alter the hydraulic gradient, thereby possibly increasing the spread or smearing of contaminants. Another concern is the potential displacement of water due to large air pocket formation in the aquifer in response to soil stratification or heterogeneities. These issues require consideration when evaluating the potential application of air sparging to remediate a particular site.

1.5 WHEN TO USE THE DECISION TOOL

In general, application of the Conceptual Decision Tool should be limited to those situations and specific sites for which air sparging is being considered during remedial technology selection. The processes which dominate air sparging will constrain application of the Tool. On the other hand, use of the Tool may confirm the appropriateness (or lack thereof) of air sparging for remediation of selected, "marginally attractive" sites.

The Tool has been designed for use by field practitioners during several stages in the decision-making and remediation strategizing processes. The Tool is intended to be used:

1. During site characterization being undertaken to determine the likelihood that air sparging (or one of several complementary technologies) may be an appropriate candidate technology, and to identify additional characterization effort(s) which may be required to confirm this;

2. During planning for and implementation of treatability studies, using the applicability, cost estimating and optimization functions, respectively;

3. Prior to and during implementation of remediation feasibility studies, using the applicability and optimization functions, respectively;

4. During planning for and implementation of field pilot-scale studies, using the applicability and optimization functions, respectively (keeping in mind that the decision tree incorporates pilot-scale testing results);

5. When planning for and designing full-scale field applications of air sparging systems (to determine system optimization or to evaluate conceptual design);

6. During operation of full-scale field applications of air sparging systems (to confirm system optimization); and

7. Following shut-down and post-closure monitoring and assessment of full-scale air sparging systems (to confirm overall system effectiveness and Tool accuracy).

Stage 3, listed above, is the most probable opportunity for Tool use. These potential stages which allow application of the Tool are not intended to be all-inclusive; instead, the list is intended to introduce the prospective user to the range of possible applications of the Tool which were anticipated and taken into account during development. Refer to Figure 2 for a schematic depiction of potential appropriate opportunities for Tool use during the site remediation process.

The most likely situations to be considered for application will be those in which the principal contaminants are volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), including chlorinated, petroleum and other hydrocarbons. Other factors influencing this Tool and the practitioner's consideration of the use of air sparging for site remediation include (in no particular order):

- site operational history;
- depth to groundwater;
- horizontal/vertical (air and water) permeability of soil;
- site geology (unconsolidated or bedrock);
- uniformity of subsurface soil matrix;
- lithology;
- proximity to potential receptors;
- presence of bedding (horizontal) or layering;
- presence of a source area or concentrated groundwater plume;
- desired remediation end-point, e.g., target level;
- length of time available for remediation;
- other regulatory or political implications;
- resources (money) available for remediation; and
- accessibility (e.g., infrastructure) of the site.

This listing of factors is not intended to be exhaustive, but provides an illustration of the issues which a prospective field practitioner should consider when applying the Tool. For more detailed information regarding these factors and their importance in applying air sparging, the user should refer to the companion revised report "Existing Air Sparging Model and Literature Review for the Development of an Air Sparging Optimization Decision Tool," dated August 1995.

1.6 WHO SHOULD USE THE DECISION TOOL

The Decision Tool is intended for use by the field practitioner or environmental manager who is responsible for remedial technology selection at one or more sites. The intended user may have had limited experience in implementing air sparging, but will be familiar with the general principles of remedial technologies involved. If intended users are familiar with general computer usage, and Windows(C) applications specifically and have access to the hardware and operating systems required, they may prefer to use the computerized version of the Tool (availability anticipated by mid-1996). If not, the prospective user can easily use the paper-based protocol, based on this Conceptual version.

SECTION 2.0

TIER 1

2.1 WELCOME TO TIER 1

Welcome to Tier 1, the Scenario Approach. The purpose of Tier 1 is to evaluate with minimal site-specific data and, hence, effort and expense by the user, if sparging is applicable and practical for your site. This will be accomplished through the use of site conceptual models. Each site conceptual model is in template form and includes: a generalized geologic cross-section with contaminant distribution and type displayed; a verbal description of the conceptual site; a description of air sparging experience for similar sites and a scale in which the likely applicability of sparging is indicated (Appendix B). Each of the site scenarios is assumed to be at water table conditions (i.e. no confining conditions exist). As a Tool user, you will compare your site with the generalized templates provided to determine if one provides a match. Each template then references the Decision Matrix of applicability for air sparging at your site. The purpose of the Decision Matrix is to provide information at a broad, conceptual level as to the potential for sparging at your site.

2.2 CONCEPTUAL GEOLOGIC MODEL

You must develop a conceptual geologic model for your site prior to advancing further through the Conceptual Decision Tool. A conceptual geologic model provides a simple "snapshot" of subsurface characteristics and contaminant distribution. If you have not yet developed a conceptual geologic model for your site, the following activities should be considered and information should be accumulated:

1) The subsurface characteristics of your site (i.e., stratigraphy and hydrogeology) should be investigated through the use of soil borings and monitoring wells or geophysical methods (i.e. gamma logging, cone penetrometer testing, or other electronic data gathering methods). Stratigraphy refers to the spatial orientation and types of materials encountered in the subsurface (i.e., consolidated [e.g., bedrock] or unconsolidated [e.g., gravels, sands, silts and/or clays], the thickness and condition [i.e., fractured or unfractured]). Hydrogeology refers to the hydraulic characteristics of the materials encountered in the subsurface (i.e., which zone(s) is/are saturated, permeability of the zone(s), saturated thickness, groundwater flow direction and groundwater velocity).

2) The contaminant(s) in the groundwater at your site should be determined and delineated (magnitude and extent) through the use of field sampling and analysis. Additional contaminant information should include the presence or absence of a smear zone (contaminant residual at the interface of the saturated and unsaturated zone), and/or a phase-separated layer or pool (e.g., LNAPLs) in the case of most petroleum hydrocarbons or DNAPLs for most chlorinated hydrocarbons or other solvents.

3) Any man-made structures such as buried utilities, underground storage tanks (UST) or basements which may be impacted by the air sparging system or its operation.

The information obtained above should be sufficient to develop your own cross-section for comparison with the site conceptual models provided. If you do not have sufficient information, you must acquire it before proceeding with the Conceptual Decision Tool.

If you believe that you have adequate information, construct your cross-section and proceed with the Conceptual Decision Tool.

2.2.1 Contaminant Composition

Contaminant composition is one of the principal inputs in Tier 1. If your contaminants of concern are either petroleum hydrocarbons (i.e., gasoline, jet fuel, etc.) and/or chlorinated hydrocarbons (i.e., trichloroethene, tetrachloroethene, etc.), then proceed. If your primary contaminants of concern are polychlorinated biphenyls (PCBs), metals, herbicides, pesticides and/or radionuclides, and there are no petroleum hydrocarbons or chlorinated hydrocarbons, you should consider alternative technologies (See Section 2.4).

To proceed with Tier 1, please answer the following two questions:

a) Are the major or regulatory-driving contaminants at your site petroleum hydrocarbons (e.g., less dense than water or typically easily biodegradable)?

b) Are the major or regulatory-driving contaminants at your site chlorinated hydrocarbons (e.g., denser than water or typically less or not biodegradable)?

If you answered "yes" to either of these questions, the Tool will guide you, as indicated in the Decision Tree (see Appendix A), along the appropriate path. If you answered "yes" to both, select the contaminant type which is either most prominent or of greatest regulatory concern. If you answered "no" to both questions, perhaps the "Other" category is appropriate (see Question d in Section 2.2.2 below).

Following analysis of and response to these questions, you are prepared to consider the geologic setting.

2.2.2 Geologic Setting

Definition and description of the geologic setting (Broun, R.A.; et al., 1991c) is the second significant input in Tier 1. If the geologic setting consists of saturated, unconsolidated materials, then continue evaluation.

If the geologic setting at your site is karst, fractured or unfractured bedrock, or predominantly clay, many practitioners believe that air sparging is probably not an appropriate technology for your site and you may wish to consider alternative technologies (See Section 2.4) rather than proceed through the Tool.

To proceed with Tier 1, please answer the following questions:

a) Is the geologic setting or the subsurface profile at your site unconsolidated and of a homogeneous grain size larger than the clay fraction?

b) Is the geologic setting or the subsurface profile at your site unconsolidated and of a grain size larger than the clay fraction and layered?

c) If the geologic setting or subsurface profile at your site is layered, does the permeability of the layers:

   1) Increase with depth?

   2) Decrease with depth?

   3) Alternate with depth?

d) Are the contaminants of concern (other than petroleum or chlorinated hydrocarbons) either volatile and/or biodegradable (Leahy, M.G.; et. al., 1994) and does the geologic setting or profile lend itself to air sparging?

By addressing these questions, the prospective user is guided through the Decision Tree (see Appendix A). As a result, sites are sorted by anticipated probability of success with respect to air sparging application. Review of previously completed efforts has indicated that air sparging will likely have a low probability of success in the following situations:

- saturated zones in unfractured or fractured bedrock;
- saturated zones in unfractured or fractured clay;
- saturated zones in karstic environments; or

- saturated zones in environments with unfavorable heterogeneities (e.g. thin depositional layers of sand in a primarily homogeneous or clayey matrix or layers of silt or clay in a predominantly homogeneous sandy or gravelly matrix). Further discussion of these situations can be found in Sections 3.4.3 and 4.2, dealing with "red flags".

Air sparging has a low probability for success in these scenarios and should not be pursued further in this Conceptual Decision Tool.

2.2.3 Remediation Objectives

The Conceptual Decision Tool next considers three principal remediation objectives for sites in general: source remediation; plume remediation; and plume containment. For the purposes of this Tool, source removal or remediation is defined as removal of separate phase accumulations or pools (i.e., DNAPLs and LNAPLs) or smear zones (i.e., where petroleum hydrocarbons have become trapped at, just above or below the water table due to its fluctuations). Similarly, plume remediation is described as reduction of the concentrations of target contaminants (e.g. including VOCs and SVOCs) which have become dissolved in the aqueous phase and distributed laterally due to groundwater flow. Finally, containment is defined as the use of horizontal sparging wells, sparging gate-wells and/or sparging curtains (in which vertical wells are closely spaced) to create a hydraulic treatment zone. In particular, for the purposes of this Conceptual Decision Tool, containment does not include installation of trenches or other structures which significantly alter the geologic setting. In installing sparging trenches, a hydraulic barrier is created, significantly disturbing the natural geology; hence, a new conceptual geologic model is required. For the purpose of this Tool, sparging trenches are considered an alternative technology for plume containment.

2.3 DECISION MATRIX

The decision matrix (Table 1) compares your site's geologic setting and contaminant composition to the three different remediation objectives:

1) Source Remediation;
2) Plume Remediation; and
3) Containment.

An applicability rating or scale is then provided for each remediation objective. The scale is based on two discrete questions:

1) Is air sparging physically and technically possible? and

2) Is your scenario a good or unique target for sparging (or are there other, perhaps more appropriate alternatives?).

If your scenario is:	Then the appropriate scale is:
1) A good physical and technical possibility and a good or unique target for sparging	++
2) A good physical and technical possibility and a justifiable (but not unique) target for sparging	+
3) Determined to be an unknown physical and technical possibility	-
4) Determined to be not physically and technically appropriate	--

Compare your site with the Decision Matrix (Table 1). Is air sparging possibly applicable at your site? If air sparging is applicable to your site continue to Tier 2. If air sparging is not applicable to your site (i.e., it scores a "--" in Table 1), you should consider alternative technologies.

2.3.1 Consideration of Local Geologic Heterogeneities

Development of the conceptual geologic model and application of the Decision Matrix to your specific site has, until this point, been based on idealized cross-sections and several simplifying assumptions. For example, it has been assumed that your entire site has similar geologic characteristics throughout. This may, but frequently does not, accurately represent sites under consideration for remedial activities.

Specifically, consideration must be given by the field practitioner to variations in geologic conditions across the site. If detailed site characterization has identified more than one predominant set of geological parameters, your site should be sub-divided (for the purposes of applying this Tool). Different conceptual geologic models may be required, as a result of this subdivision, to define your site adequately for consideration in this Tool. Determinations of the applicability of air sparging should then be made for each area and respective geologic model. The results may demonstrate that air sparging is applicable in one, but not necessarily another, adjacent area.

Similarly, consideration should be given to variations in geologic conditions within a given area of a site. Local heterogeneities, often difficult to identify and characterize during implementation of traditional site investigation procedures and protocols, may render air sparging inappropriate for a site which appears to be ideal, on the basis of the conceptual geologic model. Practitioners may wish to consider application of continuous sediment

sampling, especially if potentially difficult (to characterize) conditions are suspected. Field practitioners should be particularly watchful for and wary of the following conditions:

- thin seams or layers of dissimilar materials
- fractures and other natural voids
- boulders and rocks
- discontinuous layers
- karst formations
- underground utilities and basements at or near the site
- bedrock ledges and other rock formations

As indicated previously, these conditions are difficult to identify and interpret using traditional soil boring and monitoring well installation methodologies. If the field practitioner is aware, based on regional geology, of the possible presence of these heterogeneities, he/she may wish to consider alternate, more sophisticated (and unfortunately more expensive) characterization techniques including continuous coring.

2.4 ALTERNATIVE TECHNOLOGIES

The Conceptual Decision Tool has been developed with consideration of several alternative technologies for situations in which air sparging may not be applicable. Examples of these alternative technologies include: pump and treat, dewatering and SVE, bioventing, bioslurping, sparging trenches, and/or natural attenuation. This listing is not all inclusive. These technologies are considered below with respect to the specific remediation objectives for which they are most likely to be appropriate.

2.4.1 Source Removal or Remediation

If air sparging is not considered appropriate for the site, source removal or remediation is probably best accomplished through the application of pump and treat, bioventing, dual phase SVE, or bioslurping if LNAPL is present. In the situations where LNAPL smear zones are detected, pump and treat or dewatering (with treatment) and SVE may be feasible alternatives.

2.4.2 Plume Remediation

Depending on the material and target remedial concentrations, plume remediation may be accomplished by application of limited pump and treat options or natural attenuation. In situations where time is not a significant factor or the risk of contamination to sensitive receptors is low, natural attenuation would probably be the most appropriate remedial alternative.

2.4.3 Containment

Containment could be implemented through application of pump and treat, semi-permeable barrier walls, or sparging trenches. In any case, a barrier is developed to prevent transport of contamination beyond a specific area.

2.5 EMERGING TECHNOLOGIES

Although not necessarily commercially available or proven at field-scale at this time, several emerging technologies hold significant promise as alternatives to air sparging or other conventional technologies (e.g., pump and treat) for the remediation of chlorinated or petroleum hydrocarbons. These *in situ* remediation technologies include: chemical oxidation; anaerobic bioremediation; aquifer remediation using recirculation wells; methane enhanced bioremediation; microbial filters; and in-well air stripping. It is anticipated that, during the life of this Tool, one or more of these technologies will be proven feasible at field-scale and will become commercially available. For this reason, these technologies are introduced in this document; brief summaries of each are provided below.

2.5.1 Chemical Oxidation

Through the introduction of aggressive oxidizing agents (e.g., hydrogen peroxide or potassium permanganate) into source areas or highly concentrated plumes, removal of VOCs or SVOCs of interest to DOE (e.g., TCE, PCE, TCA, phenanthrene, pyrene) is accelerated through oxidation and enhanced bioremediation. It has been found that the VOCs produce no end-products following oxidation (Siegrist, *et al*, 1994). Full-scale demonstration of this technology at a contaminated site is being planned for FY 1996.

2.5.2 Anaerobic Bioremediation

This process destroys nitrates, carbon tetrachloride, chloroform and other hazardous chemicals through injection and mixing of nutrients in groundwater and with anaerobic microorganisms (Skeen, *et al*, 1993). This technology is undergoing field demonstration during FY 1995.

2.5.3 Aquifer Remediation Using Recirculation Wells

Using different parts of vertical or horizontal wells, contaminated groundwater is extracted from the aquifer, treated by in-well modules, and then re-injected into the aquifer without pumping the water to the surface (Siegrist, *et al*, 1993). This technology would be attractive

for plumes contaminated with extremely hazardous materials (e.g., mixed or radioactive wastes). A demonstration of this technology is planned for FY 1996.

2.5.4 Methane Enhanced Bioremediation

Indigenous microorganisms are being stimulated to degrade TCE, PCE and other VOCs through the addition of nutrients (e.g., methane/air mixtures, nitrous oxide and triethyl phosphate) to the contaminated groundwater and through surface-based off-gas treatment, i.e., catalytic oxidation (Looney, Hazen, *et al*, 1991). This technology has been fully demonstrated and is being implemented at several sites.

2.5.5 In Situ Microbial Filters

This special application of in situ bioremediation involves the deployment of funnel-and-gate systems to re-direct groundwater movement through filters constructed of a permeable wall of TCE-degrading microorganisms emplaced in the path of a contaminant plume. As the plume passes through the filter, VOCs (e.g., TCE) are removed. A field-scale demonstration of this technology has been undertaken at the Kennedy Space Center (Knapp, R.B., 1995).

In-well Air Stripping

This technology utilizes a well within a well. The inner well extends into the contaminated aquifer and is used for injecting air below the source area or plume. VOC-laden air/water mixture rises to the top of the inner well where it escapes into the annular space between the inner and outer well casings. From here, the vapor is extracted to the surface where it is recovered (Gvirtzman and Gorelick, 1992). The process is similar in principle to the UVB approach (refer to the companion report "Existing Air Sparging Model and Literature Review for the Development of An Air Sparging Optimization Decision Tool," August 1995). The technology has been demonstrated and should soon be commercially available.

SECTION 3.0

TIER 2

3.1 WELCOME TO TIER 2

Welcome to Tier 2, the Conceptual Design Approach. Tier 2 provides several calculations and other relationships to evaluate sites for applicability and potential cost and to assist in the conceptual design of air sparging systems. This tier will help end-users avoid consideration of air sparging at sites that are not conducive to air sparging. By now, you will have completed a conceptual geologic model and identified a scenario that closely approximates your site (or your geologic model may resemble the "Other" category). Whatever the case, this tier provides you with calculations or relationships, accepted or acknowledged by the technical community, to help evaluate conceptual operating conditions associated with air sparging at your site. These calculations are intended to provide guidance in evaluating potential equipment needs, capital costs, efficiency considerations, and duration of remedial activity. These results can then be compared to established remediation goals and time constraints or to cost and performance estimates for alternative treatment technologies.

3.1.1 Progression of Evaluation Process

In this process, the user will employ estimated and calculated values to further evaluate the applicability of air sparging to a site (Broun, R.A.; et. al. 1991c). This will be accomplished by proceeding through the following steps (which are discussed in greater detail in subsequent sections):

1. An "optimal" unit volatilization rate (based on an idealized, "well-mixed" case) will be calculated; well-mixed is defined as a situation in which there is sufficient contact between sparged air and groundwater to achieve and maintain saturated oxygen conditions;

2. the unit removal rate will be modified based on an efficiency factor; the efficiency factor will be qualitatively determined and will be dependent on soil stratigraphy, contaminant type and distribution, and radial impact of expected well spacing;

3. a volatilization rate (based on a "diffusion-limited" case) will be determined; "diffusion-limited" is defined as a situation in which air channel distribution is very sparse (i.e., at intervals of 20 centimeters or greater) and the matrix is comprised of

fine grained, tightly packed particles (i.e., permeability is 10^{-7} cm/sec or less) such that concentration gradients are very high (Johnson, R.L., et. al., 1994).

4. the removal rate due to biodegradation will be estimated for sites with petroleum contamination and other biodegradable compounds (e.g., TCE);

5. based on vertical extent of contamination, a calculation will be performed to estimate air entry (over) pressure for injection of air below the zone of contamination;

6. the user will utilize a nomograph (relating soil type and over pressure) to estimate a flow rate for a particular well;

7. the number and spacing of air sparging wells will be estimated based on horizontal extent of contamination and estimated areal efficiency of an air sparging well;

8. using an estimated flow rate per well and the number of wells, a system flow rate will be estimated;

9. using the system flow rate, the unit removal rate, and the concentration of contamination at the site, the minimum duration of remediation can be approximated;

10. using the system flow rate and injection pressure (including injection depth, etc.), the "order of magnitude" size (and therefore conceptual cost) of major system components can be estimated;

11. the user will then compare the estimated duration and costs with their expected (or required) duration of remediation and budgetary constraints; if the result of the comparison is (marginally) unacceptable, alternative well spacing, etc. can be considered to evaluate the impact of revised conceptual system designs for air sparging; if the conceptual design is totally unacceptable (i.e., if time required or estimated costs exceed expectations by an "order of magnitude"), the user will be referred to alternative treatment technologies, which may be more appropriate for addressing the contaminants of concern at the site;

12. the user will evaluate site-specific conditions (i.e., "red flags" such as proximity and location of sensitive receptors, localized spatial heterogeneities, etc.) which would affect the applicability of air sparging to a site; and

13. after completing the aforementioned evaluation process, if the results deem that air sparging still may be applicable, the calculated and estimated values (i.e., injection pressure, flow rate, cost, etc.) will be used to conceptually design a pilot study as part of Tier 3. The user may then compare the results of the pilot study with the values projected in Tier 2, either to confirm applicability or to optimize the conceptual design.

3.2 CONCEPTUAL CALCULATIONS

The first step in the conceptual design phase of evaluating the applicability of air sparging at a site is to estimate a probable range of the duration of the remedial action (Olsen, R.L.; et. al.). This range is estimated by calculating conceptual contamination removal rates due to volatilization and biodegradation. (In the computerized version of this tool, most of these calculations will be performed by the computer after the user completes a simple input screen.)

3.2.1 Volatilization Removal Rates

The volatilization calculation offers a range of removal values, represented by best and worst case scenarios. The range is produced by applying an efficiency factor based on site-specific information (e.g., rating from Tier 1) to estimate unit volatilization rates for the particular site. The estimate for the maximum removal rate is based on the assumption that air sparging in the aquifer creates a well-mixed case (e.g., as in a highly permeable sand and gravel matrix). Conceptually, the well-mixed case could be represented (as a physical model) by injecting air in the bottom of a tank full of equally sized marbles. The calculation is shown in Figure 3. After estimating the volatilization rate, the field practitioner applies an adjustment (scaling) factor to the rate to estimate a site-specific removal rate. The efficiency factor, estimated by using Figure 4, is based on soil stratigraphy, contaminant type and distribution, and well spacing as well as the initial rating (e.g., scale) from Tier 1.

The efficiency factor is determined by using the following procedure. Using Figure 4, the practitioner identifies the applicable range by finding the part of the curve associated with the Tier 1 scale (i.e., ++, +, etc.). The user then refines his/her approximation of the efficiency factor based on several qualitative judgements, as described below:

<u>Contaminant type and distribution</u> - Air sparging is dependent upon the injection of air beneath the zone of contamination. In the case of denser-than-water contamination (i.e., DNAPLs), it is fairly difficult to deliver air under the zone of

contamination, making air sparging less effective when addressing this particular contaminant scenario. Thus, for cases involving DNAPLs and chlorinated hydrocarbon plumes, the user should consider adjusting the efficiency factor by moving down the curve (i.e., to the right) by at least one-half of an interval on Figure 4.

Well spacing - Based on recent large-scale physical modeling and field-scale demonstration efforts (Acomb, *et al*, 1995; R. Johnson, 1994; Lundegard, 1994), the technical community's understanding of air sparging behavior and performance has improved significantly. As a general rule, practitioners should attempt to maintain air saturation levels at 10-20 percent (of available void space) to provide sufficient oxygen for volatilization and bioremediation of VOCs. Below about 10 percent air saturation, these processes are likely to become increasingly diffusion-limited and, hence, very slow (R. Johnson, 1994).

The air distribution pattern in non-layered settings tends to be conical or parabolic, radially symmetrical and inversely dependent on distance from the sparging point. Figure 5 indicates a conceptual understanding of the relationship between air saturation concentration (as a percent) and distance from the sparging point. A saturation level of 20 percent will probably produce the ideal or maximum rate of removal; concentrations above this level probably will not provide any added benefit (Acomb, et al, 1995). Below about 10 percent air saturation, the matrix will likely become increasingly diffusion-limited. Thus, depending on the geologic setting, injection depth and injection flow rate, an effective radius of influence ranging from 7 to 15 feet can be assumed. As an average, practitioners should probably use a radius of 10 feet (i.e., well spacing approaching 20 feet). In layered geologies, the radius of influence is very difficult to predict and pilot testing is reommended for definition of air migration patterns.

If the practitioner elects, for purposes of expediency, to place wells at, say, 14 foot intervals, the user should adjust the weighting factor in Figure 4 by moving up the curve by one-half an interval. If, on the other hand, the user elects a much more dispersed spacing (e.g., 30 ft), for the purposes of economy, the user should move down the curve by one-half interval to find the appropriate weighting factor.

Soil stratigraphy - It has been observed that more porous geologic units on the site (i.e., sand and/or gravel) provide better air flow through the subsurface; hence,

remediating the more porous portions of the site, which come into greater contact with the injected air, should prove easier and faster. Just as porous sediments may be more conducive to air sparging, layered settings can alter the flow pattern of the injected air in the saturated zone, significantly limiting the effectiveness. Assuming an isotropic heterogeneous stratigraphy as the norm, the user should adjust the efficiency factor upward or downward, as appropriate, based on the foregoing discussion by up to one-half an interval.

The field practitioner can use the information provided in the aforementioned sub-evaluations to adjust the efficiency factor. Multiplying the efficiency factor times the calculated (well-mixed) volatilization rate will provide the user with an approximate unit volatilization rate.

To serve as a check and to assist the user in the application of the Tool, the diffusion-limited calculation is included. This will serve as a lower bound for the volatilization rate for air sparging, given appropriate site-specific conditions. The calculation for the diffusion-limited volatilization rate is shown in Figure 6.

3.2.2 Bioremediation Removal Rates

Depending on the contaminant(s) of concern, it may also be appropriate to calculate the amount of contamination which will likely be removed by biodegradation. There are, however, several situations for which consideration of removal by bioremediation may not be warranted. These include:

1) Sites contaminated solely with chlorinated hydrocarbons. With few exceptions (most noted among these is TCE in an aerobic environment), chlorinated hydrocarbons biodegrade *in situ* very slowly or hardly at all. Bioremediation of chlorinated solvents may occur in certain site-specific cases, especially in the presence of highly biodegradable co-contaminants, such as BTEX.

2) Sites contaminated with constituents which are highly volatile but not very biodegradable. Please refer to Figure 7, which indicates the impact of physiochemical properties on the potential for volatilization and/or bioremediation of certain hydrocarbon compounds.

In a well-mixed source area scenario, typical rates of bioremediation for most petroleum hydrocarbons within the effective radius of influence (e.g., within approximately 7 feet from

the sparging well) tend to range from 3 to 10 milligrams of hydrocarbon per kilogram of aquifer material per day; practitioners should use an average of 5 mg HC per Kg per day, unless more site-specific or contaminant-specific information is available. This assumes a relatively homogeneous, fine-grained sand aquifer with 20 percent air saturation in the effective radius of influence (Acomb, *et al*, 1995). In such cases, initially the rate of oxygen supply will exceed O_2 demand. Eventually, the biodegradation rate may decline by a factor of 2 to 10, when limited by the decreasing availability of hydrocarbon contamination. Figure 8 indicates the general trend of the bioremediation rate that may be expected over time.

These rates would be somewhat lower for less soluble contaminants (e.g., diesel or heavy oil) and for diffuse plume situations. In an oxygenated dissolved plume, biodegradation rates of 0.3 to 2.4 percent per day have been reported in the literature. For the purposes of this Tool, it is proposed that an average rate of 1 percent per day be assumed. The removal rate can then be calculated as follows:

$$C = C_0 e^{-0.01t}$$

C = residual contaminant concentration (mg/L)

C_0 = initial contaminant concentration (mg/L)

t = time in days

For example, if the initial dissolved hydrocarbon concentration is 10 mg/L and the aquifer is sparged for 100 days, the non-biodegraded residual concentration would be approximately 3.7 mg/L. It should be noted that this example assumes a 100 day contact time; the user must consider the groundwater velocity and contact time in determining the time utilized in the above equation. Hinchee (1994) provides further information regarding the determination of bioremediation rates during air sparging system operations.

In diffusion-limited (also referred to as oxygen-limited) scenarios (R. Johnson, 1993), such as could occur in dense, fine-grained clays and silts, the rate of hydrocarbon biodegradation has been estimated at less than 0.02 milligrams of hydrocarbon per kilogram of aquifer material per day in the source area. For dissolved plume removal, if we assume a reduced oxygen gradient (compared to the example in R. Johnson, 1993), the rate would be approximately 0.0077 or less milligrams per kilogram per day.

Included in Figure 8 are the relationships for determining unit biodegradation rates; example calculations of their use are included in Appendix C. For further information on bioremediation rate determination, especially for heavy petroleum hydrocarbons and chlorinated hydrocarbons in general, the user is advised to consult recent literature or environmental professionals with *in situ* bioremediation expertise.

3.2.3 Over Pressure and Flow Rate

In order to estimate the duration required for remedial action utilizing air sparging, the unit volatilization and biodegradation rates must be evaluated on a system (instead of unit well) basis. To calculate the system removal rate, the system flow rate must be determined. The system flow rate is comprised of the individual well flow rates at a given over pressure. Therefore, it is necessary to calculate conceptual system operating parameters in order to evaluate the remediation system.

Over Pressure

The first parameter to evaluate is the over pressure. Figure 9 displays the calculation for determining over pressure (which is dependent on user-specified depth at which air will be injected). The user will need to ensure that the expected depth of the injection point is sufficiently below the vertical extent of the zone of contamination (i.e., at least 10-15 feet for homogeneous matrices; this may have to be less to accommodate layering or other heterogeneities). The depth below the zone of contamination is important to supply adequate quantities of air into the impacted area.

Injection Well Flow Rate

After calculating the over pressure for the site, the field practitioner will utilize the nomograph displayed in Figure 10 to estimate a conceptual well flow rate. The flow rate is a function of the over pressure and the specific stratigraphy of the site. An example on the how to use the nomograph has been included with Appendix C.

3.2.4 Well Spacing and Estimated Number of Wells

In order to assure that air sparging is providing adequate air to the subsurface, field practitioners will estimate an effective radial impact (of one air sparging well) or well spacing (distance between injection wells) for their sites. This radial impact will then be utilized with a site plan, depicting areal extent of the saturated zone contamination. Overlaying the projected impact areas onto the site plan will assist the user in estimating the conceptual number of air sparging injection wells which may be required at the site. Similarly, spacing between horizontal wells can be determined by projecting the effective area of impact onto the site plan.

Once the conceptual number of wells has been estimated, the flow rate for one injection well can be multiplied by the total number of wells; the resultant will be an estimated conceptual system flow rate for the air sparging system.

3.2.5 Theoretical Removal Rate

Using the conceptual unit volatilization rate, biodegradation rate and the system flow rate calculated above, the user can then estimate the minimum expected duration of remediation activities at the site. This is accomplished by multiplying the modified unit volatilization rate by the system flow rate. After obtaining a system flow rate (based on the number of wells and the flow rate per well) and a system volatilization rate, the duration of remediation can be approximated. This is accomplished by comparing the system removal rate to the contaminant concentration information from the site. This evaluation is displayed in the calculation in Figure 3. Utilizing this removal rate, the user will estimate the minimum duration of the remediation required, based on site-specific contaminant concentrations and remediation objectives. Based on the time required to achieve the specific remedial goals, the user may wish to re-evaluate efficiency factors to evaluate the sensitivity of the parameters he has less confidence in.

3.2.6 Conceptual Cost Evaluation

The user will now have a system flow rate (based on the expected number of wells and flow rate per well). Combining that result with the calculation for injection pressure, the user can estimate (by order of magnitude) the size of the compressor needed to perform air sparging at the site. Based on the information derived from the calculations and relationships described above, the user can now develop a conceptual air sparging design for the selected site. The conceptual design basis should include the following major elements: number and approximate depth of air sparging wells; size of compressor; presence and approximate size of vacuum pump (if appropriate, for a concurrent SVE system); vapor treatment for SVE system (if required); number and depth of SVE wells (if required); number and configuration of monitoring points; and piping to connect the air sparging wells and compressor (based on approximate size of area to be remediated and on whether concurrent SVE will be required).

Knowing this information (i.e., the number and depth of air sparging wells plus the size of the compressor required), the user should now be prepared to estimate the overall cost for implementing the conceptual design. Also, with the conceptual system design completed, the user should be prepared to compare these results with system constraints (e.g., resources or time available) and expected values (i.e., reality checks). Table 2 has been provided as a

worksheet to prompt the prospective user through conceptual (albeit somewhat detailed) cost estimating. Included within Table 2 are simple calculations, relationships and reference information to help the user develop conceptual cost estimates for the various major system components. The worksheet provided in Table 2 assists the user in preparing a conceptual cost estimate for system installation only; the worksheet does not include startup and ongoing operation, maintenance and monitoring cost guidance. The user should be aware that these costs (startup and ongoing operation, maintenance, and monitoring) can be significant and must be considered during the planning of the remediation project. Due to the high degree of variability of requirements for these activities, at both the user and regulatory levels, it is not appropriate or practical to provide a conceptual cost worksheet for operating and related costs. However, the following provides a general list of items to be considered by the user when planning for the remediation project:

- Site Visit Frequency (weekly, monthly, etc.).
- Confirmatory Sampling and Monitoring Frequency (for system effluent streams, etc., as required) to ensure and satisfy compliance with permitting requirements.
- Confirmatory Sampling and Monitoring Frequency (for soil, groundwater and soil vapor characteristics, etc.) to determine effectiveness and performance of remediation system operation and to quantify the progress made toward clean-up goals.
- Preventative Maintenance Program (for the remediation system equipment), including waste management and disposal (i.e., spent carbon).
- Reporting Frequency and Requirements (at both the user and regulatory levels).
- Duration (of start-up and ongoing operation, maintenance and monitoring for the system), i.e., the estimated life of the remediation project after the completion of start-up activities.

To assist the user in developing rough system installation costs, a cost estimating guide based on total well footage has been provided (Figure 11). The guide includes the equipment purchase and installation costs for the major elements of the system (e.g., compressor, vacuum pump, well installation, etc.) and an aggregation of the costs for peripheral and associated materials, equipment and labor required to ensure the proper installation and functioning of the principal elements of the system. After the user has completed the conceptual design for the system, Figure 11 may be utilized to determine a rough estimate for the system installation prior to or instead of using the cost worksheets of Table 2. As with Table 2, Figure 11 does not encompass costs associated with system startup, operation, maintenance and monitoring.

To utilize Figure 11, the user should proceed through the following steps:

1. Determine Total Well Footage to be installed in accordance with the conceptual system design. Note: Total well footage includes all wells and points to be installed - air sparging, soil vapor extraction, monitoring wells, monitoring points, etc.

2. Enter the x-axis of the graph at the corresponding Total Well Footage Value.

3. Utilize the Total Well Footage Value to intercept the curve of the graph.

4. The intersection of the Total Well Footage Value and the curve of the graph will provide the user with a range of values for Cost per Foot of Well.

5. The user will then multiply the Cost per Foot of Well by the Total Well Footage to obtain a range for system installation costs. The user may use the range or a single system installation cost estimate, depending on requirements.

3.2.6.1 Comparing Cost Calculations with Expected Values

By completing the worksheet found in Table 2 and/or utilizing Figure 11, the user will have developed a reasonably complete estimate of the costs for installing the conceptual system designed in preceding steps. The user should now determine whether the estimated conceptual system cost is appropriate and reasonable, within the financial and other resource constraints available and within the level of expectations originally identified for the remediation project.

Criteria which may be used for determining conceptual system design reasonableness include:

a. Does the system achieve remediation objectives (i.e., reduce contaminant concentrations to target levels)?

b. Is the remediation objective reached within the prescribed (by enforcement order or regulatory deadline) time-frame?

c. Is the conceptual system design practical and feasible (e.g., component sizes are reasonably available)?

d. Is the level of resource required to implement the conceptual system design within the expected financial constraint (i.e., budget)?

e. Is there a more cost-effective or time-efficient technology for remediating this site (see below for information on a discussion of other technologies)?

3.3 ALTERNATIVE TECHNOLOGIES

In evaluating the appropriateness of utilizing air sparging to remediate a site, it may be necessary to consider alternative technologies (Ardito, C.D., et al, 1990b) which may be more

effective. The following is a discussion of select technologies which may also be considered for the remediation of the saturated zone. This discussion does not attempt to address an all inclusive listing of available or emerging technologies, it is intended to present only those example technologies universally available. For a discussion of other emerging technologies, refer to Section 2.5.

Groundwater Recovery and Treatment

Groundwater recovery and treatment (e.g., "pump and treat") has been the remedial technology most commonly used for addressing contamination found in the saturated zone. By employing groundwater recovery systems, subsurface water is removed from the water-bearing zone, usually by pumping, and treated in an above-ground system. Any residual contamination within the saturated zone is eventually removed as it becomes soluble and is pumped from the ground with the recovered groundwater. Groundwater pump and treat may also be used for hydraulic control, while natural attenuation occurs. Costs associated with this technology include installation, operation, and maintenance of recovery wells, pumps, and the treatment system. There also are costs associated with the disposal of wastes generated during the treatment process (e.g., regeneration of the activated carbon). Life-cycle costs for pump and treat systems may be higher when compared with other options. The duration of remedial projects using this technology also tend to be long (i.e., often ten or more years).

Dewatering and Soil Vapor Extraction (SVE)

This technology is a combination of two technologies. Dewatering is simply the pump and treat option described above. After the water elevation has been sufficiently lowered below residual source areas, a soil vapor extraction (SVE) system can be utilized to remediate exposed soil. Costs of this system include the installation, operation, maintenance, and monitoring of the equipment required for these two systems as well as associated waste disposal costs. Costs for this approach can be quite high if the zone of contamination recharges rapidly (i.e., the matrix is highly permeable); in some cases, a perimeter groundwater barrier may also be required, adding to the overall cost. In addition, SVE vapor treatment (e.g., by thermal oxidation, carbon adsorption, or recovery) may be required, significantly increasing installation and operating costs.

Sparging Trenches

Sparging trenches are utilized for containment applications. When installing a sparging trench, the geology of the site is altered and the mechanisms of volatilization and

biodegradation are promoted within the confines of the trench. For this reason, sparging trenches may be applicable for use in geologic settings which are not well-suited for sparging injection application. The cost for this approach can be less expensive than pump and treat, particularly in shallow aquifers. If there is a continuing source area at the site that is not being addressed and which continues to impact the saturated zone, the duration of operation can be rather lengthy.

Natural Attenuation

Natural attenuation is the remedial technology exploiting the natural degradation (dispersion and dilution) of a contaminant (particularly petroleum hydrocarbons). In some instances, the application of air sparing does not significantly enhance the natural degradation activity already occurring at a site. If this is true (or suspected to be true), then air sparging would not be suitable for application at the site. Costs associated with natural attenuation include monitoring and evaluation of site information to determine the rate of natural degradation. Long-term monitoring costs may also be required to ensure that off-site receptors (if present) are not adversely affected. Overall, this technology can provide the most cost-effective approach, if time constraints and contamination levels are not too severe or high, respectively.

3.4 USER CRITERIA

There are other site-specific conditions which must be considered in evaluating the applicability of utilizing air sparging to address saturated zone contamination at a particular site. These conditions or "red flags" are described below.

3.4.1 Sensitive Receptors

The presence and proximity of sensitive receptors must be considered when evaluating the use of air sparging at a particular site. The goal of air sparging is to volatilize and mobilize contamination from an aqueous state to a vapor state. When this mobilization occurs, the vapors can migrate into unwanted zones, for example, collecting in basements and other subsurface structures and possibly causing hazardous or explosive conditions in those locations. In such cases, an SVE system must be operational at the site to control vapor migration. Other receptors, such as utility vaults and manways present similar concerns. Utility lines can also provide preferential pathways for the uncontrolled migration of vapors.

These and other sensitive receptors should be identified and evaluated when considering the application of air sparging at a particular site.

3.4.2 Politics and Regulatory Requirements

Other issues which may impact the application of air sparging include political and regulatory pressures. In some states, the regulatory agencies may discourage the use of innovative technologies, such as air sparging. In other states, air sparging is being encouraged by state regulators with little regard for site-specific conditions. In many state and local political jurisdictions, the permitting process may be extremely rigorous and complicated. These issues may impact the applicability of air sparging at a site to a greater degree than the technical (e.g., feasibility) issues.

3.4.3 Spatial Heterogeneities

Consideration must be given by the field practitioner to variations in geologic conditions across the site. If detailed site characterization has identified more than one predominant set of geological parameters, the user may be required to subdivide the site into separate areas and determine applicability of air sparging for each area independently. The results may demonstrate that air sparging is applicable in one, but not necessarily another, adjacent area.

Similarly, consideration should be given to variations in geologic conditions within a given area. Spatial heterogeneities, often difficult to identify and characterize, may render air sparging inappropriate for a site which otherwise appears to be ideal (e.g., homogeneous sand matrix with a thin silty layer just below the water table). Field practitioners should be particularly wary of the following conditions:

- thin seams or layers of dissimilar materials
- fractures and other natural voids
- boulders and rocks
- discontinuous layers
- karst formations
- vapor movement into underground utilities
- bedrock ledges and other rock formations

Another consideration is site operational history. The field practitioner should be aware of old septic areas, buried conduits which held piping or access routes, and old distribution (product piping) locations.

As indicated previously, these conditions are sometimes difficult to identify using traditional investigative methodologies. If the field practitioner is aware, based on regional geology, of the possible presence of these heterogeneities, consideration of alternative remediation technologies may be appropriate.

3.5 GENERATION OF CONCEPTUAL DESIGN BASED ON CALCULATIONS

As part of Tier 2, the user will generate a conceptual design based on previously discussed calculations and relationships. The user will have a system flow rate (based on the expected number of wells and flow rate per well). Combining that result with the calculation for injection pressure, the user will estimate (by order of magnitude) the size of the compressor needed to perform air sparging at the site. Based on the information derived from the calculations and relationships described above, the user can develop a conceptual air sparging design for the selected site. The conceptual design basis should include the following major elements: number and approximate depth of air sparging wells; size of compressor; presence and approximate size of vacuum pump (if appropriate, for a concurrent SVE system - including vapor treatment); number and depth of SVE wells (if appropriate); number and configuration of monitoring points; and piping to connect the air sparging wells and compressor (based on approximate size of area to be remediated and on whether concurrent SVE will be required).

3.6 COMPARISON OF CONCEPTUAL DESIGN WITH SYSTEM PERFORMANCE

Having progressed through the site-specific evaluation of applicability of air sparging at the selected site, the next step in the process is to confirm many of the Tier 2 assumptions in a pilot-scale field study of air sparging performance. Guidance for conducting the pilot test is provided in the next section (Tier 3). However, to evaluate the performance of the air sparging pilot test, test results will be compared to the values estimated earlier (i.e., flow rate, injection pressure, etc.). This comparison will provide an estimate of how "close" the analysis conducted during this Tier compares to actual design and performance results (e.g., well spacing, rough costs, etc.). Once again, refer to the various figures, tables, and calculations to estimate operating parameters, to determine the conceptual system design, and compare the actual pilot study results with those predicted in Tier 2.

SECTION 4.0

TIER 3

4.1 WELCOME TO TIER 3

Welcome to Tier 3, the Pilot-Scale Testing Approach. By the time you have reached this stage in the decision-making process, you will have already completed the first two tiers of the Conceptual Decision Tool. In Tier 1, you developed a conceptual geologic model of your site; you then compared that model to the several generalized scenarios provided as an initial screening to determine if air sparging is applicable to your site. In Tier 2, you performed several basic calculations and made a number of simplifying assumptions to further evaluate the feasibility of utilizing an air sparging system at your site.

In this tier (Tier 3), you will further evaluate the applicability of air sparging to your site by conducting a pilot-scale field test (or pilot test). The results of the pilot test will demonstrate whether air sparging is physically feasible at your site. As part of this tier, guidance will be provided for determining what information can realistically be obtained during a pilot study (Table 3). The information provided in this tier is only to evaluate the potential "infeasibility" of air sparging. It is not the Project Team's intention to provide a complete guidance on how to conduct pilot studies for use in the design of full-scale air sparging remediation systems, but rather it is intended that the user be provided with sufficient guidance to supervise or observe pilot studies conducted by professional consultants (see Section 4.2.1). Also, the data obtained from the pilot test will be compared with the results calculated in Tier 2 (i.e., removal rate, injection pressure, well spacing, rough system costs, etc.) to determine if you should continue pursuing air sparging for application at your site. Furthermore, results of the pilot test can be used to optimize the conceptual design which you developed in Tier 2; by comparing pilot test and calculation results, a more optimal approach may be attempted.

A complete discussion of pilot studies, including air sparging design issues and pilot study protocol is part of the document titled "*In Situ* Air Sparging: Evaluation of Petroleum Industry Sites and Considerations for Applicability, Design and Operation" (Draft 1994) developed for the American Petroleum Institute by Envirogen, Inc.

4.2 PILOT TESTING

An air sparging pilot test is conducted to evaluate and determine the feasibility of applying the technology to a specific site. For this reason, during pilot tests, it is important to look for

adverse signs or "red flags" (see Tables 4 and 5), that may indicate potential problems with the application of air sparging at the site. Possible problems may include:

- observation of adverse impacts caused by air sparging (e.g., uncontrolled migration of vapors).

- poor air distributions (e.g., highly stratified or undirectional air flows).

- possible presence of very thin layers in homogeneous settings (lower permeability causing an air bubble or higher permeability causing lateral movement);

- drying of discrete monitoring points located in the saturated zone (indicating the presence of an air pocket);

- inability to inject significant air flow (over pressure is too great).

- apparently significant dissolved oxygen increases or hydrocarbon concentration reductions during the pilot study (could signal very localized impact or removal of small residual concentrations in pores near air channels, but the remediation mechanism may, in fact, be diffusion-limited); and

- excessively high flow rate required to maintain or achieve pressure as calculated in Tier 2 (possible short-circuit or other conduit present).

If an air sparging pilot test is conducted for a period of less than one day, it is important to consider the limitations of the data that are generated. For example, during a 2- to 4-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, or immediately adjacent to, 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 (or even less indicative of DO levels in the aquifer at points remote from the well) under longer term (e.g., one week or greater) testing or during full-scale system operation. Furthermore, measurements of groundwater movement in response to the short-term system testing may be more representative of transient, instead of full-scale system, operating conditions. Table 3 presents a brief synopsis of what can

reasonably be learned from pilot studies, depending on the duration of and resources utilized in the tests.

Air sparging pilot tests are usually, but not necessarily, conducted in conjunction with soil vapor extraction feasibility tests. A major reason for conducting air sparging in conjunction with soil vapor extraction (both during pilot-testing and during full-scale operation) is to control the migration of VOC vapors.

Air sparging pilot testing may not always be warranted, especially if the sole purpose is to determine applicability. For instance, in well characterized, homogeneous sites, pilot testing may not provide additional information to justify the cost of conducting the test. It should be noted, however, that air sparging pilot tests usually serve two functions: to determine applicability and to assist the field practitioner with conceptual design of the air sparging system.

4.2.1 Pilot Testing Guidance

Equipment used in an air sparging pilot test generally includes one (or more) air sparging test well(s), one (or more) discrete monitoring point(s), air sparging equipment (i.e., compressor, pressure relief valve, regulator, etc.), and monitoring equipment for the collection of static (background) and dynamic physical and/or chemical measurements. If required for safety reasons (i.e., presence of sensitive receptors), one (or more) SVE well(s), blower and associated equipment may be required as well. In some states or localities, vapor control equipment may also be required; typically this latter requirement may be waived for short-term pilot tests, however. Discrete monitoring points which may be utilized in an air sparging test include: saturated zone piezometers; vadose zone monitoring points (vapor probes); SVE well(s) and any existing appropriately located groundwater monitoring wells. An example pilot study layout is shown in Figure 12.

The screened interval of the air sparging well is generally positioned directly below the delineated vertical extent of contamination. The areal placement of the well(s) is generally within the remedial target area.

It should be noted that all sites may not require pilot-testing, based on the user's experience with similar sites. However, pilot testing is suggested for determining and confirming conceptual system design information.

4.2.1.1 Physical Equipment

Discrete Monitoring Points

Piezometers installed in the saturated zone can be used to monitor the performance of the air sparging test well. Saturated zone probes are generally used to monitor water quality, pressures and the presence of air flow. For optimal monitoring, nested (i.e., multi-level) sets of saturated zone probes should be installed. Saturated zone probes should be placed at various depths and distances from the test well to better characterize the air distribution in the saturated zone. In general, saturated zone probes can be positioned in varying radial directions from the air sparging well to provide data on the relative symmetry of injected air flow distribution about the well.

Unsaturated zone vapor probes should be installed above the target zone of contamination to monitor the concentrations of VOC, O_2, CO_2 and inert tracer gas (if used) occurring within the vadose zone during air sparging testing. Tracer gas (e.g., helium, sulfur hexafluoride) studies may be used to determine the area of impact and to identify preferential air flow channels.

The layout of the air sparging test well and discrete monitoring points is generally designed to obtain data representative of as many of the site-specific geologic and chemical heterogeneities as possible. An example pilot study layout is shown in Figure 12. For instance, at a site which has contaminated areas in several different soil types (e.g., fill and native materials), the pilot test system should be designed to determine the physical and chemical parameters in each distinct area.

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 oil-less air compressor), high-pressure air hose, pressure gauges, in-line flowmeter, control valves, and an air sparging well head assembly.

The oil-less air compressor should be large enough to inject sufficient flow at sufficient pressure to at least one well and possibly to multiple wells simultaneously. Designers generally avoid using high-pressure compressors that may, if improperly operated, pneumatically fracture the aquifer and/or rupture the air sparging borehole annular seal(s). Oil-less compressors should be used to avoid injection of compressor oils into the subsurface. Failures of borehole seals, with subsequent short circuiting of the injected air flow or upward

movement of the air sparging well, have also been recorded. Suggested maximum injection pressures for unconsolidated materials are approximately 0.6 to 0.8 psi per foot of overburden.

The compressor is 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 (and, thus fracturing or fluidizing the aquifer).

Flexible, high-pressure air hoses equipped with quick-disconnect air fittings (couplers and plugs) provide a cost-effective method of manifolding the compressor to the air sparging 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 air sparging well head assembly in order to determine the air pressure in the air sparging well.

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. A high quality rotameter is generally the most appropriate measuring device for the relatively low flows associated with air sparging. In general, pitot tubes 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 becomes important when 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 steel or stainless steel pipe immediately after the compressor discharge to a PVC manifold is generally sufficient to dissipate excess heat. Temperature measurements may also be necessary for determining the factor used in correcting flow meter readings.

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

4.2.1.2 Pilot Test Monitoring

Before, during and after an air sparging 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 (if applicable);
- Water quality measurements (e.g., dissolved oxygen concentrations);
- Soil gas VOC concentrations in vapor probes/unsaturated zone probes;
- Soil gas CO_2/O_2 concentrations;
- Tracer gas concentrations (if applicable) and;
- Visual observations such as air bubbling in wells or piezometers.

If SVE is operating at a site, the SVE system is generally shut down for a period of time (for at least for one week, depending on soil and contaminant type) to allow soil gas contaminant concentrations in the vicinity of vapor probes to equilibrate with the contaminants on the soils. This enables changes in soil gas constituent concentrations, as a result of air sparging pilot system operation, to be more accurately quantified. Obviously, if the potential for hazardous vapor migration to sensitive receptors exists, the SVE system should not be shut down during air sparging testing without sufficient vapor monitoring which can be utilized to avoid health and safety problems.

Measurements of aqueous phase dissolved oxygen and soil gas CO_2 and O_2 are taken prior to the pilot test (background measurements) 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 air 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 air sparging in the saturated zone may be more difficult to delineate. If pilot testing does not indicate a significant improvement of the rate of bioremediation (when compared with natural attenuation), air sparging may not be appropriate.

Ideally, if biosparging is the primary objective of an air sparging system (biological degradation being the principal aim of the air sparging system, instead of volatilization),

background and source area biosparging tests (similar to vadose zone bioventing/respiration tests) may be performed. In these tests, dissolved oxygen utilization should be monitored over a period of several days following aquifer oxygenation through air sparging. It should be noted, however, that some practitioners dispute the utility of these tests because the impacts are often difficult to measure and the results are difficult to interpret.

4.2.1.3 Start-up of a Pilot Test

Following the collection of background measurements, the pilot test can be initiated. The field personnel generally initiate and carefully increase the delivery/injection of air to the air sparging well using an air pressure regulator. Air sparging wellhead pressure and flow readings are typically monitored simultaneously to evaluate whether the pressure and flow rates have stabilized. Again, excessive pressures should be avoided. In order to capture the sparged vapors, the SVE flow rate should be greater than the air sparging flow rate. The SVE/air sparging flow ratio is variable but tends to be in excess of 2:1 (Johnson, R.L., *et al.* 1993). The SVE/air sparging flow ratio may be determined on a site-specific basis by demonstrating that the sparge vapors are being contained or through the recovery efficiency of tracer gases.

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 of 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.

4.2.1.4 Pilot Test Data Collection

In addition to the previously suggested pilot test parameter measurements, changes in the conditions in existing site groundwater monitoring wells are typically monitored. Visual observations such as mounding or bubbling at groundwater monitoring wells or piezometers should be noted. Each of the test parameters are generally measured as frequently as practical over the duration of the test.

Test results obtained from a single sparging well, in conjunction with discrete monitoring points installed in a uniform sand, are likely to provide data representative of the entire site. 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 well test may reflect biased performance as a result of local geologic/permeability heterogeneities (stratifications or preferential air flow channels). In these situations, more than one test well may be needed.

4.2.1.5 Data Interpretation

Due to the current, limited level of understanding of the mechanisms governing air sparging, present practice in pilot testing is to collect data using several different indicators of potential system performance.

4.2.1.5.1 Electrical Resistivity Tomography (ERT) Monitoring

Electrical resistivity tomography (ERT) is an experimental technique used at some research sites to investigate the distribution of air as a result of *in situ* air sparging (Lundegard 1994, 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 in many cases (Lundegard, 1994). The ERT technique requires considerable instrumentation and data analysis (and, hence, expense) and therefore should be viewed primarily as a research tool at this time.

4.2.1.5.2 Pressure/Vacuum Considerations

The comparison of vadose zone pressures, in a combination air sparging/SVE system while cycling the air sparging system on and off, has been used in the evaluation of air sparging system applicability. The application of SVE at a site results in a negative pressure distribution within the vadose zone. When an air sparging system is activated, air exiting the saturated zone can lead to a decrease in the magnitude of the negative pressures in the vadose zone. However, due to the propagation of a pressure wave from an air source, the potential for recording a false positive 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 the 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 evaluate air sparging applicability from vacuum change data is limited.

Measurements of positive pressure distributions in the saturated zone have been suggested as a means to determine area of effectiveness. The measurements are reported to directly represent the forced displacement of pore water. Changes in subsurface pressures resulting from air sparging systems appear to vary exponentially with distance. However, as with the

concerns discussed earlier on the use of vacuum differences 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 more likely on pressure propagation from an injection source.

4.2.1.5.3 VOC Analysis

The composition of gases within the air space of groundwater monitoring wells or in vapor monitoring probes can be indicative of air sparging effects. VOCs that have been mobilized by air sparging from beneath a water table can be detected within the vadose zone using a variety of portable instruments (combustible vapor detectors or 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 air sparging 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. It should be noted, however, that CO_2 levels in background soils can be high; therefore, elevated CO_2 readings should be used cautiously as an indicator of air sparging performance.

A few limitations in using VOC concentration changes in the soil gas with respect to evaluating air sparging system effectiveness should be considered:

- If VOC concentrations are measured only at the SVE system discharge, the data developed will indicate the potential positive impacts of the overall air sparging system but will not provide information with respect to the probable areal extent influenced by air sparging. Measurements at discrete vadose zone monitoring points are also needed.

- Changes in VOC concentrations at the vadose zone monitoring points can result due to the contact of sparged air with vadose zone contaminated soils. While this effect may be an overall benefit to site remediation, it is not proof of effective sparging of the saturated zone. Conversely, if the vadose zone VOC level is relatively high, then the effect of VOCs removed from the saturated zone by air sparging may be masked by the background conditions.

- If air sparging 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 evaluating air sparging feasibility. This is particularly pertinent in the vicinity of the SVE well.

4.2.1.5.4 Tracer Gases

The use of helium (He) or sulfur hexafluoride (SF_6) as tracer gases has been shown to be a productive method for evaluating the effectiveness of air sparging. 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 air sparging 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 spatial 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 vadose zone making determination of areal impact 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 TCD's do not typically operate by continuously sampling and analyzing 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.

4.2.1.5.5 Air Bubbling

Air bubbling observed in monitoring wells in a pilot test is a key indicator of air movement in the saturated zone. Bubbling is a direct sign of the presence of air channels. However, since monitoring wells are generally screened over a significant interval and present a preferred vertical pathway for air movement, care must be taken in data interpretation. It will be generally unclear whether one (or a number of) channel(s) is (are) intersecting the well screen interval(s). Further, without the preferred vertical pathway provided by monitoring wells, the air channel would likely continue its lateral migration until a natural preferred vertical pathway was intersected. Bubbling has been observed at locations far beyond the expected, effective area of impact (as determined by other test parameters). Bubbling that occurs outside of an expected, effective area of impact (based on other measurement

parameters) should be considered a concern, in particular with respect to the potentially uncontrolled migration of hazardous vapors.

4.2.1.5.6 Groundwater Mounding

Groundwater mounding (i.e., upwelling) is often used to determine area of effectiveness because it is easily measured. While mounding is indicative of bulk water displacement, its use as an indicator of impact may result in overestimation of the effectiveness of an air sparging system (Lundegard, P.D., 1994). Depending on the soil conductivity and quantity of water displaced, mounding may spread laterally beyond the impacted area. If upwelling is measured, periodic measurements should be taken in multiple monitoring wells to evaluate upwelling effects over time. It should be noted that concerns have been raised with respect to 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, R.L., *et al.* 1993). Again, care must be taken to separate the effects of the vacuum generated by a SVE system from those generated by air sparging on groundwater mounding.

4.2.1.5.7 Dissolved Oxygen (DO) Monitoring

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. Air sparging can directly impact the DO levels of water in contact with the air sparging channels. Air sparging can also impact the DO levels by transfer within the saturated zone due to the mixing associated with air sparging 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.* 1993). Combined air sparging and SVE systems may also influence DO levels as a result of air transport occurring within the unsaturated zone or may contribute to elevated DO levels via equilibrium between the aqueous and air phases.

One concern with using measurement of DO levels as an effectiveness indicator is that, over the typical short-term of an air sparging pilot test, an observed DO increase may not be indicative of an increase in DO throughout the impacted area. Instead it may be a more likely representation of a localized DO increase in the vicinity of a preferred air channel. Appropriate groundwater sampling procedures should help determine the extent of DO change in the aquifer.

Consideration should also be given to the potential for detecting 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 a reduced state due to anoxic groundwater conditions). In addition, alternate biological demands (natural organics degradation) could be a sink for the injected oxygen. Running air sparging tests over a period of a few days should minimize the potential for a measured false negative. Obviously, DO increases associated with air sparging systems are a critical factor in the design of biosparging systems.

In summary, there are a number of parameters that have been measured in the field to determine the effectiveness of air sparging systems. 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. Additional research should be completed and additional experience should be gained in order to determine the effectiveness of air sparging systems more definitively. In any case, as indicated earlier, it may prove useful to collect system performance data using several different methodologies.

4.3 COMPARISON AND EVALUATION OF PILOT TEST RESULTS vs. CONCEPTUAL DESIGN

After conducting a pilot study, utilizing the aforementioned guidance, the next step in the process of evaluating the applicability of air sparging to a particular site is to compare the pilot testing results with the calculated values from Tier 2.

In Tier 2, the following operating parameters were estimated for your selected site: expected value(s) of flowrates, injection pressure(s), and area of impact. As the field practitioner, you need to compare the data obtained from the pilot study with the values and information projected in Tier 2 to re-evaluate the applicability of air sparging to your particular site. The first step in the re-evaluation process is to ensure that the measured parameters do not signal "red flags" or potential infeasibility of an air sparging system (i.e., extreme injection pressures, excessively high (or low) flowrates, etc.). The next step is to re-evaluate the applicability of air sparging to your site by proceeding through the conceptual design process in Tier 2. Having conducted a pilot study to evaluate the applicability of air sparging, you, as the practitioner, have checked the feasibility of and the conceptual design basis for air sparging at your site.

SECTION 5.0

OPTIMIZATION

The Conceptual Decision Tool has been developed both for determining applicability of air sparging to selected sites and for the optimization of existing air sparging systems. The latter feature may also be used to determine the optimal design of new systems. It is intended that the prospective user would commence application of the Tool for the purposes of determining technology applicability and system optimization at the same point (i.e., at the beginning) and in the same manner (i.e., following the same steps). There would be opportunities for the prospective user to "skip" certain steps, which had already been completed in implementing an air sparging system. The practitioner would use the results of conceptual geologic modelling, detailed system design and performance monitoring as inputs to the Tool, where appropriate. In any case, the user would confirm geologic model details, system design features and performance information as he/she followed the decision path through the Tool.

5.1 COMPLETION OF CONCEPTUAL GEOLOGIC MODEL

In the first step of application of the Tool for air sparging system optimization, the prospective user should confirm (or for pre-existing air sparging system review, develop) an applicable conceptual geologic model. As defined in Tier 1 of the Tool and related help screens, the model should provide a description of the geologic setting, including hydrogeological aspects, and of the nature and extent of contamination. For existing systems, any additional information, discovered as a result of full-scale air sparging system installation and operation, should be used to confirm that the original conceptual geologic model for the site is accurate or should be used to update the model, as appropriate. The confirmed or updated model should then be used to confirm (or identify) the selection of the most appropriate scenario. As appropriate, revised scenario selection may result in changes in decision-making with respect to the applicability of air sparging to the site. If the revised scenario selection suggests that air sparging would be considered inappropriate for the subject site, the attempt at optimization may result in a recommendation for system shut-down and removal.

5.2 COMPLETION OF CONCEPTUAL SYSTEM DESIGN

Having confirmed or revised the conceptual geologic model for your site, the next stage in the decision-making process towards the objective of optimization is to complete, confirm and/or revise the conceptual system design. Following the protocol described in Section 3 (for Tier 2), the user inputs known system parameters (e.g., actual injection pressure, measured during system operations). The user then compares the resulting "conceptual system design" with the actual design (i.e., number and placement of injection wells, operating air pressure and flow rate, capacity of compressor, etc.). Proposed improvements to the existing system design then are identified and, as appropriate (especially from a resource constraint perspective), detailed and implemented.

5.3 DEVELOPMENT OF OPTIMAL DESIGN

Development of the optimal design for existing sparging systems is an iterative process. The user, following the conceptual design process in Tier 2, first identifies the parameter(s) which will probably make the most significant improvement(s) in system operating performance. Once identified, the practitioner then varies the selected parameter (e.g., flow rate) while keeping all other operating conditions constant. The impact of the variation in operating parameter is then noted and compared with the original result. This process is repeated until the parameter in question is optimized (i.e., as determined by monitoring system results or, more specifically, the rate of contaminant removal). When the first parameter has been optimized, the entire procedure is repeated for subsequent parameters until the system is optimally efficient.

5.4 COMPARISON OF SYSTEM PERFORMANCE TO TOOL RESULTS

Following operation of a sparging system for an extended period of time (at least an order of magnitude greater than pilot-scale testing) the practitioner can compare actual system performance with performance predicted by the Tool. The comparison with Tool predictions should only be made following the optimization of the system described above. The result of this comparison will be an evaluation of the effectiveness of the Tool in providing a first-order estimate of sparging performance. This evaluation will be invaluable in refining the Tool for future user application and for developing more accurate predictions of sparging effectiveness.

Feedback on comparisons of actual system performance results versus Tool predictions should be provided to:

Ms. Andrea Hart
MSE, Inc.
Western Environmental Technology Office (WETO)
Industrial Park
Butte, Montana 59701

or to the Project Team:

Mr. Richard Volpi
Parsons Engineering Science, Inc.
19101 Villaview Road, Suite 301
Cleveland, Ohio 44119

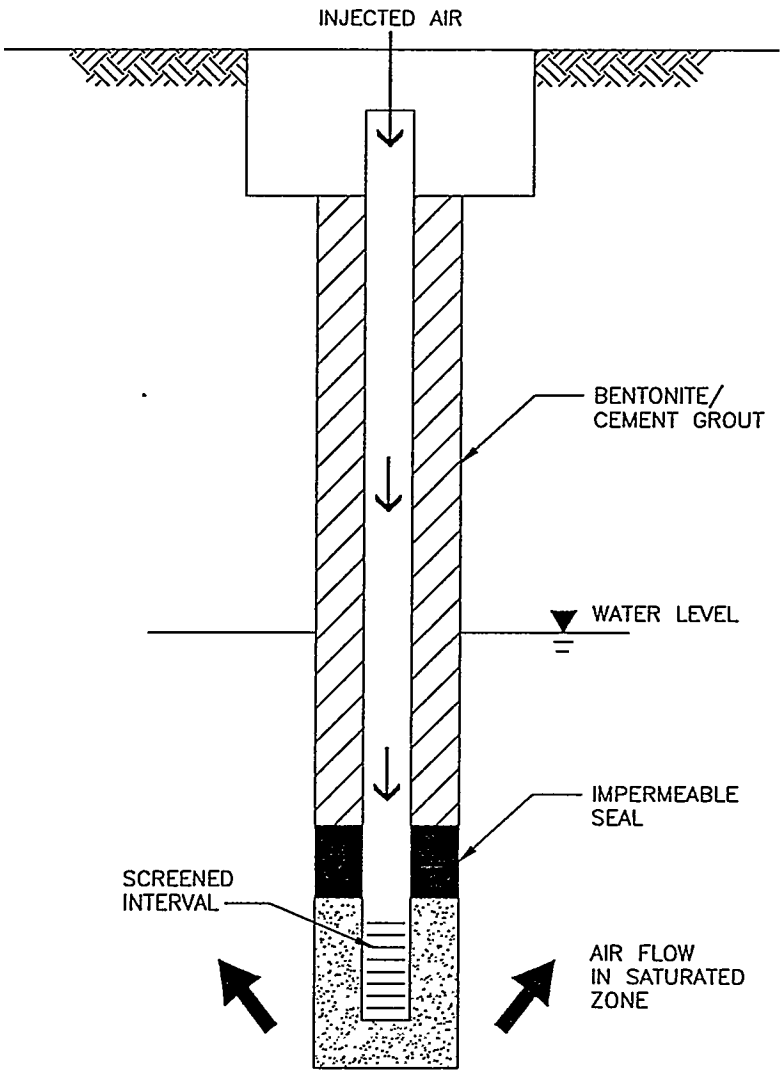
As part of the site-specific feedback regarding application of the Tool, please answer the following questions:

What predictions made by the Tool were most accurate?

What predictions were least accurate?

For predictions that were less accurate than expected or desired, based on experience at your site, what is the Tool's main weakness?

A copy of the site conceptual model developed for your site, the input parameters used in the Tool, and any actual sparging system performance data would be very useful to the Project Team. Your consideration in collecting and forwarding this information to MSE and the Project Team will be greatly appreciated.



CONCEPTUAL VIEW OF AIR SPARGING WELL

CONCEPTUAL REPRESENTATION

FIGURE 2

POTENTIALLY APPROPRIATE OPPORTUNITIES FOR DECISION TOOL USE DURING THE SITE REMEDIATION PROCESS

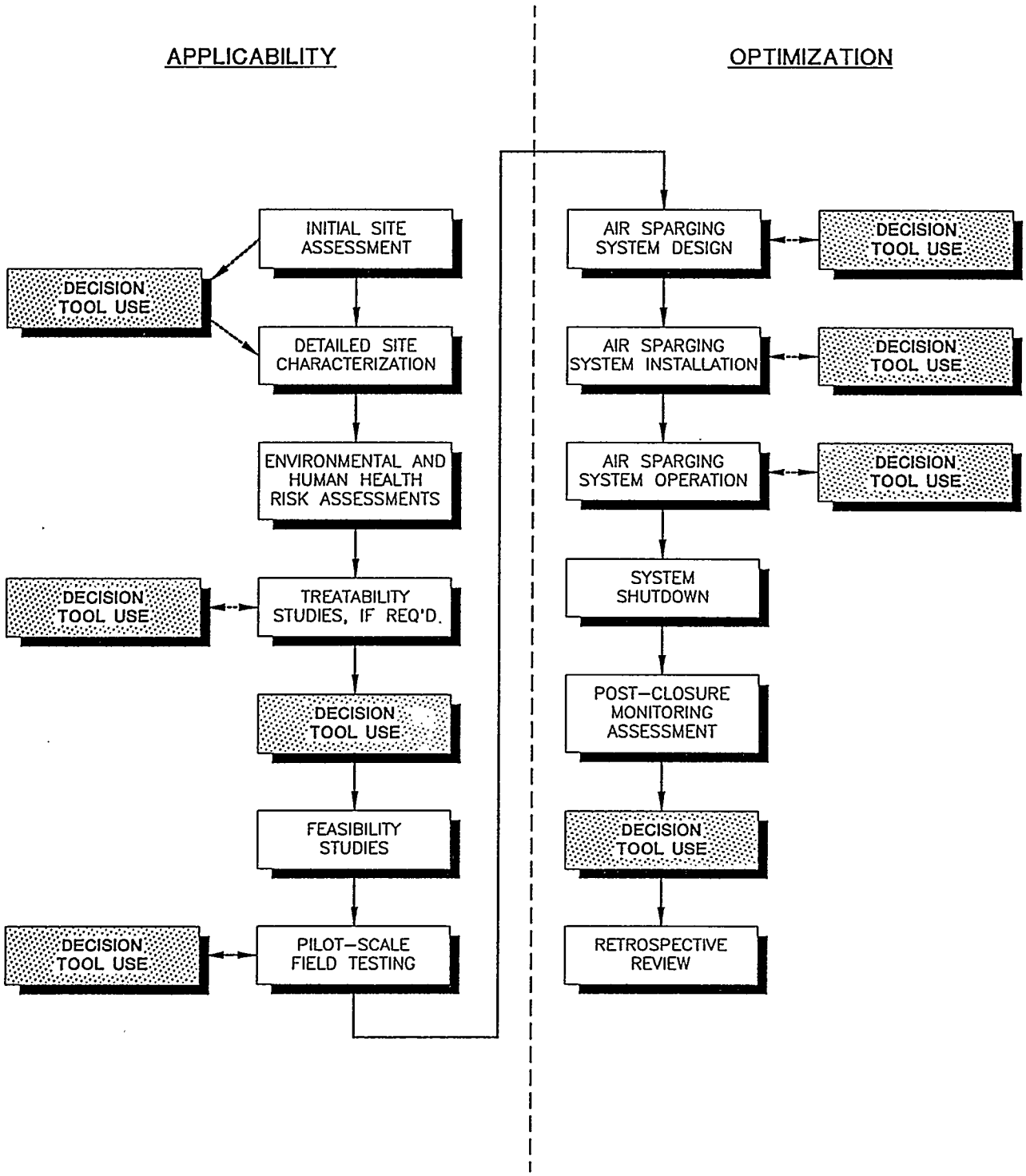


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FIGURE 3
Evaluation of Removal Rate for Volatilization (Well-Mixed Case)

Removal Rate for Volatilization Calculation

Removal $Rate_v$ (mg/day) = C_{est} x Flowrate (ft^3/min)

Where:

Removal $Rate_v$ = Removal Rate for Volatilization (mg/day)

$C_{est} = C_{iw} H_i$

Flowrate (ft^3/min) determined from Figure 10

Where:

C_{est} = Estimate of contaminant vapor concentration (mg/L)

C_{iw} = dissolved concentration of compound i (mg/L)

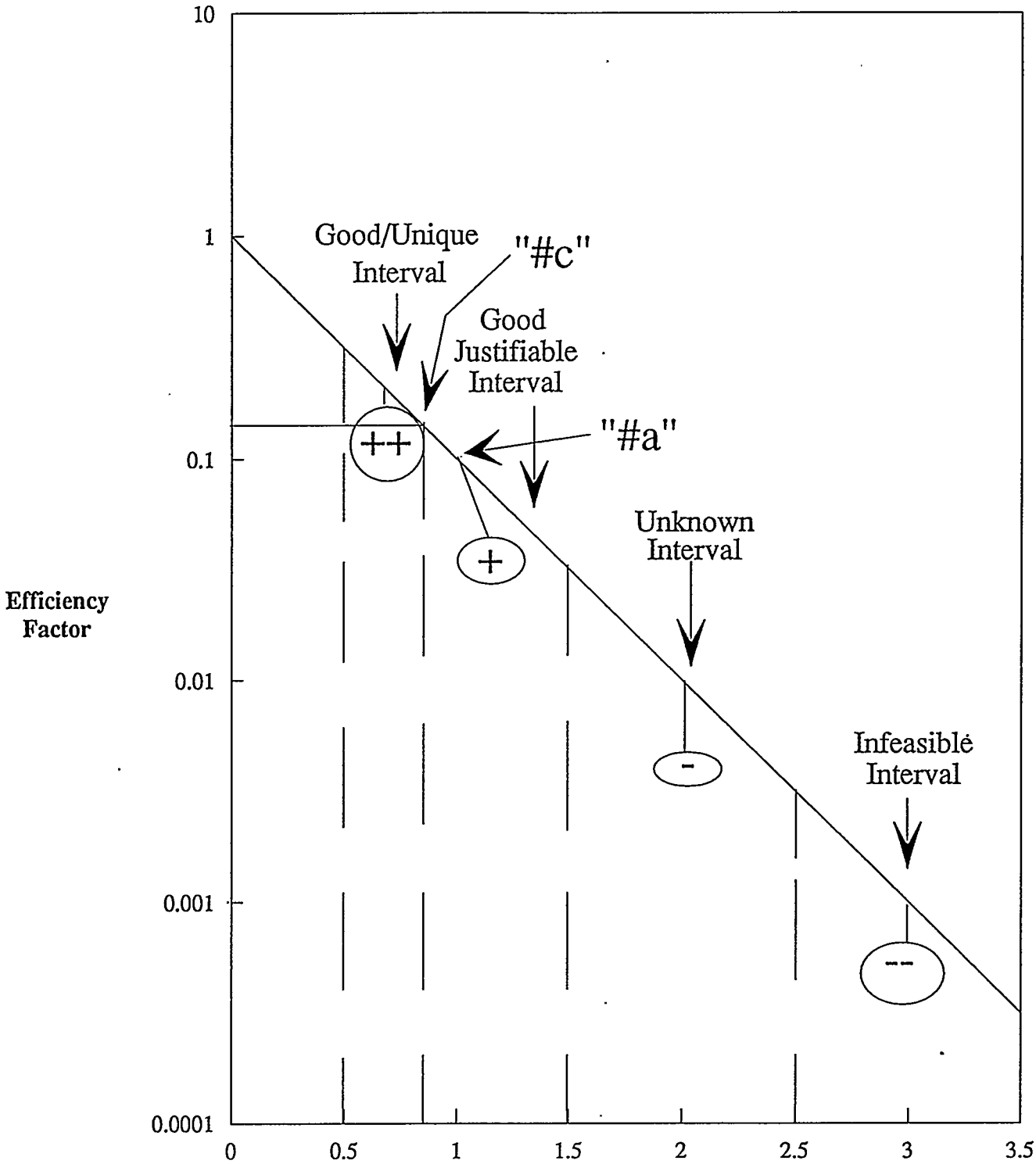
H_i = Henry's Law constant for compound i (unitless) (from Table 6)

Example:

See Appendix C.

FIGURE 4

Efficiency Factor Based on Soil Stratigraphy and Rating From Tier 1

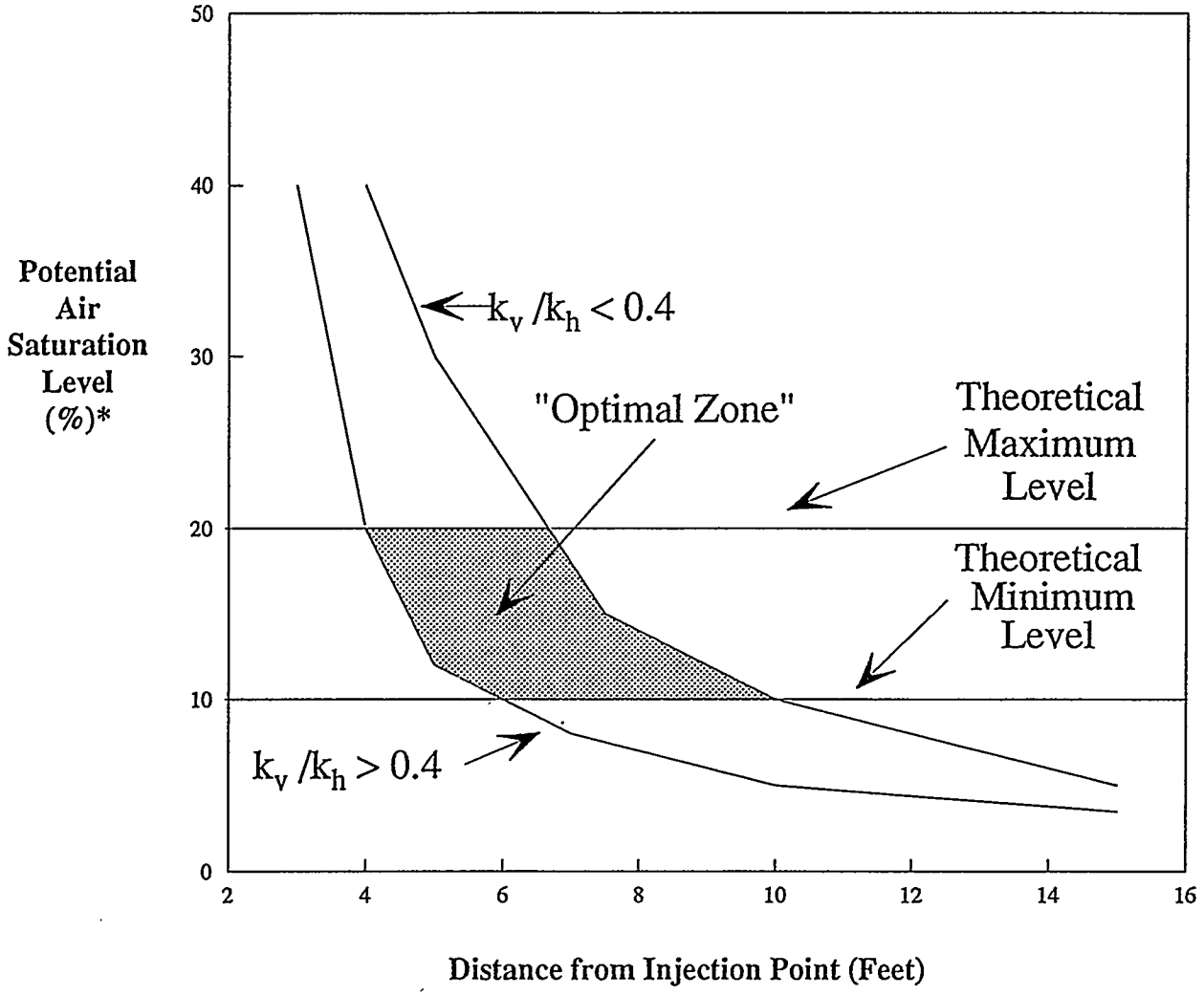


++ = determined to be a good physical or technical possiblity and a good/unique target for sparging.
+ = determined to be a good physical or technical possiblity and a justifiable (but not unique) target for sparging.
- = Determined to be an unknown physical or technical possibility
- = Determined to be not physically or technically possible.

Note: Based on contaminant type and distribution, well spacing, and soil stratrigraphy.

FIGURE 5

Radial Efficiency of Air Sparging Well



* indicates percentage of available pores which are potentially saturated.
k_v/k_v = Vertical Hydraulic Conductivity/Horizontal Hydraulic Conductivity.
References: (Lundegard, 1994; Acomb, et.al, 1995)

FIGURE 6
Evaluation of Removal Rate for Volatilization (Diffusion-Limited Case)

Removal Rate for Volatilization Calculation

To derive the graph:

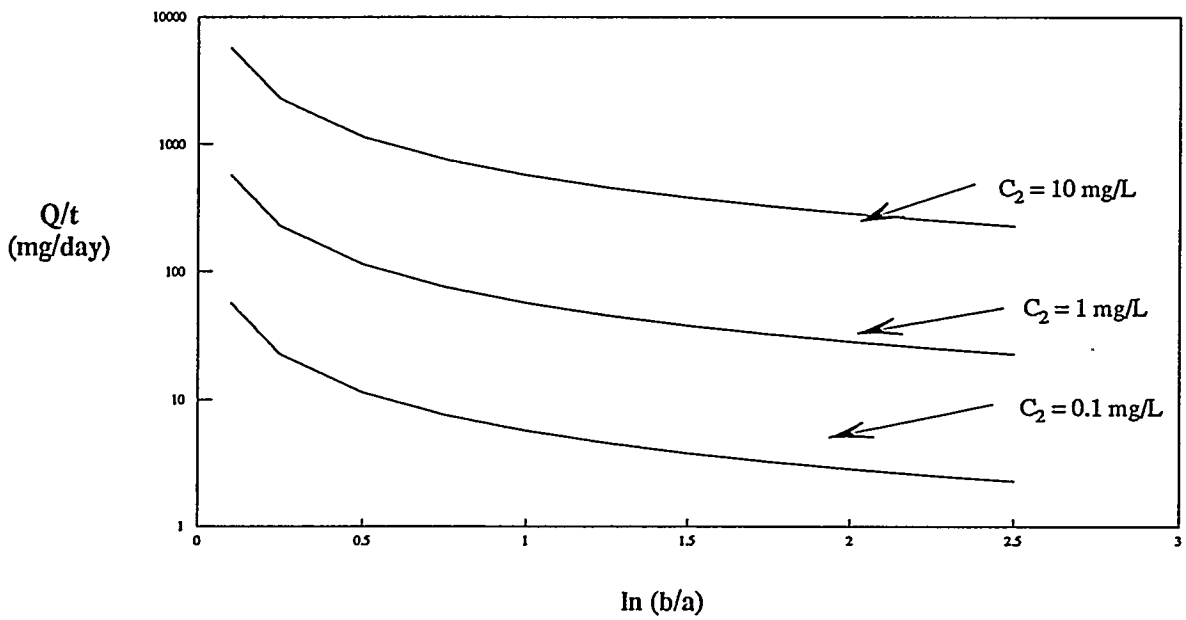
$$(Q_t / t) = \text{mass loss per time} = \frac{(2 \times 3.1415 \times 86{,}400 \text{ sec} \times D \times L \times (C_2 - C_1))}{\ln (b/a)}$$

Where:

(Q_t / t) = mass loss per time (mg/day) = Removal Rate
D = Effective diffusion coefficient = $0.00001 * 0.33^{1.33}$ (cm^2/sec)
L = Length of channel = number of channels (between 10 and 100)* and depth below water table (cm)
b = thickness of diffusion zone (measured from edge of channel)(cm)
a = channel radius (cm)
C_2 = average dissolved concentration (mg/L)

Assume $C_2 >> C_1$, where C_2 equals the average dissolved concentration in bulk water/channel interface and C_1 is concentration at the air/water interface:

$C_1 = 0$

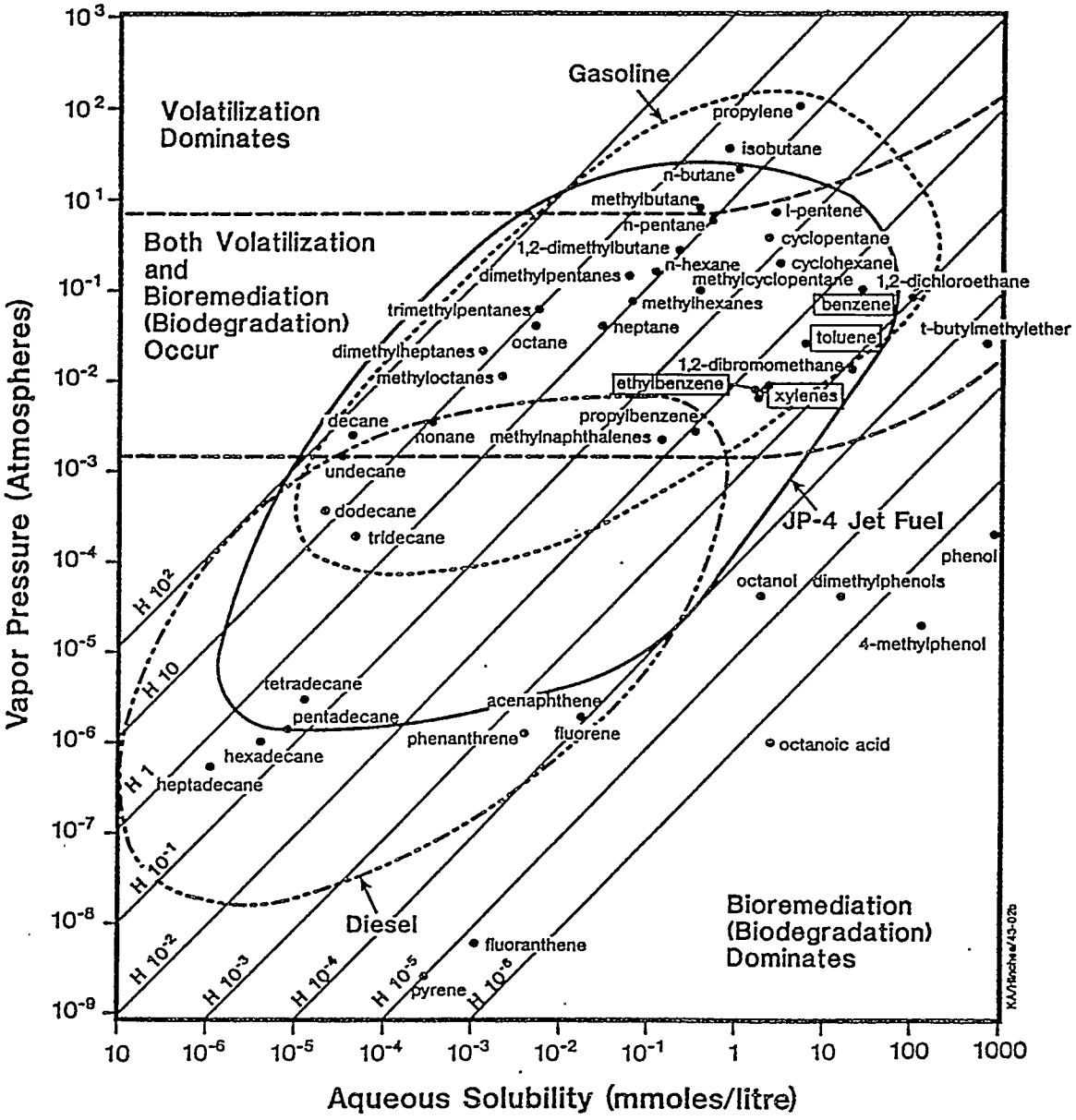


EXAMPLE:
See Appendix C.

REFERENCE:
(Johnson, R. L. etal, 1994, Johnson, P. C., personal communication, 6 September 1995)

FIGURE 7

RELATIONSHIP BETWEEN CONTAMINANT PHYSIOCHEMICAL PROPERTIES AND POTENTIAL FOR VOLATILIZATION AND/OR BIOREMEDIATION



H = Henry's Law Coefficient (atm • m³/mole)

[1] Note: This figure should only be utilized for conceptual purposes. In practice, air sparging feasibility is very much dependent on site-specific conditions.

Adapted from "Bioventing" by R.E. Hinchee, R.N. Miller, and C. Vogel, presented at and included in Proceeding of Air Force Center of Environmental Excellence (AFCEE), Technology Transfer Symposium, San Antonio, May 1991.

FIGURE 8
EVALUATION OF REMOVAL RATES FOR BIODEGRADATION

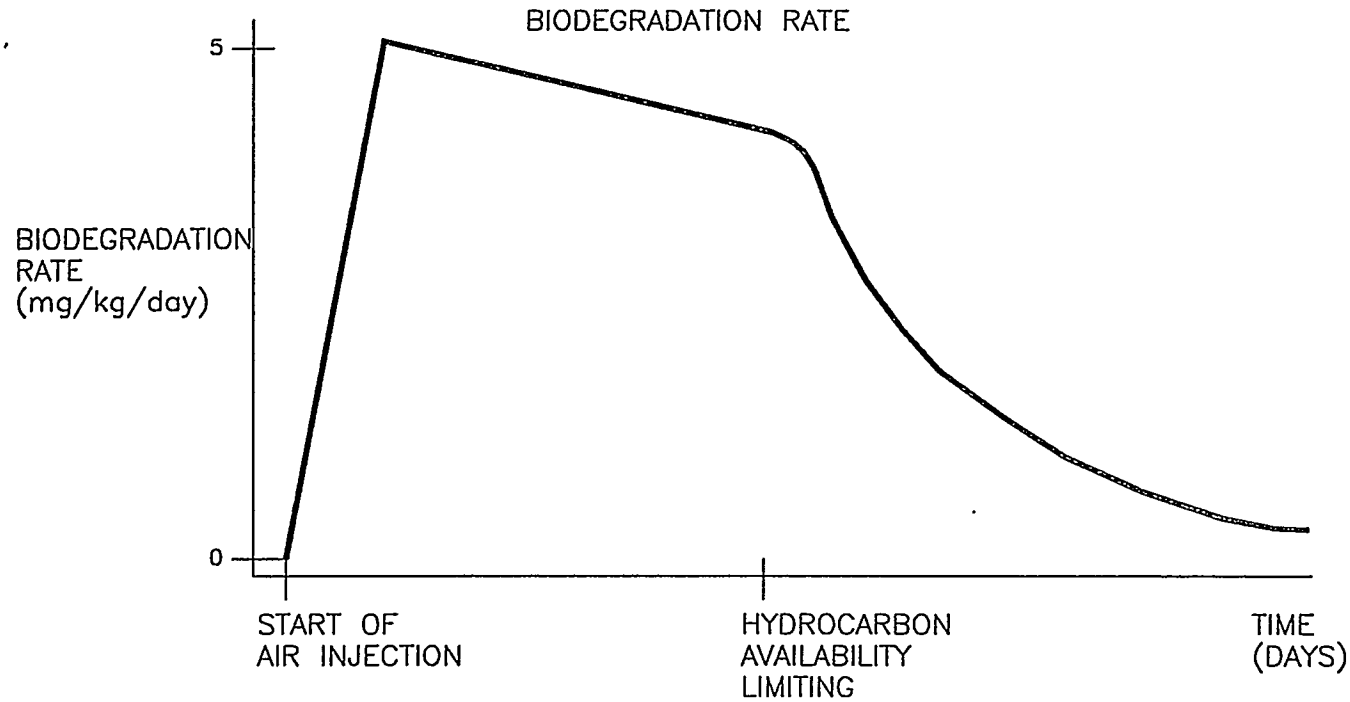


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FIGURE 8 CONTINUED

EVALUATION OF REMOVAL RATES FOR BIODEGRADATION

During NAPL removal, the biodegration rate is almost constant:

$C_n = C_o - 5t$ (Assume Constant Rate = 5mg/kg/day)

Where:
C_n = residual NAPL concentration (mg/kg of aquifer material)
C_o = initial contaminant concentration (mg/kg of aquifer material)
t = time (days)

Subsequent to NAPL removal (i.e., for plume remediation), the biodegration rate varies exponentially:

$C_p = C_o E^{-0.01t}$ (Rate Range = 0.3 to 2.4 %/day; Assume Rate = 1%/day)

Where:
C_p = residual plume concentration (mg/L)
C_o = initial plume concentration (mg/L)
t = time (days)
E = 2.71828 (unitless)

In diffusion-limited scenarios, the biodegradation rate is:

$C_d = C_o - At$ (Rate Range = 0.02 to 0.0077 mg/kg/day)

Where:
C_d = residual contaminant concentration in diffusion-limited cases (mg/kg of aquifer material)
C_o = initial contaminant concentration (mg/kg of aquifer material)
t = time (days)
A = rate coefficient equals 0.0077 mg/kg/day or 0.02 mg/kg/day oxygen gradient; assume 0.02 mg/kg/day for very steep gradients (e.g., 10 mg/L over 1 cm) and 0.0077 mg/kg/day for reduced gradients (e.g., 10 mg/L over 10 cm).

EXAMPLE:
See Appendix C.

REFERENCES:
(Johnson, R. L., 1993, Hinchee, R. E., 1994, Acomb, L. J., etal 1995)

FIGURE 9

Evaluation of Over Pressure, Minimum Injection Pressure and Operating Pressure

Over Pressure Calculation

Step 1: Calculation of Weight of Soil

Weight of Soil (lbs/ft^2) = Depth to Top of Screen (ft) x Soil Bulk Density(lbs/ft^3)

Where: Soil Bulk Density (lbs/ft^3) is available from Table 8

Step 2: Calculation of Weight of Water

Weight of Water (lbs/ft^2) = Water Column Depth (ft) x 62.4 lb/ft^3 x effective porosity

Where: Water Column Depth (ft) = Depth to Top of Screen (ft) - Depth to Water Table (ft)
Note: Effective porosity typically varies from from <1% for tight/fractured matrices to about 30% for sand and gravel matrices

Step 3: Calculation of Total Weight

Total Weight (lbs/ft^2) = Weight of Soil (lbs/ft^2) + Weight of Water (lbs/ft^2)

Step 4: Conversion to Over Pressure

$$\text{Pressure (psig)} = \frac{\text{Total Weight } (lbs/ft^2)}{144\ in^2/ft^2}$$

Step 5: Add Safety Factor

Literature (Marley, M.C.; Btuell, C.J., Oct 94) suggests that a safety factor of 0.6 to 0.8 be applied (i.e., to minimize the chance of over pressurization). For this tool use 0.8.
Over Pressure = 0.8 Pressure (psig)

Evaluation of Minimum Injection Pressure

Step 6: Calculate Minumum Inection Pressure

Pressure (psig) = Weight of Water Column (lb/ft^2)/ (144 in^2/ft^2)

Evaluation of Operating Pressure

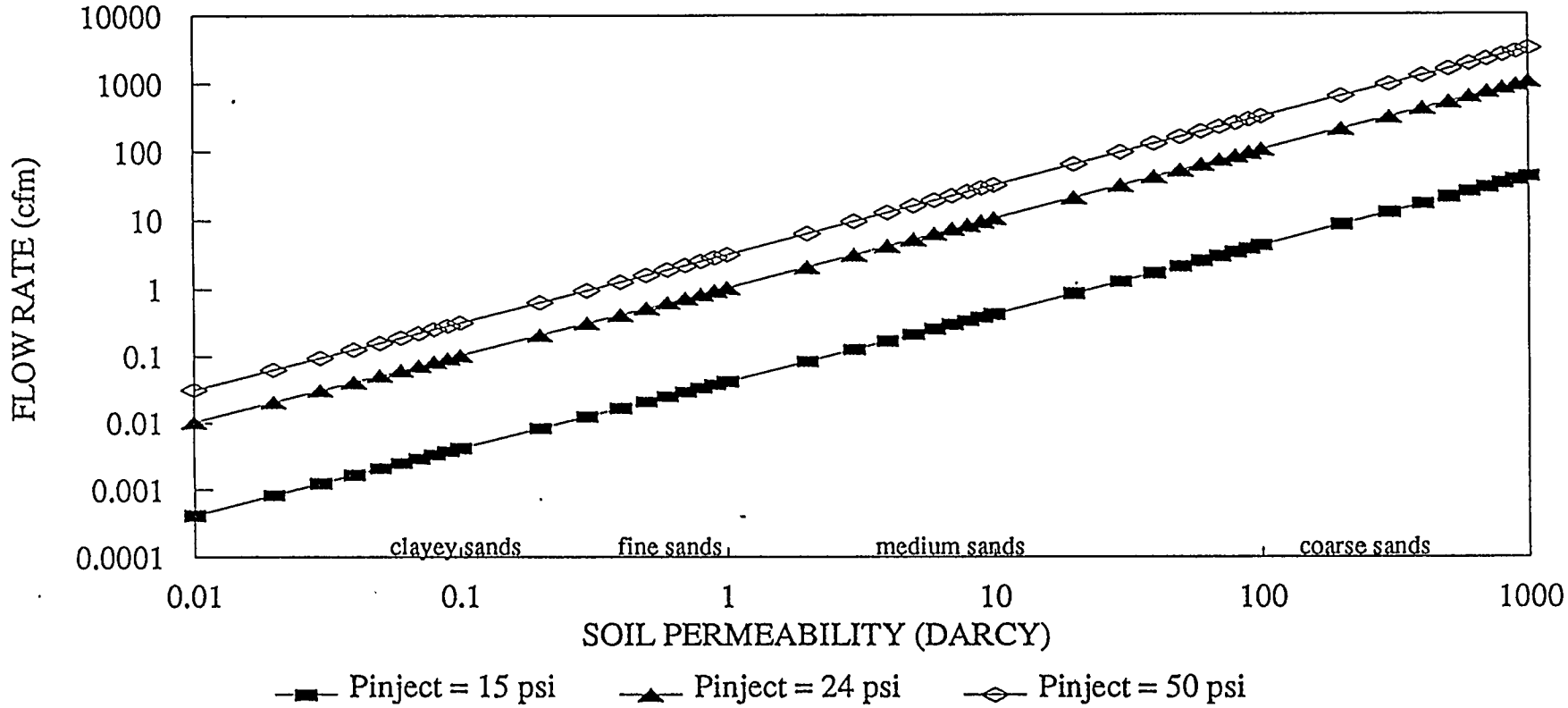
Step 7: Determine Operating Pressure

Based on calculations above, the operating pressure can vary between the minimum injection pressure (e.g., at no flow) and the over pressure depending on flow rate and permeability. Refer to Step #18 and and Figure 10 to determine these values.

EXAMPLE:
See Appendix C.

REFERENCE:
(Marley, M.C.; Bruell, C.J., October 1994)

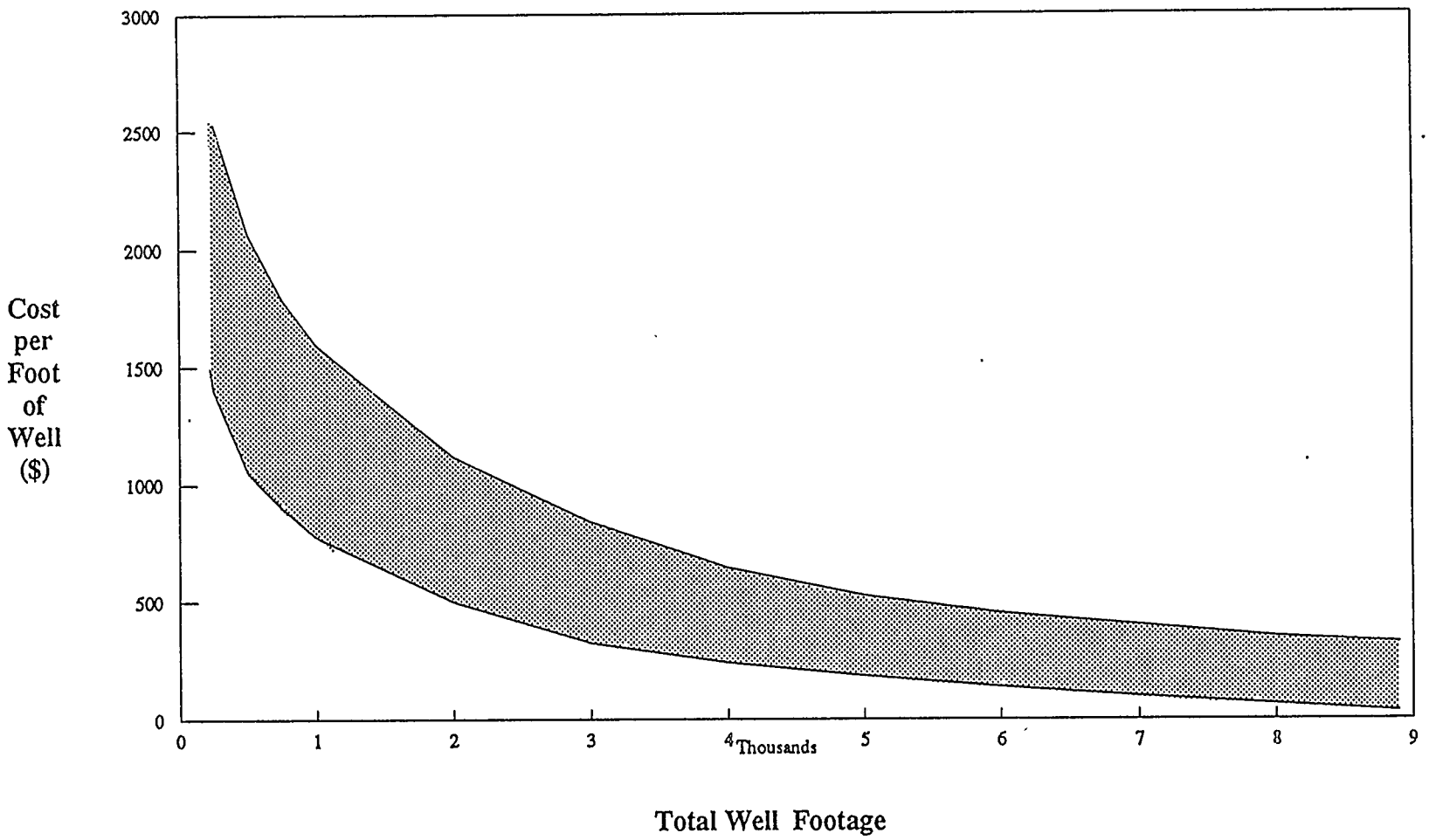
FIGURE 10
FLOW RATE NOMOGRAPH



Where:
Pinject = pressure at the injection depth
L = Distance of injection point below water table = 10 feet. Different L values may be approximated by scaling.

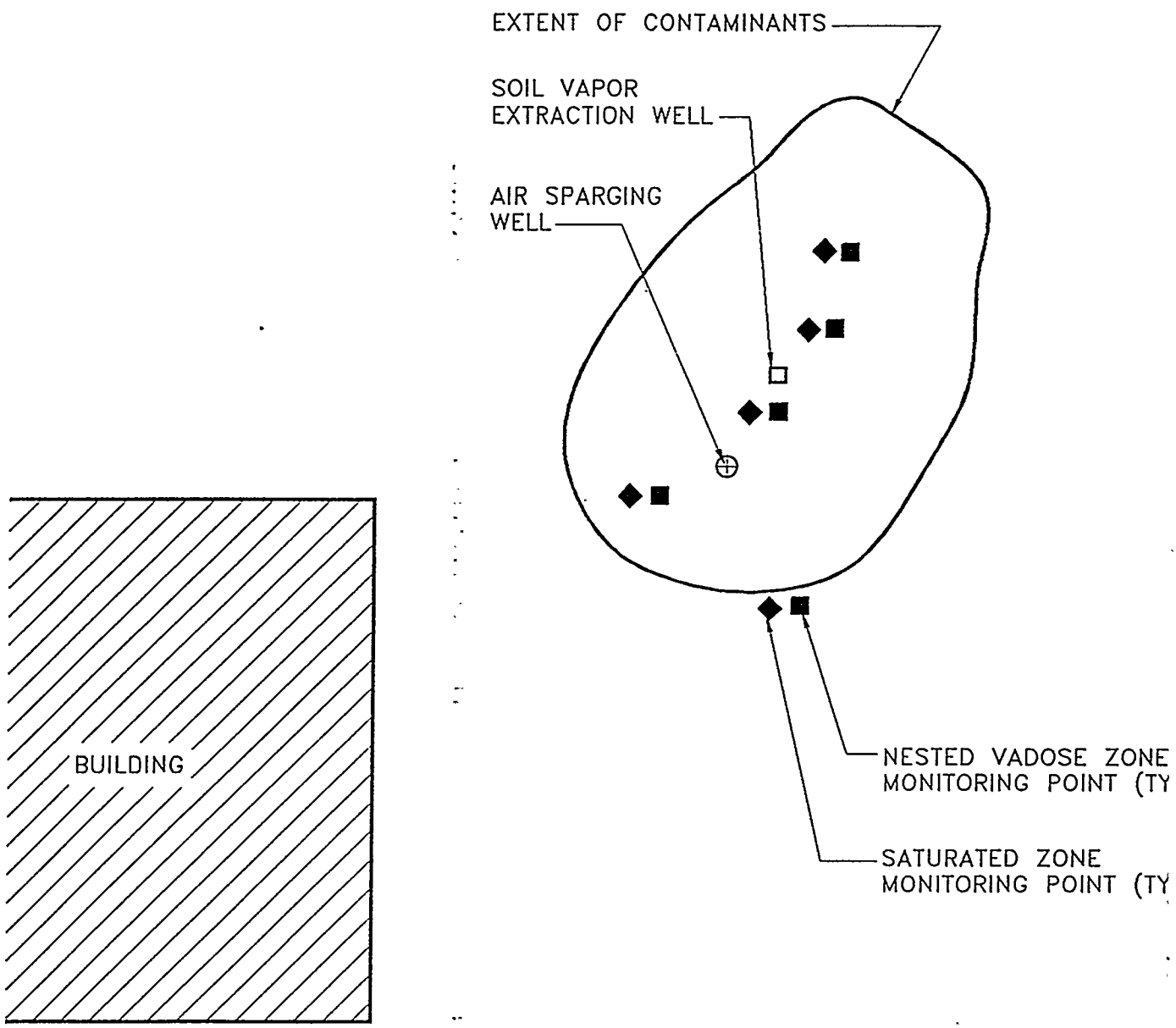
Adapted from (Johnson, P.C., et al., 1990b) and personal communication with P.C. Johnson, September 1995.

FIGURE 11
Cost Guidance - System Installation



Note: Cost curve based on typical large-scale government projects. Smaller industrial projects may be significantly discounted. Based on General Accounting Office study, a factor of about 3.0 may be used.

CONCEPTUAL
PILOT STU



CONCEPTUAL SITE PLAN

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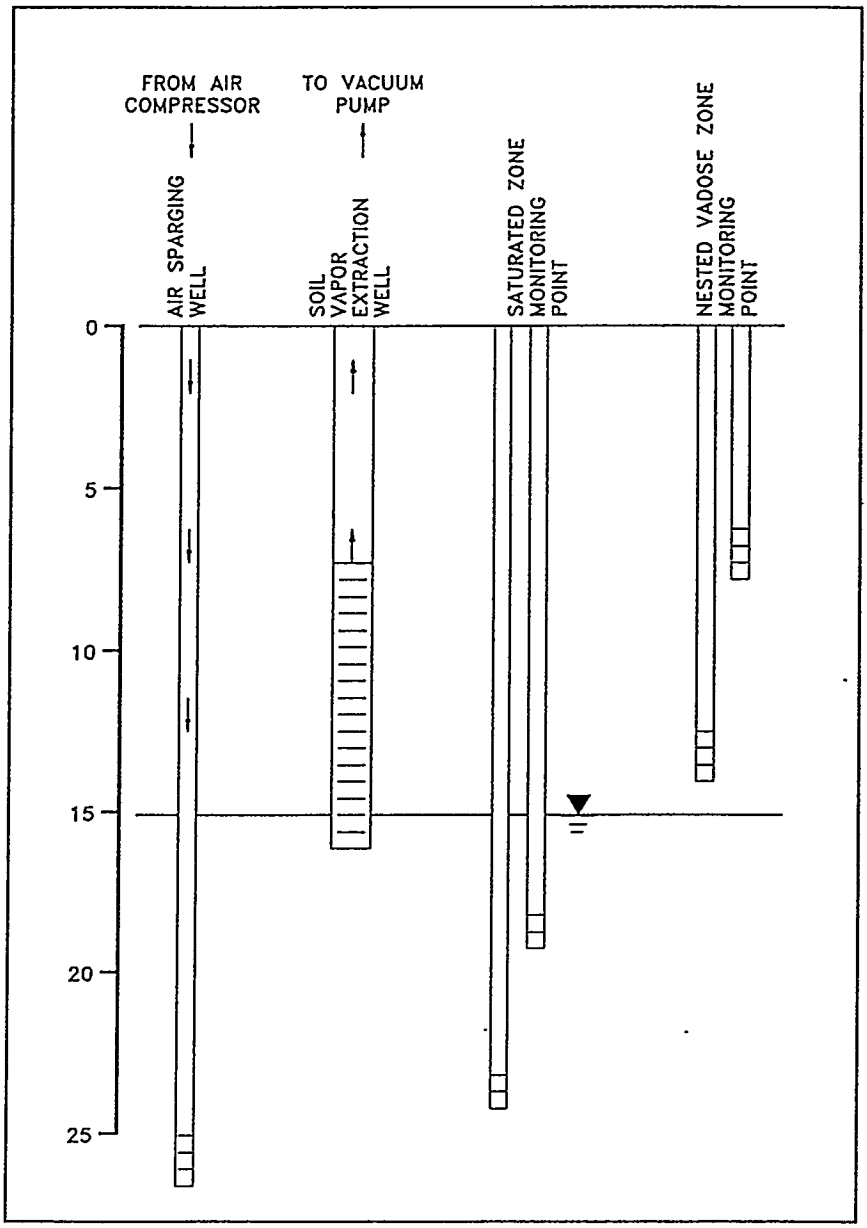
AIR SPARGING
IDY LAYOUT



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CONCEPTUAL CROSS SECTION

TABLE 1
AIR SPARGING OPTIMIZATION DECISION TOOL
SUMMARY OF DECISION TOOL SCENARIOS

Scenario Number	Description of Scenarios	Objectives		
		Source Remediation	Plume Remediation	Containment
1	Chlorinated Hydrocarbon - Layered Formation (Decreasing Permeability with Depth)	-	+	+
2	Chlorinated Hydrocarbon - Layered Formation (Increasing Permeability with Depth)	--	-	-
3	Chlorinated Hydrocarbon - Layered Formation (Alternating Permeability with Depth)	--	-	-
4	Petroleum Hydrocarbon - Layered Formation (Decreasing Permeability with Depth)	++	+	+
5	Petroleum Hydrocarbon - Layered Formation (Increasing Permeability with Depth)	-	-	-
6	Petroleum Hydrocarbon - Layered Formation (Alternating Permeability with Depth)	-	-	-
7	Chlorinated Hydrocarbon - Fractured/Tight Formation	--	--	--
8	Petroleum Hydrocarbon - Fractured/Tight Formation	--	--	--
9	Chlorinated Hydrocarbon - Homogeneous Formation	-	+	+
10	Petroleum Hydrocarbon - Homogeneous Formation	++	+	+
11	Other	?	?	?

Legend:

++ = Determined to be a good physical or technical possibility and a good/unique target for sparging.
+ = Determined to be a good physical or technical possibility and a justifiable (but not unique) target for sparging.
- = Determined to be an unknown physical or technical possibility.
-- = Determined to be not physically or technically possible.

TABLE 2

AIR SPARGING OPTIMIZATION DECISION TOOL

ESTIMATED INSTALLATION COSTS – WORKSHEET

	Unit Cost	Units
Well Installation		
Geologist	_____/day	_____days
Travel Costs		
Air Travel	_____/unit	_____units
Mileage	_____/mile	_____miles
Rental Vehicle	_____/day	_____days
Per Diem	_____/day	_____days
Miscellaneous Costs (computer, telephone, fax, etc.)	_____/unit	_____units
Subcontractor Services –Drilling Costs(1)(2)		
Mobilization and demobilization	_____/unit	_____units
Per Diem	_____/day	_____days
Drilling Rates:		
1.) Install ___" ID PVC well with continuous wrap screen, no spilt–spoon sampling		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft
AND / OR		
Install ___" ID PVC well with 10–slot screen, no split–spoon sampling		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft
2.) Install ___" ID PVC well with continuous wrap screen, continuous split–spoon sampling included		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft
AND / OR		
Install ___" ID PVC well 10–slot screen, continuous split–spoon sampling included		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft

TABLE 2 (continued)

AIR SPARGING OPTIMIZATION DECISION TOOL

ESTIMATED INSTALLATION COSTS – WORKSHEET

	Unit Cost	Units
Monitoring Point Installation		
Geologist	_____/day	_____days
Travel Costs		
Air Travel	_____/unit	_____units
Mileage	_____/mile	_____miles
Rental Vehicle	_____/day	_____days
Per Diem	_____/day	_____days
Miscellaneous Costs (computer, telephone, fax, etc.)	_____/unit	_____units
Subcontractor Services –Drilling Costs(1)(2)		
Mobilization and demobilization	_____/unit	_____unit
Per Diem	_____/day	_____/days
Drilling Rates:		
1.) Install ___" ID PVC well with continuous wrap screen, no split–spoon sampling		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft
AND / OR		
Install ___" ID PVC well with 10–slot screen, no split–spoon sampling		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft
2.) Install ___" ID PVC well with continuous wrap screen, continuous spilt–spoon sampling included		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft
AND / OR		
Install ___" ID PVC well with 10–slot screen; continuous split–spoon sampling included		
0 to 15 ft with ___ft of screen	_____/ft	_____ft
16 to 30 ft with ___ft of screen	_____/ft	_____ft
31 to 45 ft with ___ft of screen	_____/ft	_____ft
46 to 60 ft with ___ft of screen	_____/ft	_____ft
61 to 75 ft with ___ft of screen	_____/ft	_____ft

TABLE 2 (continued)

AIR SPARGING OPTIMIZATION DECISION TOOL

ESTIMATED INSTALLATION COSTS – WORKSHEET

	Unit Cost	Units
System Installation		
Engineer	_____/day	_____days
Technician	_____/day	_____days
Construction Oversight	_____/day	_____days
Travel Costs		
Air Travel	_____/unit	_____units
Mileage	_____/mile	_____miles
Rental Vehicle	_____/day	_____days
Per Diem	_____/day	_____days
Miscellaneous Costs (computer, telephone, fax, etc.)	_____/unit	_____units
Contractor Labor, Equipment and Materials:		
Labor: Superintendent / Foreman	_____/day	_____days
Operator(s)	_____/day	_____days
Pipefitter(s) / Plumber(s)	_____/day	_____days
Electrician(s)	_____/day	_____days
Laborer(s)	_____/day	_____days
Per Diem	_____/day	_____days
Equip.: Mobilization and demobilization	_____/unit	_____units
Excavator	_____/day	_____days
Multi–purpose Uniloader	_____/day	_____days
Dump Truck	_____/day	_____days
Concrete saw rental	_____/day	_____days
Plate compactor	_____/day	_____days
Storage/Tool Trailer	_____/day	_____days
Project Field Trailer	_____/day	_____days
Materials:		
Pipe / Hose:		
Schedule 40 PVC – ____" Diameter	_____/ft	_____ft
Schedule 40 PVC – ____" Diameter	_____/ft	_____ft
Schedule 40 PVC – ____" Diameter	_____/ft	_____ft
PVC Fittings(elbows, tees, unions,etc.)(3)	_____/unit	_____/units
Schedule 40 Galv. Steel – ____" Diameter	_____/ft	_____ft
Schedule 40 Galv. Steel – ____" Diameter	_____/ft	_____ft
Galv. Steel Fittings(elbows, tees, unions,etc.)(3)	_____/unit	_____/units
High Pressure Air Hose – ____" Diameter	_____/ft	_____ft
High Pressure Air Hose – ____" Diameter	_____/ft	_____ft
High Pressure Fittings(quick disconnects,etc.)(3)	_____/unit	_____/units
Other Fittings:		
Ball Valve, Sch. 80 PVC – ____" Diameter	_____/fitting	_____fittings
Ball Valve, Sch. 80 PVC – ____" Diameter	_____/fitting	_____fittings
Ball Valve, Copper – ____" Diameter	_____/fitting	_____fittings
Ball Valve, Copper – ____" Diameter	_____/fitting	_____fittings
Gate Valve, Steel – ____" Diameter	_____/fitting	_____fittings
Gate Valve, Steel – ____" Diameter	_____/fitting	_____fittings
Check Valve, Copper – ____" Diameter	_____/fitting	_____fittings
Solenoid Valve – ____" Diameter	_____/fitting	_____fittings

TABLE 2 (continued)

AIR SPARGING OPTIMIZATION DECISION TOOL

ESTIMATED INSTALLATION COSTS – WORKSHEET

	Unit Cost	Units
Miscellaneous:		
Trench Backfill Material	_____/yd^3	_____yd^3
Pavement Subbase Material	_____/yd^3	_____yd^3
Concrete Pav't Replac., 8" thk. with wire mesh	_____/yd^2	_____yd^2
Asphalt Pave't Replac., 4" base with 2" top	_____/yd^2	_____yd^2
Equipment Building	_____/unit	_____units
Electrical Service	_____/unit	_____units
System Controls	_____/unit	_____units
Air Sparging Equipment:		
Compressor / Vacuum Pump	_____/unit	_____units
Regulator	_____/unit	_____units
Pressure gauge	_____/unit	_____units
Pressure relief valve	_____/unit	_____units
Soil Vapor Extraction Equipment:		
Blower / Vacuum Pump	_____/unit	_____units
Vacuum relief valve	_____/unit	_____units
Moisture removal tank with level controls	_____/unit	_____units
Transfer pump to evacuate tank	_____/unit	_____units
Lower explosive limit device	_____/unit	_____units
Particulate filter	_____/unit	_____units
Off–gas Treatment	_____/unit	_____units

(1) Hollow Stem Auger Technique in Sandy Soils

(2) Daily Production Rate Estimates:

1" thru 4" diameter wells:	100 feet / day, no split–spoon sampling
	60 feet / day, continuous split–spoon sampling
6" and higher diameter wells:	60 feet / day, no split–spoon sampling
	50 feet / day, continuous split–spoon sampling

(3) PVC Fittings: Cost / Unit = 30% of cost of 1000 feet of pipe
Galv. Steel Fittings: Cost / Unit = 20% of cost of 1000 feet of pipe
High Pressure Fittings: Cost / Unit = 20% of cost of 1000 feet of pipe

<u>Assumptions / Clarifications:</u>

- Well installation should be supervised by a qualified geologist.
- System installation should be supervised by a qualified representative/firm.
- Other Installation and Non–installation Costs (not included on table)
  - Final design and/or preparation of Bid Documents (plans and specifications).
  - Bonds, Permits, Licenses, etc.
  - Barricades, Shoring and Dewatering of Excavations.
  - Appropriate disposal of impacted or non–impacted soil and water generated by installation activities., excavated from trenching or drill cuttings.
  - Reporting Requirements
  - Project Management
  - System Startup and Ongoing Operation, Maintenance and Monitoring.
  - Appropriate disposal of Soil Vapor Extraction, Off–gas Treatment Media, if used.

TABLE 3
AIR SPARGING OPTIMIZATION DECISION TOOL
PILOT TEST SPARGING SUMMARY

What You Expect to Learn	Activities	Required Equipment	Duration
Feasibility of injecting air into subsurface	Inject air, pressure monitoring, and observations of impact.	1 injection well and 1 monitoring well if available.	1-2 days
First determination of air sparging performance	Monitor increased recovery in a SVE system (compared with pre-established baseline).	Turn on soil vapor extraction or assume previous soil vapor extraction operational performance history.	2-3 days
Qualitative determination of air sparging performace	Monitor for changes in vadose zone concentrations (CO_2,O_2, VOCs, etc.).	Add vadose zone monitoring points.	1-2 days
Better understanding of horizontal and vertical distribution of air flow	Monitor for changes in DO in the saturated zone and for changes in vadose concentrations (CO_2,O_2, VOCs, etc.).	1 injection well, 1 monitoring well, and 2 multi-depth piezometers.	1-2 days
Changes in dissolved oxygen level distribution and potential for biodegradation	Longer term monitoring for changes in vadose zone and saturated zone concentrations.	1 injection well, multiple monitoring wells, and 2 multi-depth piezometers	3-5 days
Three dimensional conceptual model of air flow and saturation	Monitor tracers and percentage of sparge air (tracer) recovered with soil vapor extraction. Measure appearance of tracer in vadose zone. Determine air flow patterns from tracer test.	1 injection well, multiple monitoring wells, 2 multi-depth piezometers, and add tracers (He, SF_6)	1-5 days

TABLE 4
AIR SPARGING OPTIMIZATION DECISION TOOL
SUMMARY OF PILOT TESTING "RED FLAG" ISSUES

"Red Flag"	Concern
Observation of adverse impacts caused by air injection (e.g., uncontrolled migration of vapors)	May indicate short-circuiting, explosion potential
Poor air distributions	May indicate highly stratified or unidirectional air flow
Possible presence of very thin layers in homogeneous setting	May cause air pocket to form (lower permeability) or lateral movement (higher permeability)
Drying of discrete monitoring points located in the saturated zone	May indicate the presence of an air pocket
Excessive injection pressures	Combined hydrostatic head and soil overburden pressure may be too great
Significant increase in dissolved oxygen or decrease in hydrocarbon concentrations	May indicate localized impact or removal of small residual concentrations in pores near air channels
Excessive flow rate	May indicate possible short-circuit or other conduit present

TABLE 5
AIR SPARGING OPTIMIZATION DECISION TOOL
SUMMARY OF CONCEPTUAL GEOLOGIC MODEL "RED FLAG" ISSUES

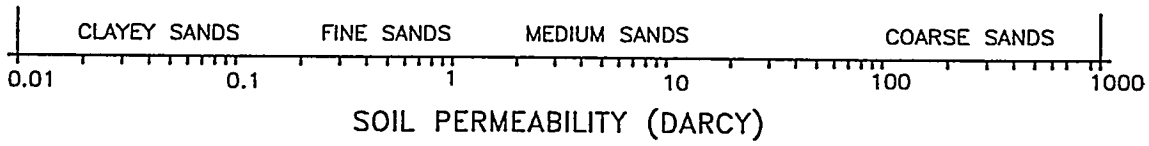
"Red Flag"	Concern
Observation of adverse impacts caused by air injection (e.g., uncontrolled migration of vapors)	May indicate short-circuiting, explosion potential
Possible breaks in confining layers	May cause contaimination migration (esp. with DNAPL or higher concentrations of chlorinated hydrocarbon plume
Possible presence of very thin layers in homogeneous setting	May cause air pocket to form (lower permeability) or lateral movement (higher permeability)
Presence of and proximity of natural fractures in clay or bedrock	May cause uncontrolled contaminant migration and/or uncontrolled remediation

TABLE 6
AIR SPARGING OPTIMIZATION DECISION TOOL

HENRY'S CONSTANTS

Chemical	Henry's Constant (atm x m^3/mole)	Henry's Constant (unitless)
Benzene	0.00543	0.221
Carbon Tetrachloride	0.02	0.813
Chlorobenzene	0.00346	0.141
Chloroethane	0.011	0.447
Chloroform	0.00375	0.152
Cis-1,2-dichloroethene	0.0075	0.305
1,1-Dichloroethane	0.0057	0.232
1,2-Dichloroethane	0.0011	0.0447
1,1-Dichloroethene	0.154	6.26
1,2-Dichloropropane	0.0036	0.146
Ethylbenzene	0.0079	0.321
Methylene Chloride	0.00257	0.104
Styrene	0.00228	0.0927
1,1,2,2-Tetrachloroethane	0.0005	0.0203
Tetrachloroethene	0.0227	0.923
Toluene	0.00661	0.269
Trans-1,2-dichloroethene	0.0066	0.268
1,1,1-Trichloroethane	0.00276	0.112
1,1,2-Trichloroethane	0.00117	0.0476
Trichloroethene	0.00892	0.363
Vinyl Chloride	0.695	2.83
Xylene	0.0054	0.22

TABLE 7
AIR SPARGING OPTIMIZATION DECISION TOOL SOIL PERMEABILITY



REFERENCE: (JOHNSON, P.C., ETAL; 1990b)

TABLE 8
AIR SPARGING OPTIMIZATION DECISION TOOL

SOIL BULK DENSITY

Material	pounds/feet^3
Sand Ottawa (dry)	92 - 110
Sand Ottawa (wet)	93 - 131
Sand, fine to medium (dry)	83 - 118
Sand, fine to medium (wet)	84 - 136
Sand and gravel (dry)	89 - 146
Sand and gravel (wet)	90 - 155
Silt (dry)	80 - 118
Silt (wet)	81 - 136
Silty Sand (dry)	87 - 127
Silty Sand (wet)	88 -142
Clay (dry)	50 - 112
Clay (wet)	94 - 133
Clay with sand or silt (dry)	60 - 135
Clay with sand or silt (wet)	100 - 147

APPENDIX A

DECISION TREE

DECISION TREE

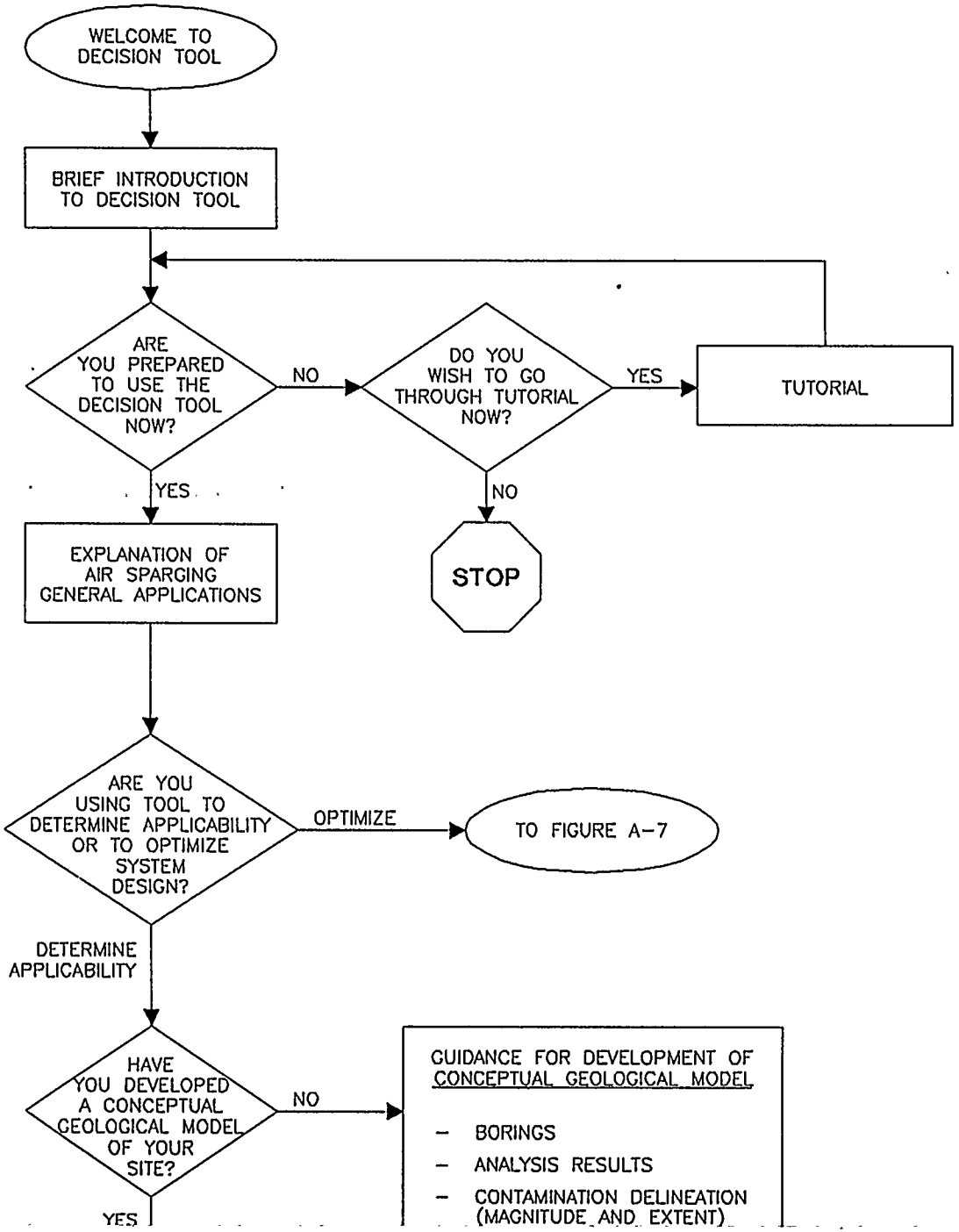
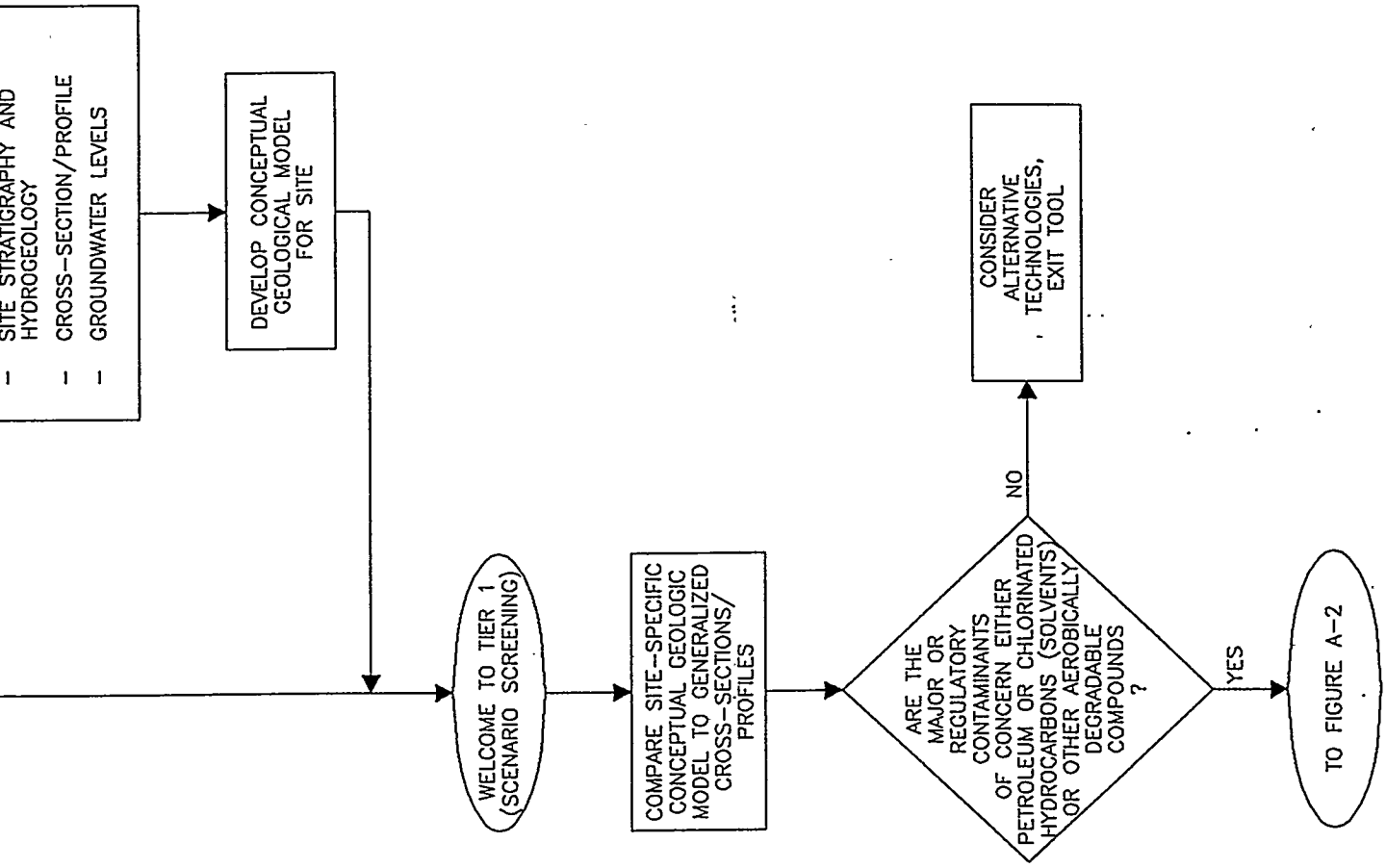
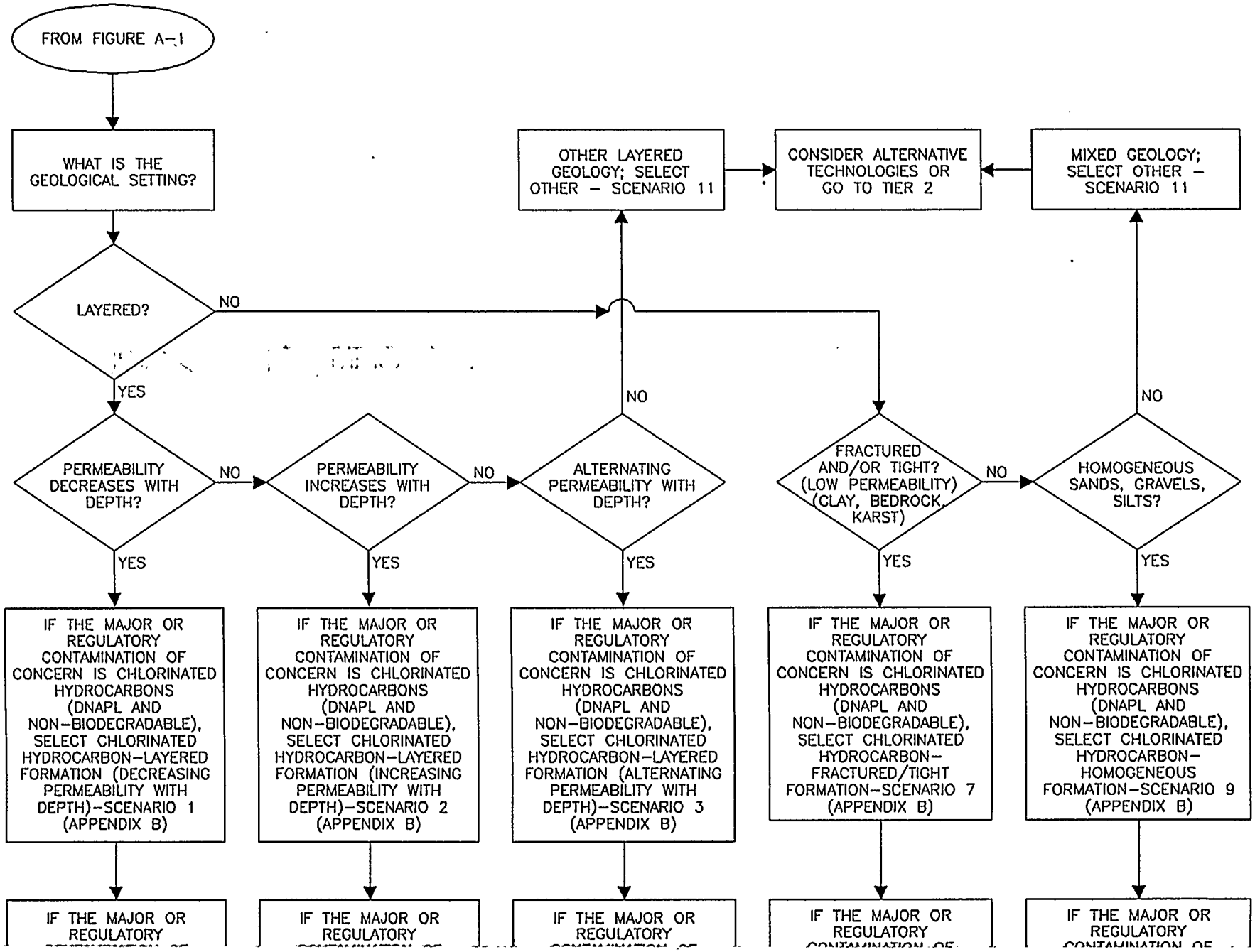


FIGURE A-1


- SITE STRATIGRAPHY AND HYDROGEOLOGY
- CROSS-SECTION/PROFILE
- GROUNDWATER LEVELS
DEVELOP CONCEPTUAL GEOLOGICAL MODEL FOR SITE
WELCOME TO TIER 1 (SCENARIO SCREENING)
COMPARE SITE-SPECIFIC CONCEPTUAL GEOLOGIC MODEL TO GENERALIZED CROSS-SECTIONS/ PROFILES
ARE THE MAJOR OR REGULATORY CONTAMINANTS OF CONCERN EITHER PETROLEUM OR CHLORINATED HYDROCARBONS (SOLVENTS) OR OTHER AEROBICALLY DEGRADABLE COMPOUNDS ?
NO
CONSIDER ALTERNATIVE TECHNOLOGIES, EXIT TOOL
YES
TO FIGURE A-2


FROM FIGURE A-1
WHAT IS THE GEOLOGICAL SETTING?
LAYERED?
NO
YES
OTHER LAYERED GEOLOGY; SELECT OTHER – SCENARIO 11
CONSIDER ALTERNATIVE TECHNOLOGIES OR GO TO TIER 2
MIXED GEOLOGY; SELECT OTHER – SCENARIO 11
PERMEABILITY DECREASES WITH DEPTH?
PERMEABILITY INCREASES WITH DEPTH?
ALTERNATING PERMEABILITY WITH DEPTH?
FRACTURED AND/OR TIGHT? (LOW PERMEABILITY) (CLAY, BEDROCK, KARST)
HOMOGENEOUS SANDS, GRAVELS, SILTS?
IF THE MAJOR OR REGULATORY CONTAMINATION OF CONCERN IS CHLORINATED HYDROCARBONS (DNAPL AND NON-BIODEGRADABLE), SELECT CHLORINATED HYDROCARBON-LAYERED FORMATION (DECREASING PERMEABILITY WITH DEPTH)-SCENARIO 1 (APPENDIX B)
IF THE MAJOR OR REGULATORY CONTAMINATION OF CONCERN IS CHLORINATED HYDROCARBONS (DNAPL AND NON-BIODEGRADABLE), SELECT CHLORINATED HYDROCARBON-LAYERED FORMATION (INCREASING PERMEABILITY WITH DEPTH)-SCENARIO 2 (APPENDIX B)
IF THE MAJOR OR REGULATORY CONTAMINATION OF CONCERN IS CHLORINATED HYDROCARBONS (DNAPL AND NON-BIODEGRADABLE), SELECT CHLORINATED HYDROCARBON-LAYERED FORMATION (ALTERNATING PERMEABILITY WITH DEPTH)-SCENARIO 3 (APPENDIX B)
IF THE MAJOR OR REGULATORY CONTAMINATION OF CONCERN IS CHLORINATED HYDROCARBONS (DNAPL AND NON-BIODEGRADABLE), SELECT CHLORINATED HYDROCARBON-FRACTURED/TIGHT FORMATION-SCENARIO 7 (APPENDIX B)
IF THE MAJOR OR REGULATORY CONTAMINATION OF CONCERN IS CHLORINATED HYDROCARBONS (DNAPL AND NON-BIODEGRADABLE), SELECT CHLORINATED HYDROCARBON-HOMOGENEOUS FORMATION-SCENARIO 9 (APPENDIX B)
IF THE MAJOR OR REGULATORY
IF THE MAJOR OR REGULATORY
IF THE MAJOR OR REGULATORY
IF THE MAJOR OR REGULATORY
IF THE MAJOR OR REGULATORY

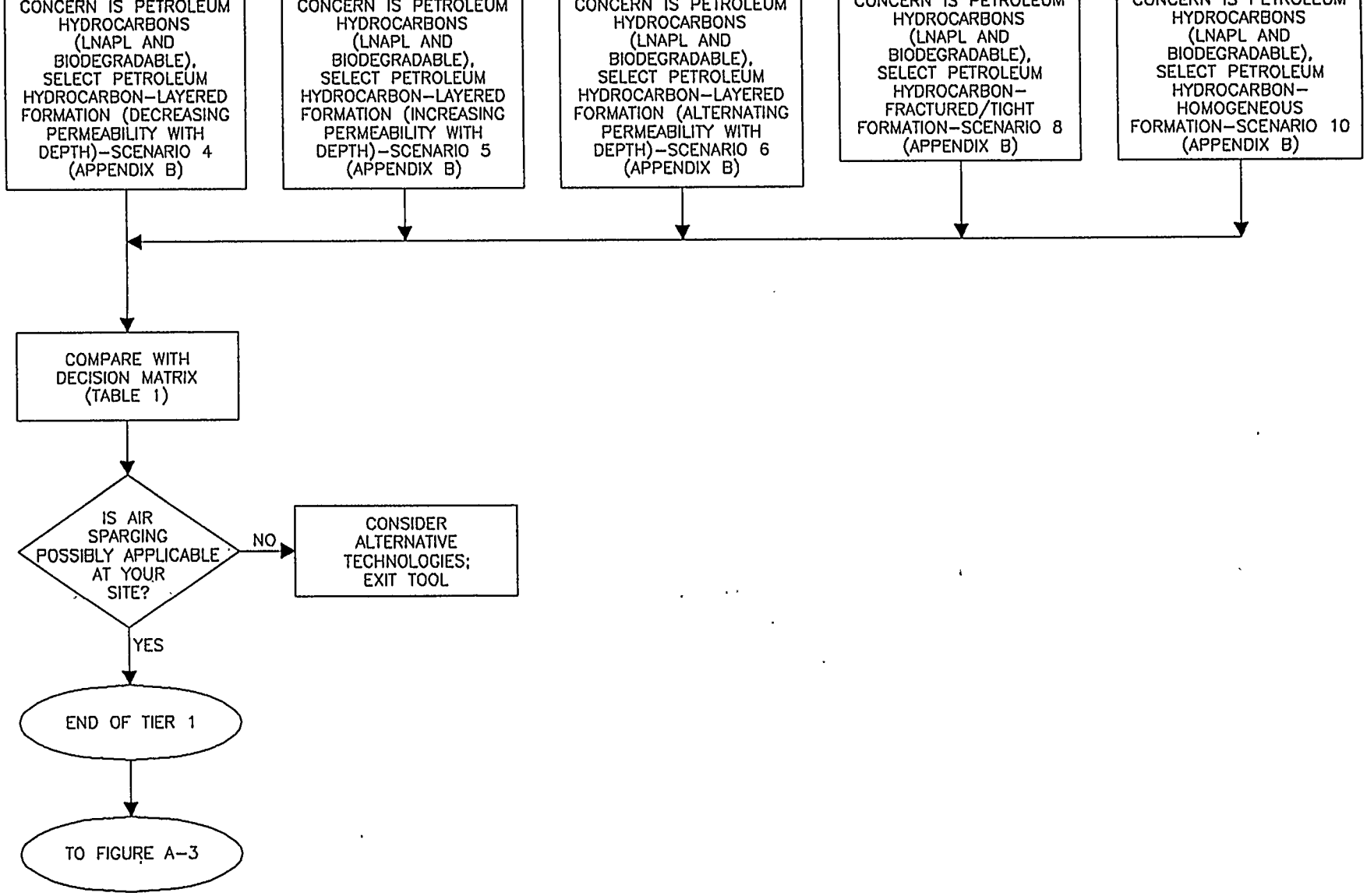
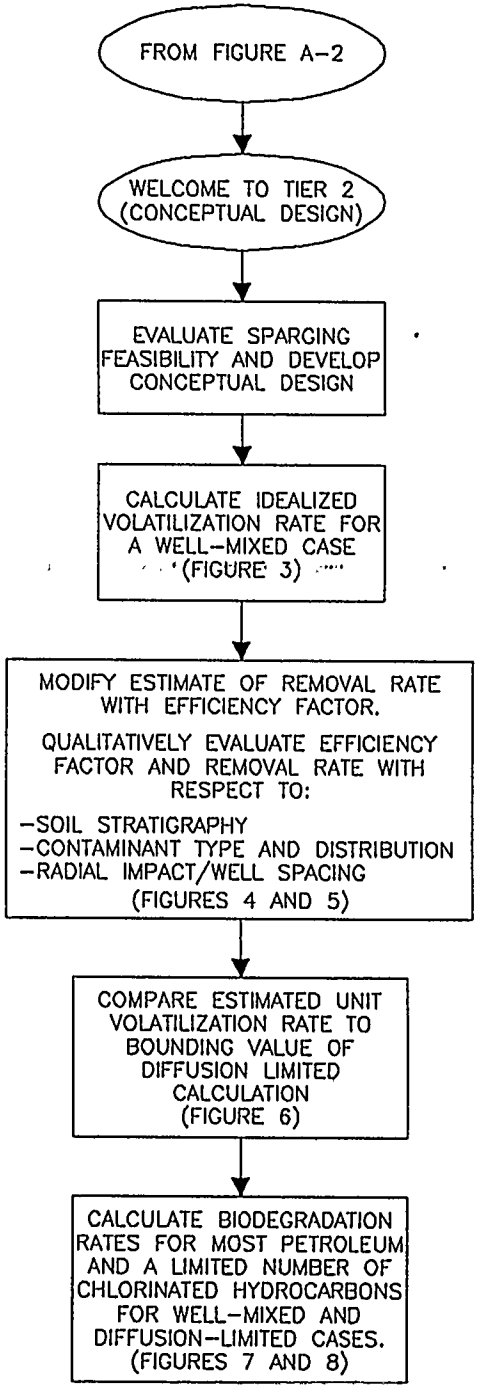

CONCERN IS PETROLEUM HYDROCARBONS (LNAPL AND BIODEGRADABLE), SELECT PETROLEUM HYDROCARBON–LAYERED FORMATION (DECREASING PERMEABILITY WITH DEPTH)–SCENARIO 4 (APPENDIX B)
CONCERN IS PETROLEUM HYDROCARBONS (LNAPL AND BIODEGRADABLE), SELECT PETROLEUM HYDROCARBON–LAYERED FORMATION (INCREASING PERMEABILITY WITH DEPTH)–SCENARIO 5 (APPENDIX B)
CONCERN IS PETROLEUM HYDROCARBONS (LNAPL AND BIODEGRADABLE), SELECT PETROLEUM HYDROCARBON–LAYERED FORMATION (ALTERNATING PERMEABILITY WITH DEPTH)–SCENARIO 6 (APPENDIX B)
CONCERN IS PETROLEUM HYDROCARBONS (LNAPL AND BIODEGRADABLE), SELECT PETROLEUM HYDROCARBON–FRACTURED/TIGHT FORMATION–SCENARIO 8 (APPENDIX B)
CONCERN IS PETROLEUM HYDROCARBONS (LNAPL AND BIODEGRADABLE), SELECT PETROLEUM HYDROCARBON–HOMOGENEOUS FORMATION–SCENARIO 10 (APPENDIX B)
COMPARE WITH DECISION MATRIX (TABLE 1)
IS AIR SPARGING POSSIBLY APPLICABLE AT YOUR SITE?
NO
CONSIDER ALTERNATIVE TECHNOLOGIES; EXIT TOOL
YES
END OF TIER 1
TO FIGURE A–3

FIGURE A–2


FROM FIGURE A-2
WELCOME TO TIER 2 (CONCEPTUAL DESIGN)
EVALUATE SPARGING FEASIBILITY AND DEVELOP CONCEPTUAL DESIGN
CALCULATE IDEALIZED VOLATILIZATION RATE FOR A WELL-MIXED CASE (FIGURE 3)
MODIFY ESTIMATE OF REMOVAL RATE WITH EFFICIENCY FACTOR.
QUALITATIVELY EVALUATE EFFICIENCY FACTOR AND REMOVAL RATE WITH RESPECT TO:
-SOIL STRATIGRAPHY
-CONTAMINANT TYPE AND DISTRIBUTION
-RADIAL IMPACT/WELL SPACING
(FIGURES 4 AND 5)
COMPARE ESTIMATED UNIT VOLATILIZATION RATE TO BOUNDING VALUE OF DIFFUSION LIMITED CALCULATION (FIGURE 6)
CALCULATE BIODEGRADATION RATES FOR MOST PETROLEUM AND A LIMITED NUMBER OF CHLORINATED HYDROCARBONS FOR WELL-MIXED AND DIFFUSION-LIMITED CASES. (FIGURES 7 AND 8)

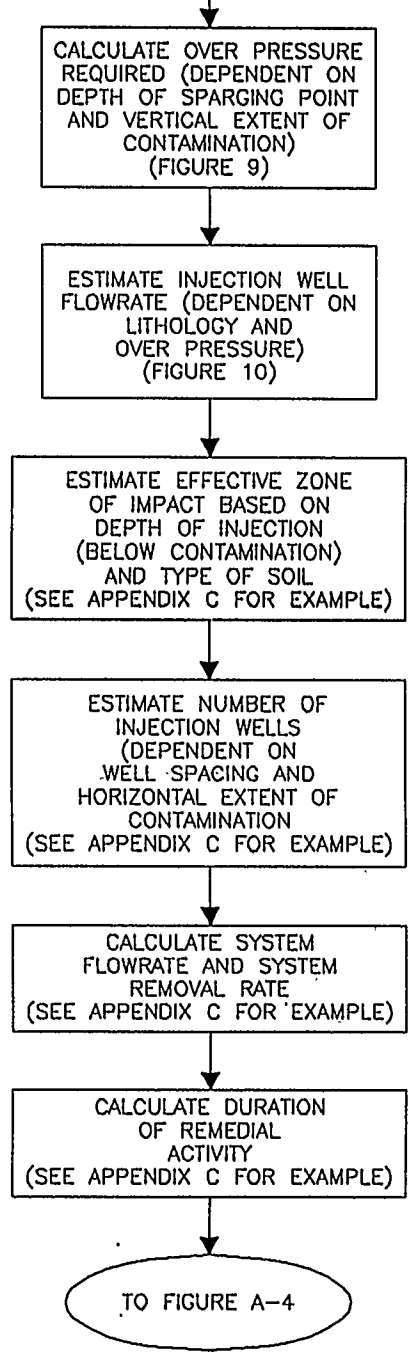
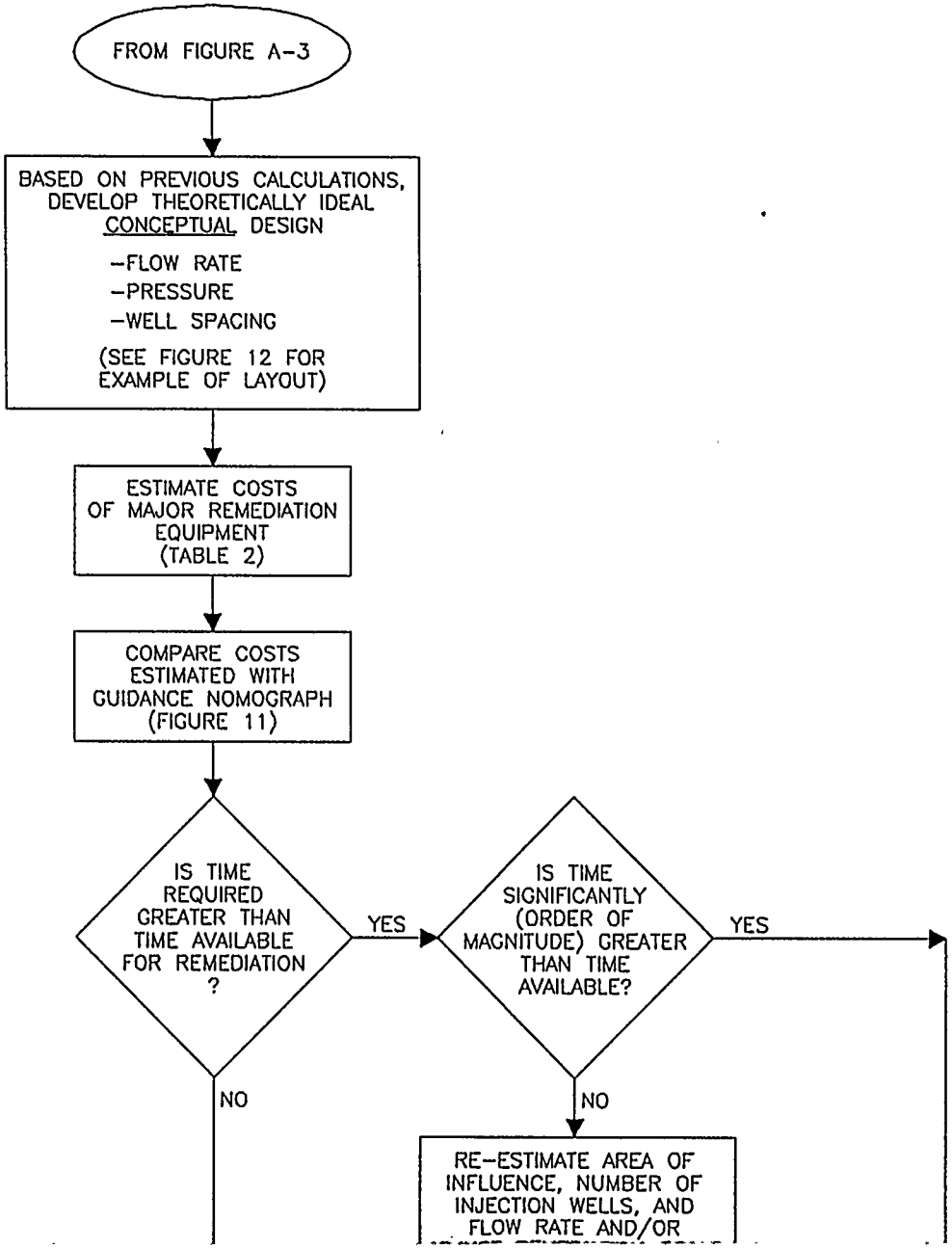

CALCULATE OVER PRESSURE REQUIRED (DEPENDENT ON DEPTH OF SPARGING POINT AND VERTICAL EXTENT OF CONTAMINATION) (FIGURE 9)
ESTIMATE INJECTION WELL FLOWRATE (DEPENDENT ON LITHOLOGY AND OVER PRESSURE) (FIGURE 10)
ESTIMATE EFFECTIVE ZONE OF IMPACT BASED ON DEPTH OF INJECTION (BELOW CONTAMINATION) AND TYPE OF SOIL (SEE APPENDIX C FOR EXAMPLE)
ESTIMATE NUMBER OF INJECTION WELLS (DEPENDENT ON WELL SPACING AND HORIZONTAL EXTENT OF CONTAMINATION (SEE APPENDIX C FOR EXAMPLE)
CALCULATE SYSTEM FLOWRATE AND SYSTEM REMOVAL RATE (SEE APPENDIX C FOR EXAMPLE)
CALCULATE DURATION OF REMEDIAL ACTIVITY (SEE APPENDIX C FOR EXAMPLE)
TO FIGURE A-4

FIGURE A-3



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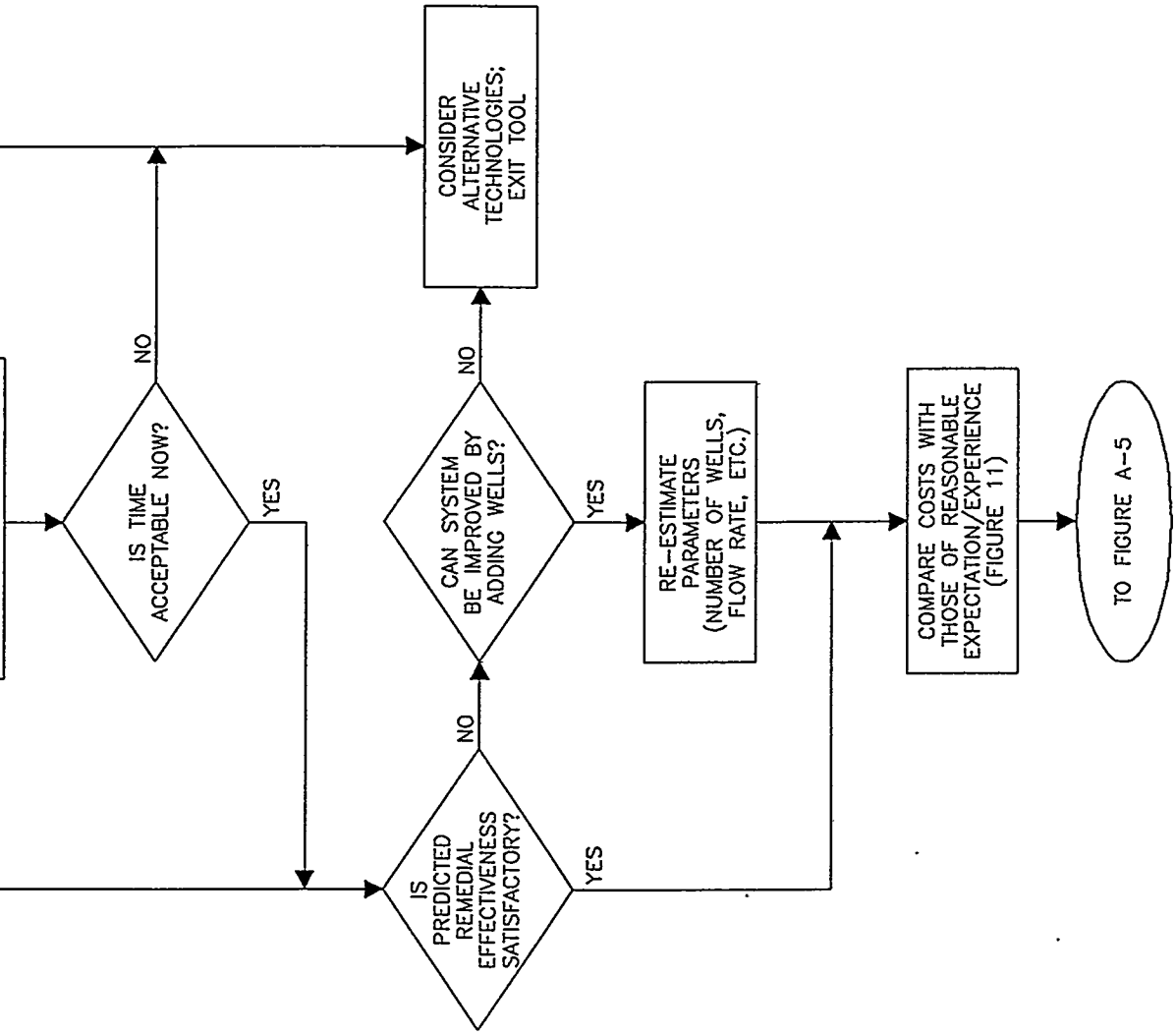
PARSONS ENGINEE

FIGURE A-4


IS TIME ACCEPTABLE NOW?
NO
YES
CONSIDER ALTERNATIVE TECHNOLOGIES; EXIT TOOL
IS PREDICTED REMEDIAL EFFECTIVENESS SATISFACTORY?
NO
YES
CAN SYSTEM BE IMPROVED BY ADDING WELLS?
NO
YES
RE-ESTIMATE PARAMETERS (NUMBER OF WELLS, FLOW RATE, ETC.)
COMPARE COSTS WITH THOSE OF REASONABLE EXPECTATION/EXPERIENCE (FIGURE 11)
TO FIGURE A-5

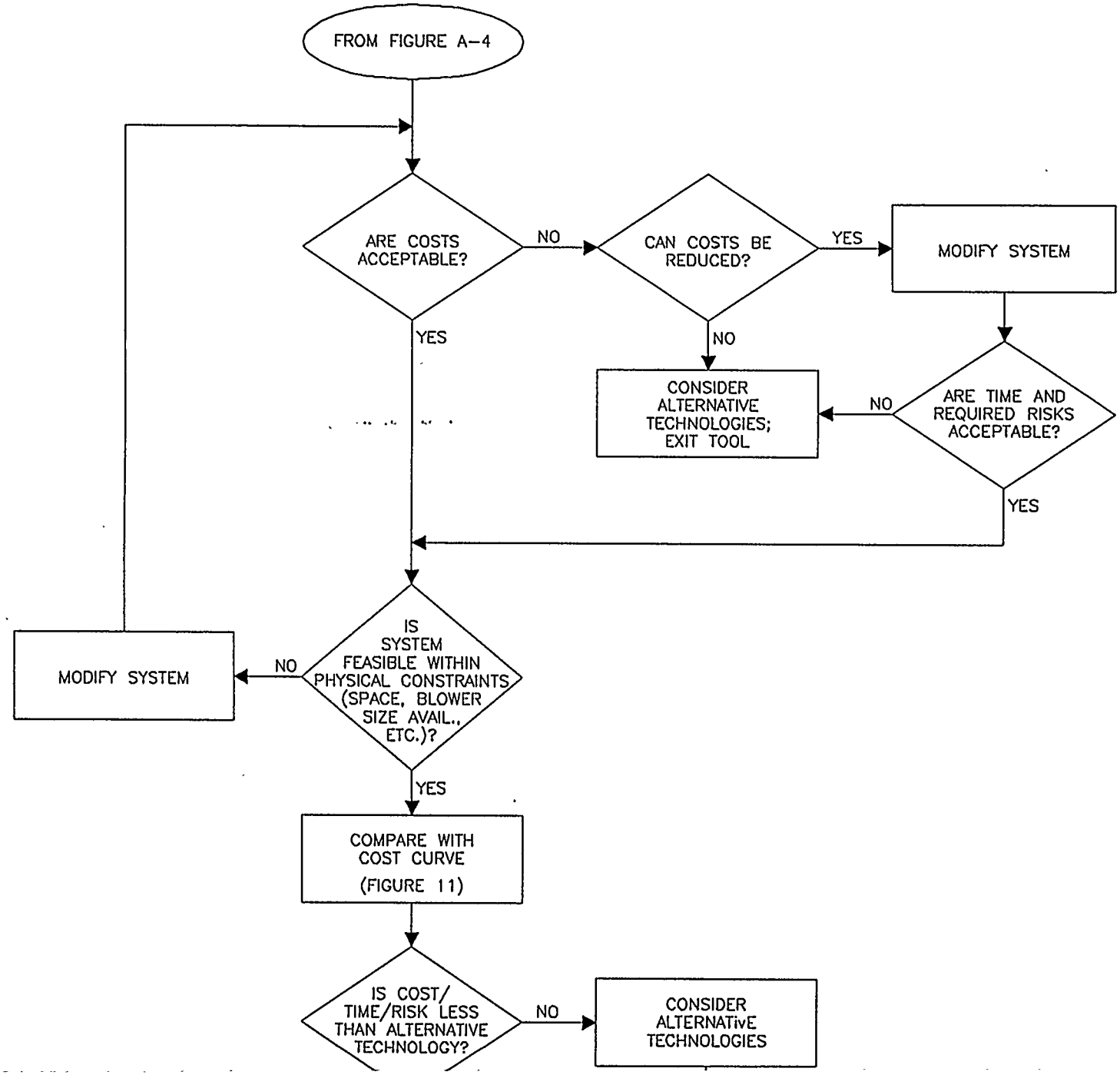
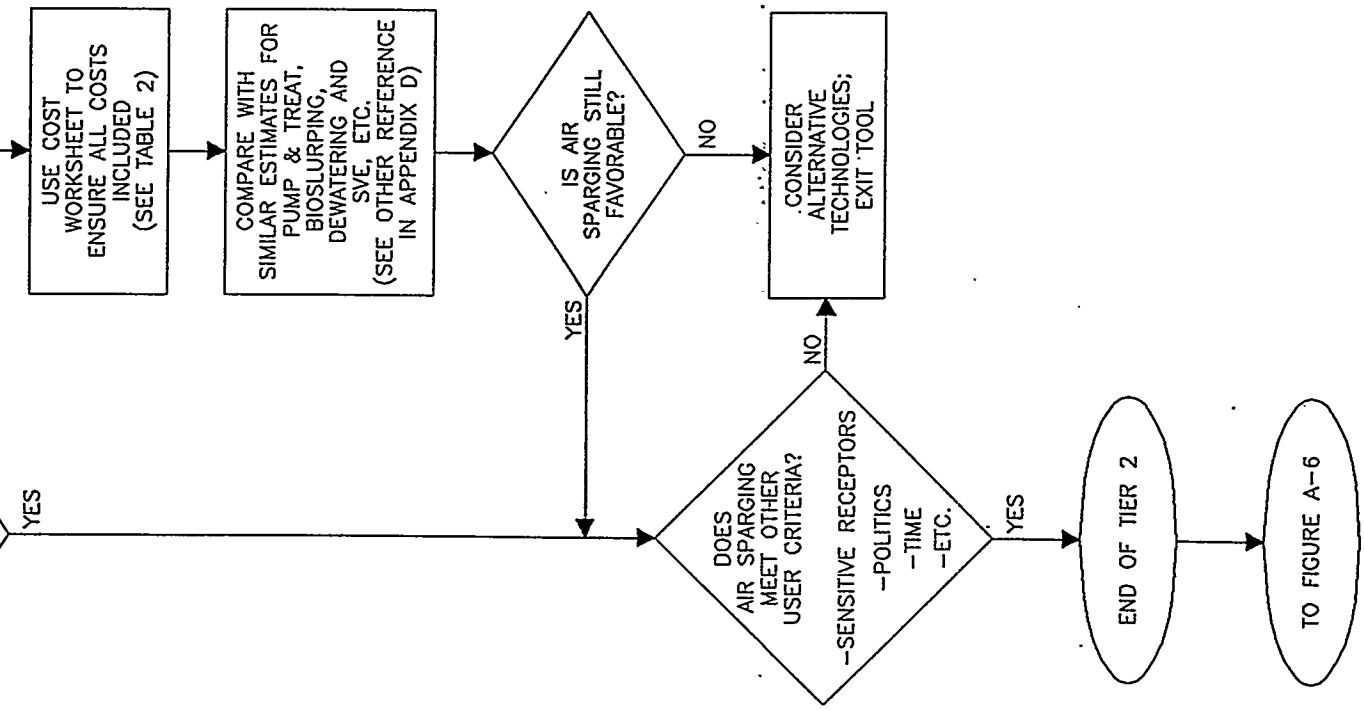

FROM FIGURE A-4
ARE COSTS ACCEPTABLE?
NO
CAN COSTS BE REDUCED?
YES
MODIFY SYSTEM
YES
NO
CONSIDER ALTERNATIVE TECHNOLOGIES; EXIT TOOL
NO
ARE TIME AND REQUIRED RISKS ACCEPTABLE?
YES
MODIFY SYSTEM
NO
IS SYSTEM FEASIBLE WITHIN PHYSICAL CONSTRAINTS (SPACE, BLOWER SIZE AVAIL., ETC.)?
YES
COMPARE WITH COST CURVE (FIGURE 11)
IS COST/ TIME/RISK LESS THAN ALTERNATIVE TECHNOLOGY?
NO
CONSIDER ALTERNATIVE TECHNOLOGIES

FIGURE A-5


YES
USE COST WORKSHEET TO ENSURE ALL COSTS INCLUDED (SEE TABLE 2)
COMPARE WITH SIMILAR ESTIMATES FOR PUMP & TREAT, BIOSLURPING, DEWATERING AND SVE, ETC. (SEE OTHER REFERENCE IN APPENDIX D)
IS AIR SPARGING STILL FAVORABLE?
NO
CONSIDER ALTERNATIVE TECHNOLOGIES; EXIT TOOL
YES
NO
DOES AIR SPARGING MEET OTHER USER CRITERIA?
-SENSITIVE RECEPTORS
-POLITICS
-TIME
-ETC.
YES
END OF TIER 2
TO FIGURE A-6

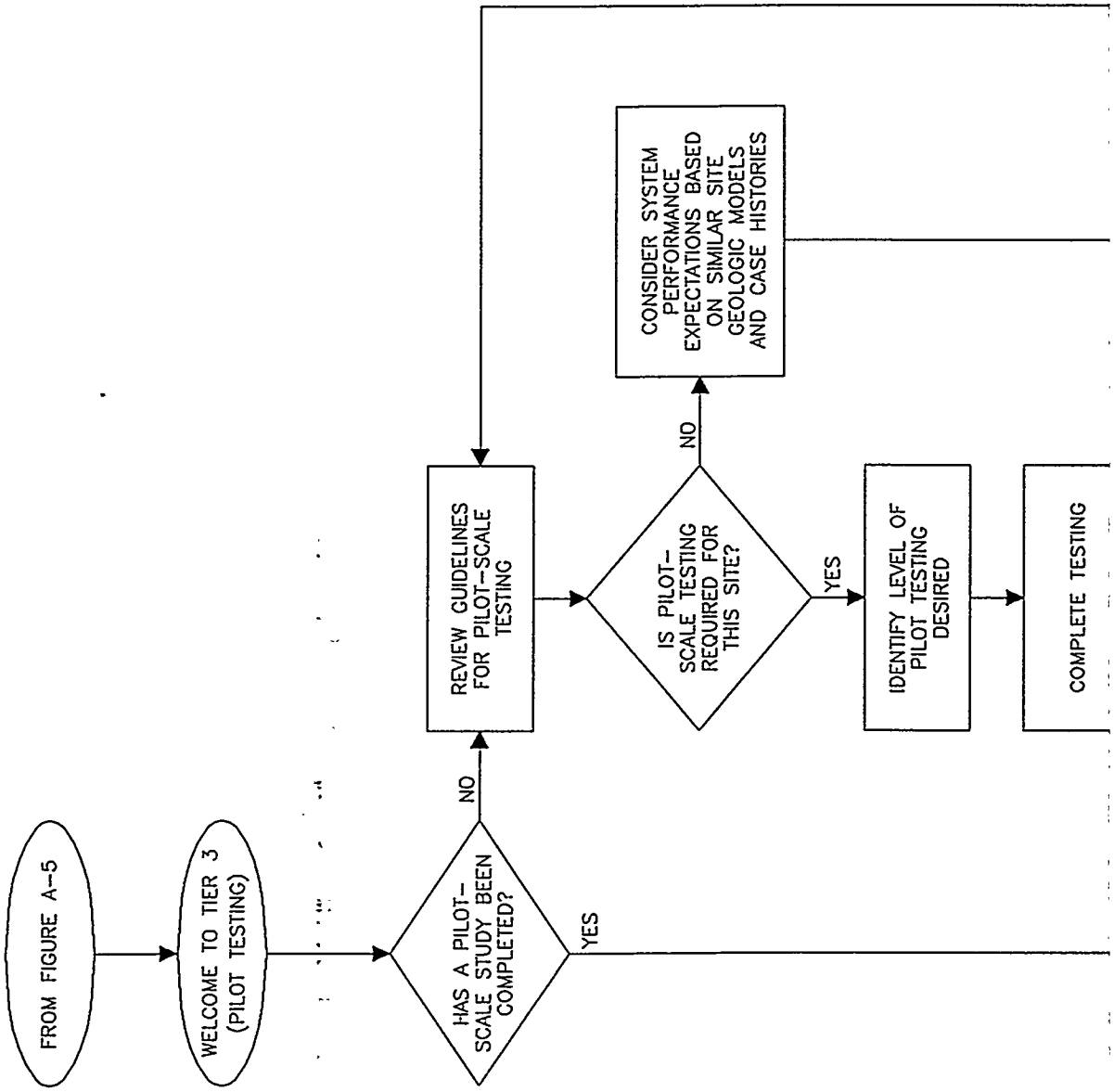

FROM FIGURE A-5
WELCOME TO TIER 3 (PILOT TESTING)
HAS A PILOT-SCALE STUDY BEEN COMPLETED?
NO
YES
REVIEW GUIDELINES FOR PILOT-SCALE TESTING
IS PILOT-SCALE TESTING REQUIRED FOR THIS SITE?
NO
YES
CONSIDER SYSTEM PERFORMANCE EXPECTATIONS BASED ON SIMILAR SITE GEOLOGIC MODELS AND CASE HISTORIES
IDENTIFY LEVEL OF PILOT TESTING DESIRED
COMPLETE TESTING

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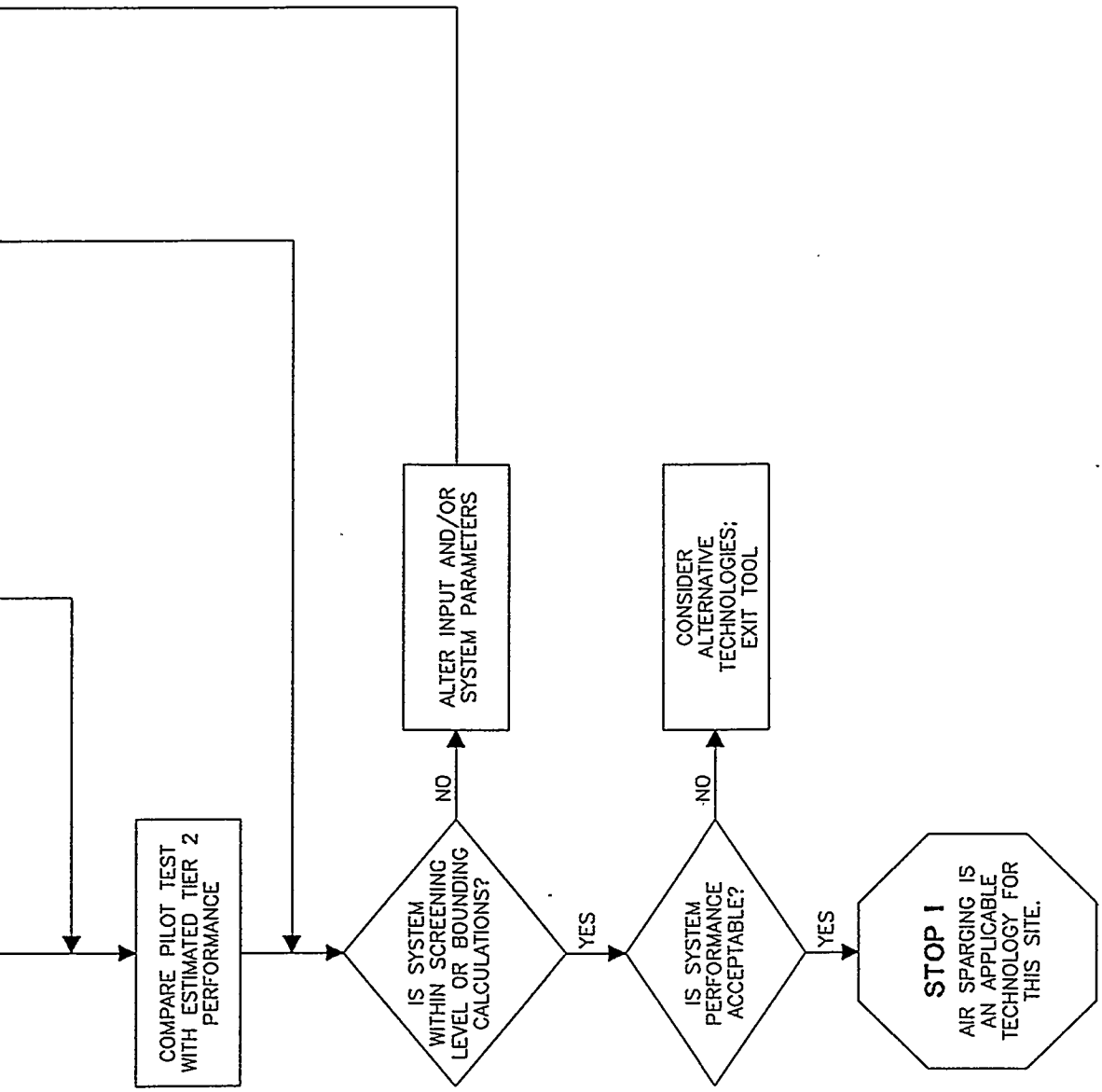
FIGURE A-6


COMPARE PILOT TEST WITH ESTIMATED TIER 2 PERFORMANCE
IS SYSTEM WITHIN SCREENING LEVEL OR BOUNDING CALCULATIONS?
NO
ALTER INPUT AND/OR SYSTEM PARAMETERS
YES
IS SYSTEM PERFORMANCE ACCEPTABLE?
NO
CONSIDER ALTERNATIVE TECHNOLOGIES; EXIT TOOL
YES
STOP I
AIR SPARGING IS AN APPLICABLE TECHNOLOGY FOR THIS SITE.

OPTIMIZATION OF EXISTING SYSTEMS

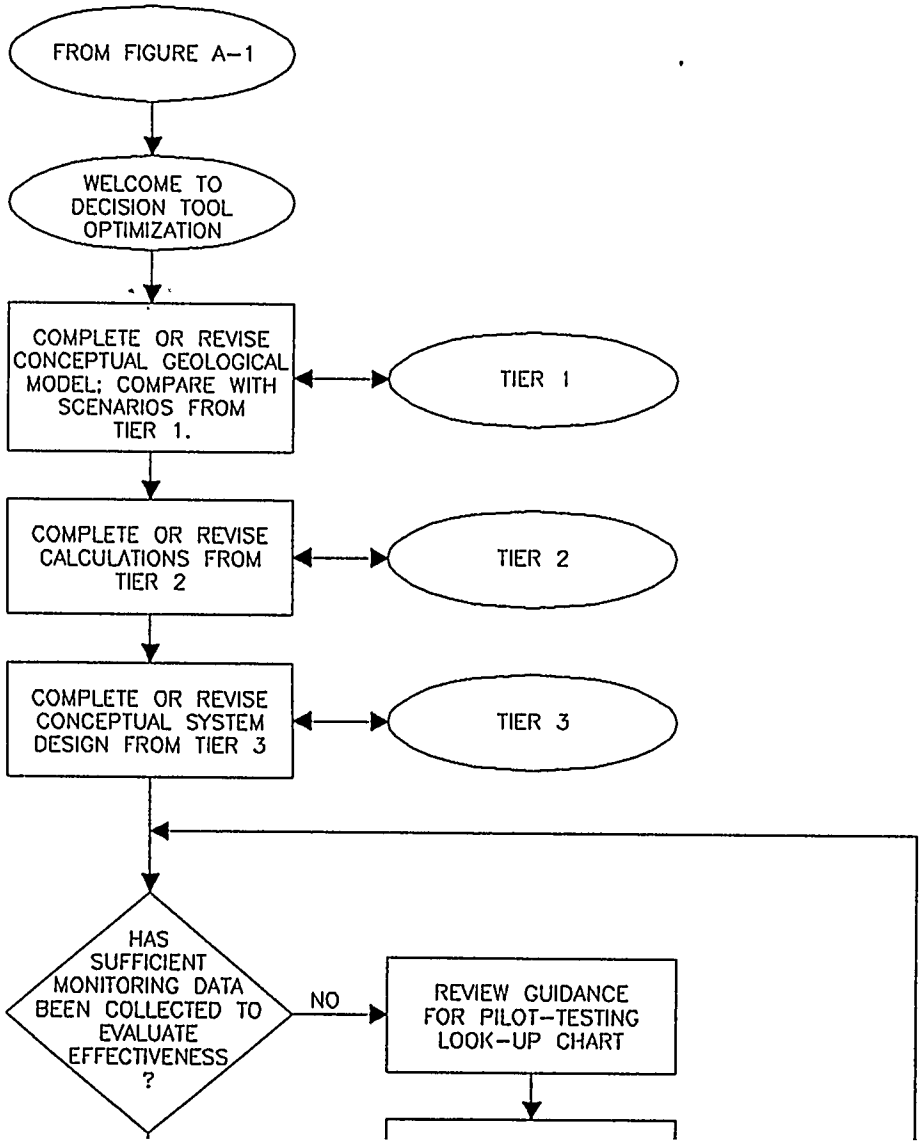
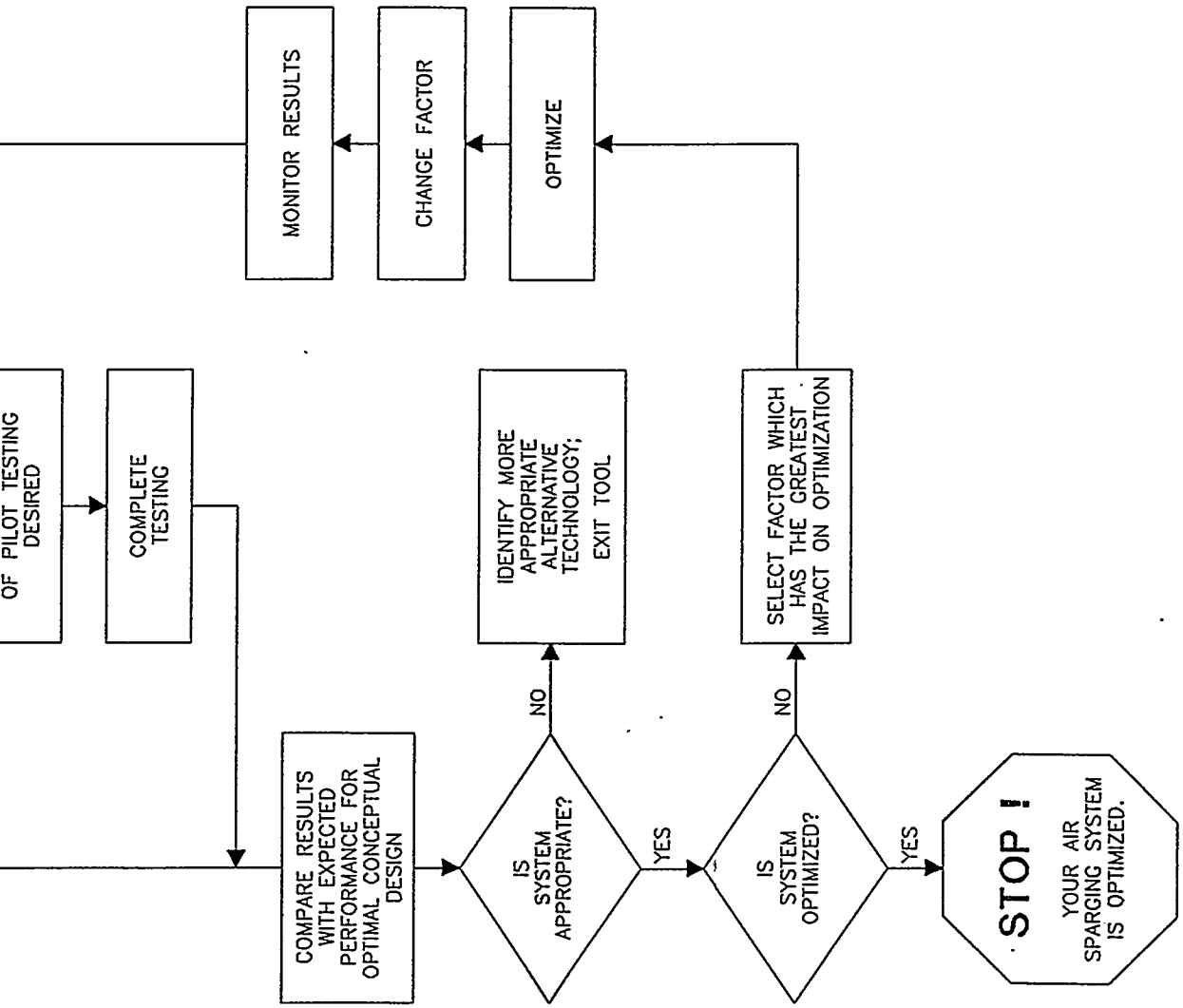


FIGURE A-7


OF PILOT TESTING DESIRED
COMPLETE TESTING
MONITOR RESULTS
CHANGE FACTOR
OPTIMIZE
COMPARE RESULTS WITH EXPECTED PERFORMANCE FOR OPTIMAL CONCEPTUAL DESIGN
IS SYSTEM APPROPRIATE?
NO
IDENTIFY MORE APPROPRIATE ALTERNATIVE TECHNOLOGY; EXIT TOOL
YES
IS SYSTEM OPTIMIZED?
NO
SELECT FACTOR WHICH HAS THE GREATEST IMPACT ON OPTIMIZATION
YES
STOP !
YOUR AIR SPARGING SYSTEM IS OPTIMIZED.

APPENDIX B

SITE CONCEPTUAL MODELS

APPENDIX B

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INTRODUCTION

Included in Appendix B are 10 generalized site conceptual scenarios; the elevation scenario, other, is not represented. Each site conceptual scenario includes a generalized geologic cross-section with contaminant distribution and type displayed, a verbal description of the conceptual site, a description of air sparging experience for similar sites and an approximate scale in which the likely probability of successfully applying air sparging is indicated. After the descriptions of air sparging experience are presented for the different remediation objectives (i.e., source; plume; or containment), an artist's view of the air distribution pattern is presented for each scenario. In some cases, due to potential variations in contaminant characteristics (i.e., density greater or less than water) and/or contaminant concentration (i.e, presence or absence of separate phase), which my be found in the natural environment, supplemental or alternative generalized cross-sections have been included. These may prove helpful to the user in identifying the scenario(s) most representative of the user's selected site.

You are to compare your site-specific conceptual geologic model with the conceptualized scenarios to determine if one provides a match or near match. For each conceptualized scenario, you are then referred to the Decision Matrix (Table 1) for identifying the applicability of air sparging at your site. Progressing further in the Decision Tool will depend on how your site and remediation objective compare with the conceptualized scenarios and the applicability rating.

Please note that in the computerized version of the Decision Tool, the scenarios in Appendix B will be stored in a library. Your answers to the questions posed in Tier 1 will automatically transfer you to the proper conceptual site scenario for review and concurrence.

Scale of Conceptual Drawings

To avoid confusion in using the following set of site conceptual scenarios, please note that the drawings depicting geologic conditions and probable air distribution patterns are not to scale (NTS). Graphic images of familiar objects such as houses, trees, and storage tanks (located either above or below grade), are provided for esthetics only and are in no way intended to define scale. The immediate implication of this caveat is that the effective radius of impact of an air sparging injection point is typically in the range of 5 to 20 feet, not to 50 to 200 feet as might be implied by these conceptual drawings.

Please keep in mind that these scenarios are depicted strictly as conceptual drawings. With the exception of very few sites, significant amounts of simplification must be applied to the geologic environment typically found in your site to use these scenarios. Due to the great variation found in actual geologic settings, accurate, detailed depiction would be almost impossible and is beyond the scope of this project.

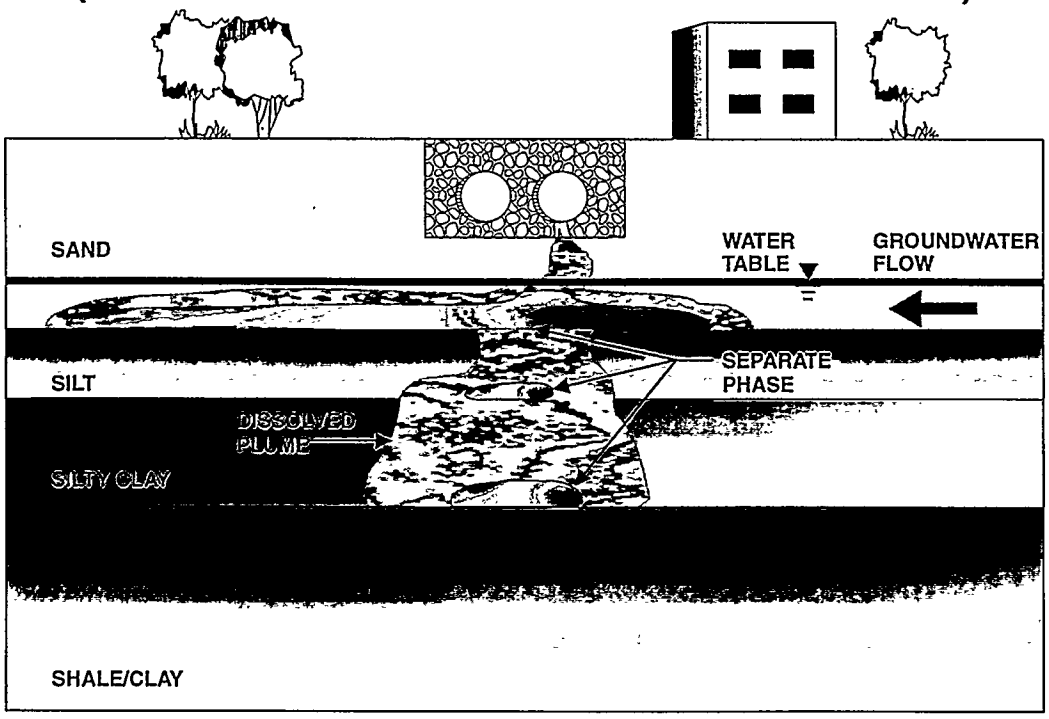
In any case, local heterogeneities cannot be ignored when developing your site-specific conceptual geologic model or determining applicability of air sparging to your site. For example, thin layers of clay or silt interbedded in a sandy matrix or thin layers of sand in a predominantly silty or clayey structure, may be difficult to detect during site characterization. These, and many other features, can be the most important factors, however, in determining air sparging applicability for your site. As a field practitioner, you must be aware of these features and accommodate their occurrence when using the accompanying site conceptual scenarios. If you are unsure of the implications of such factors in your site-specific evaluation, contact an experienced environmental consultant for assistance.

References to Air Sparging Experience

Many case histories, describing air sparging experience for the different applications, may be found in the literature. References for a number of these case histories, providing examples of previous air sparging experience, are listed either in the text for each site conceptual scenario or collectively in a table provided at the end of this Appendix. The complete citations of these references can be found in Appendix D, Bibliography.

SCENARIO 1:

CHLORINATED HYDROCARBON - LAYERED FORMATION (DECREASING PERMEABILITY WITH DEPTH)



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively permeable materials which were deposited in discrete layers. The permeability of the layers decreases with depth. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate that the subsurface layers have the characteristics of "gravels", "sands", or "silts".

Here the water-bearing unit has been impacted by a release of chlorinated hydrocarbons that are denser than water (DNAPLs e.g., trichloroethene, tetrachloroethene, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) chlorinated hydrocarbons which migrate downward and may appear at one or more of the layer contacts.

Dissolved contaminants of concern in such settings are often trichloroethene, tetrachloroethene, and/or vinyl chloride.

EXPERIENCE - AIR SPARGING APPLICATIONS

This scenario has no case studies in the current technical literature. Results are suspected to be less than promising when remediating a source due to the likely location of the majority of the contamination (at semi-confining layer contacts). The chance of injecting air below the source and controlling migration is minimal. An overriding concern is air sparging in a source may spread contamination.

The site geological characteristics have very strong implications for the use of sparging in this scenario. For example, the presence of numerous discrete sediment layers, of decreasing permeability, make it very likely that DNAPL could be present on the contact between each of these layers. In addition, the decreasing permeability with depth could cause vast differences in the areal extent of contamination between sediment layers. That is, the upper sandy (more permeable) zone may have a very large extent of chlorinated hydrocarbons while the lowest zone, may have a very limited extent, even though DNAPL could be present in each of the zones.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (-)
Unknown physical or technical possibility.

Plume Remediation (+)
Possibly a good physical or technical possibility, but not unique.

Containment (+)
Possibly a good physical or technical possibility, but not unique.

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. The chance of injecting air below the source and controlling migration is minimal. An overriding concern is air sparging in a source may spread contamination.

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. However, air sparging would both be technically and physically possible and might provide a good or unique target for air sparging in this particular conceptual scenario.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control system. However, air sparging may be technically and physically possible for geologic setting such as this.

CONCERNS

The following are issues that should be addressed by the practitioner:

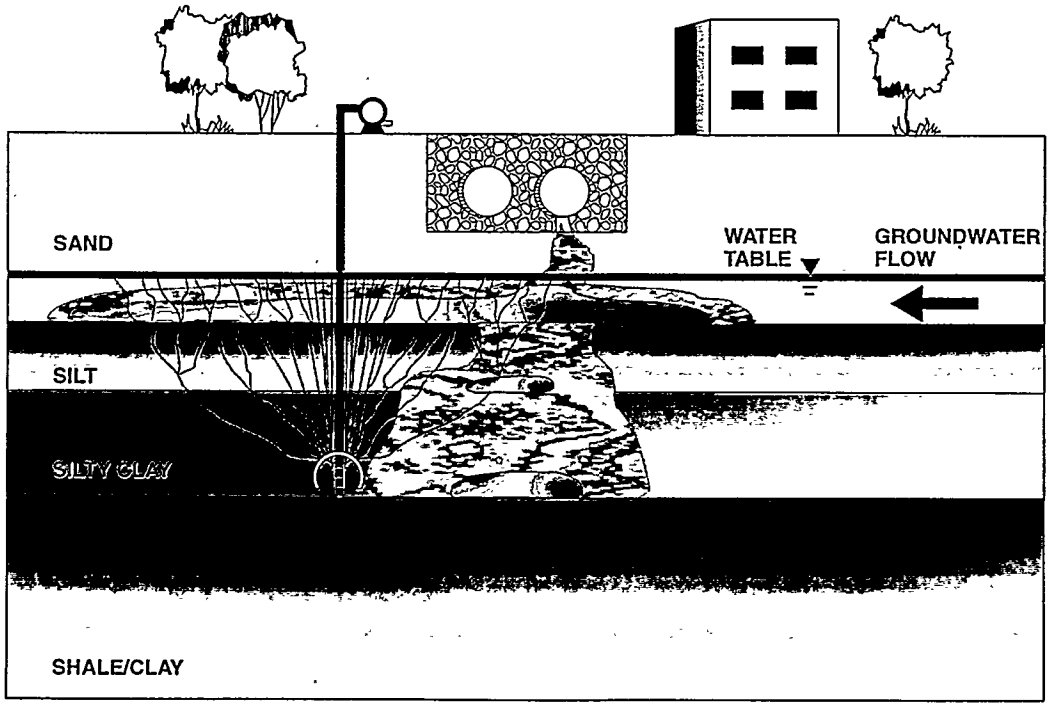
a) Was the site characterization sufficiently detailed such that it is very likely that the site is true layered and that the permeability decreases with depth? Alternately, are there any thin discontinuous heterogeneities within the layers they would impact the effectiveness of sparging?

b) Could uncontrolled vapor migration produce safety and/or health hazards?

c) Is it economical to install a system, considering the depth to the source area or plume?

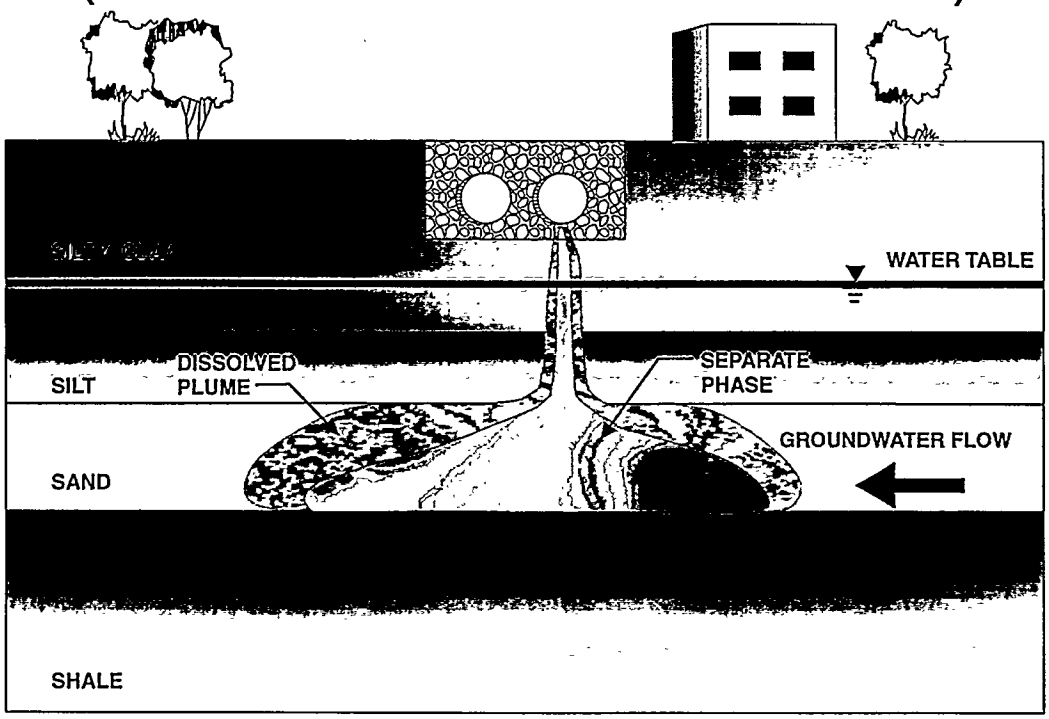
d) If a source is targeted, how will the practitioner insure that sparging does not spread DNAPL?

CONCEPTUAL AIR DISTRIBUTION



SCENARIO 2:

CHLORINATED HYDROCARBON - LAYERED FORMATION (INCREASING PERMEABILITY WITH DEPTH)



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively permeable layers which were deposited in discrete layers. The permeability of the materials increases with depth. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate that the subsurface layers have the characteristics of "gravels", "sands", or "silts".

Here the water-bearing unit has been impacted by a release of chlorinated hydrocarbons that are denser than water (DNAPLs e.g., trichloroethene, tetrachloroethene, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) chlorinated hydrocarbons which migrate downward and may appear at a confining layer.

Dissolved contaminants of concern in such settings are often trichloroethene, tetrachloroethene, and/or vinyl chloride.

EXPERIENCE - AIR SPARGING APPLICATIONS

This scenario has no case studies in the current technical literature. Results are suspected to be less than promising when remediating a source due to the likely location of the majority of the contamination (at a confining layer contacts). The chance of controlling subsurface air migration is minimal. In addition, disproportionate air flow patterns are expected as the result of less permeable materials overlying more permeable materials. These air flow patterns would most likely not allow for specific zones in the subsurface to be targeted for remediation. An overriding concern is air sparging of a source may spread contamination.

A major impact of this scenario of increasing permeability with depth would be that the exent of the plume would increase greatly with depth. This increased plume size with depth would occur because the chlorinated solvents would tend, as a separate phase, to migrate to the lowest layer above a confining layer. Thus, there would be a greater plume dispersion in the deepest, more difficult to remediate saturated zone.

Another major impact that the increasing permeability of sediments would have on the practical use of air sparging would be the effects on air distribution. In this scenario, if air were used in the sand layer, the much lower permeability of the silt and the overlying silty clay would (at each interface) inhibit the upward movement of air and cause, outward, uncontrolled movement of vapor/air and allow for the creation of air pockets. The uncontrolled migration of vapors could result in "fugitive vapors" appearing in unfavorable locations (i.e. basements). If other preferential

pathways exist, such as utility conduits, the vapors could migrate along these zones of higher permeability and appear elsewhere.

REMEDIATION OBJECTIVE AND RATING

Source Remediation (--)	Plume Remediation (-)	Containment (-)
Not technically or physically possible.	Unknown technical or physical possibility.	Unknown technical or physical possibility.

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. Due to the inherent uncertainty of air flow in a layered setting and the concern of chlorinated hydrocarbons sinking, air sparging is not considered to be a viable remedial technology for source zones.

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. It is unknown whether air sparging is a viable remedial technology for dissolved plumes in this layered geologic setting.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control system. It is unknown whether air sparging is a viable remedial technology for barrier control, in this layered geologic setting.

CONCERNS

The following are issues that should be addressed by the practitioner:

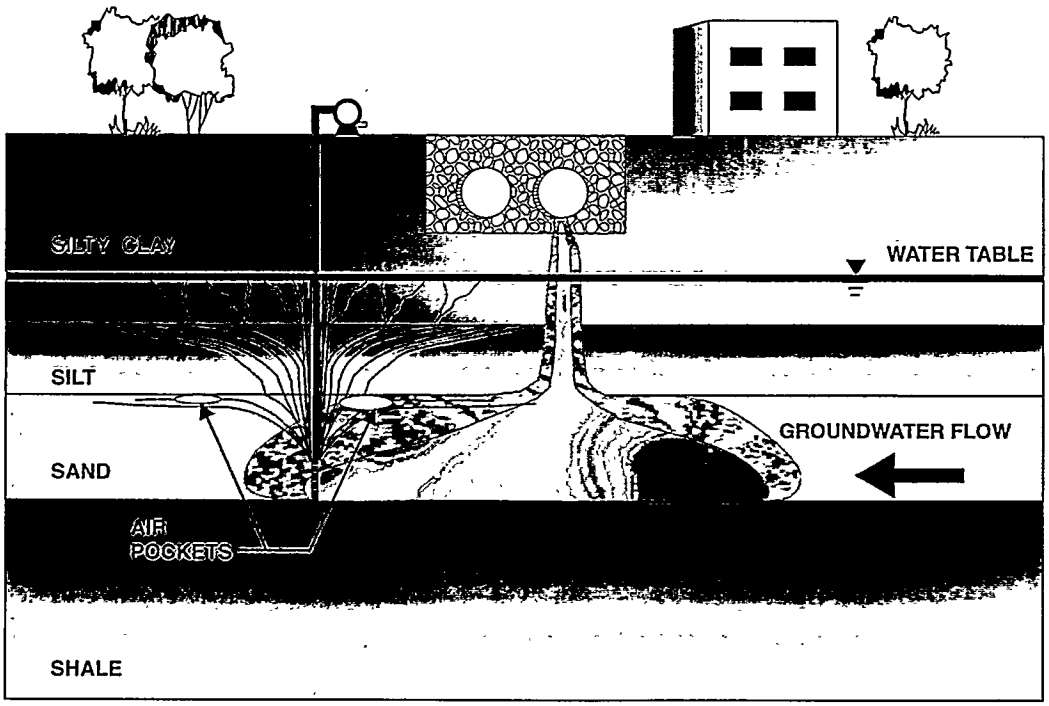
a) Was the site characterization sufficiently detailed such that it is very likely that the site is true layered and that the permeability increases with depth?

b) Could uncontrolled vapor migration, due to the presence of fractures or channels in the overlying sediment of unknown orientation, produce safety and/or health hazards and, therefore tend to be a risky technology?

c) Is it economical to install a system?

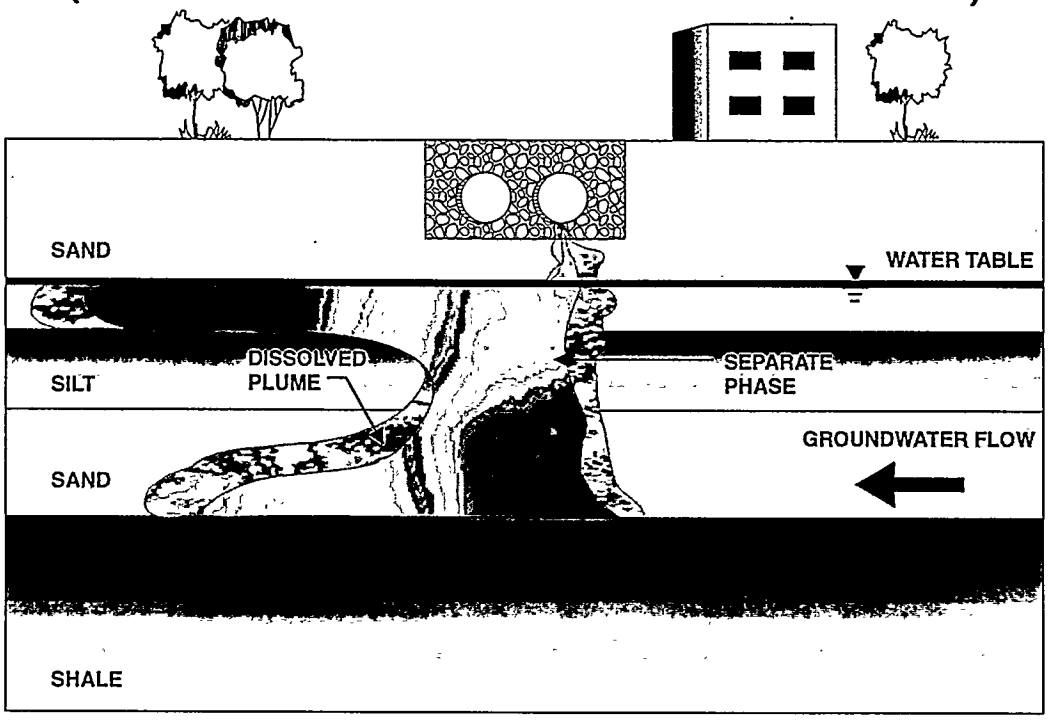
d) If a source is targeted, how will the practitioner insure that sparging does not spread DNAPL or dissolved plume?

CONCEPTUAL AIR DISTRIBUTION



SCENARIO 3:

CHLORINATED HYDROCARBON - LAYERED FORMATION (ALTERNATING PERMEABILITY WITH DEPTH)



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively permeable layers which were deposited in discrete layers. The permeability of the materials alternates with depth. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate that the subsurface layers have the characteristics of "gravels", "sands", or "silts".

Here the water-bearing unit has been impacted by a release of chlorinated hydrocarbons that are denser than water (DNAPLs e.g., trichloroethene, tetrachloroethene, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) chlorinated hydrocarbons which migrate downward and may appear at a confining or semi-confining layer or at other layer contacts.

Dissolved contaminants of concern in such settings are often trichloroethene, tetrachloroethene, and/or vinyl chloride.

EXPERIENCE - AIR SPARGING APPLICATIONS

This scenario has no case studies in the current technical literature. However, OGI large scale physical modeling results indicate a limited potential for source area remediation. In addition, results are suspected to be less than promising when remediating a source due to the likely location of the majority of the contamination at confining layer contacts or other layer contacts. The chance of injecting air below the source and controlling migration is minimal. In addition, disproportionate air flow patterns are expected as the result of less permeable materials overlying more permeable materials. These air flow patterns would most likely not allow for specific zones in the subsurface to be targeted for remediation. An overriding concern is air sparging of a source may spread contamination.

The effects of site geology on air flow distribution will be noticeable and crucial factor in this scenario. Obviously, one way in which site geology would impact air sparging as a remediation tool would be that the aerial extent of contamination could vary greatly depending sediment layer type. For example, in this scenario, the extent of dissolved phase in the upper sand layer would be much more extensive that the extent in the silt layer, due to groundwater flow/permeability differences. Moreover, the areal extent of contamination in the lower sand unit would very likely be of greater than the extent in the silt, for the same reasons. These complications would make the use of air sparging more difficult.

Another major impact that the alternating sediment layers would have on the practical use of air sparging would be the effects on air distribution. In this scenario, if air sparging were used in the lower sand layer, the much lower permeability of the silt would inhibit upward air movement, cause outward, uncontrolled air movement and allow for the creation of air pockets. This could result in "fugitive vapors", appearing in unfavorable locations (i.e. basements), if the vapors follow possible preferential pathways.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (--)	Plume Remediation (-)	Containment (-)
Not physically or technically possible.	Not physical or technical possibility.	Unknown physical or technical possibility.

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. Due to the inherent uncertainty of air flow in a layered setting and the concern of chlorinated hydrocarbons sinking, air sparging is not considered to be a viable remedial technology for source zones.

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. It is unknown whether air sparging is a viable remedial technology for dissolved plumes, in this geologic setting.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control system. It is unknown whether air sparging is a viable remedial technology for barrier control, in this geologic setting.

CONCERNS

The following are issues that should be addressed by the practitioner:

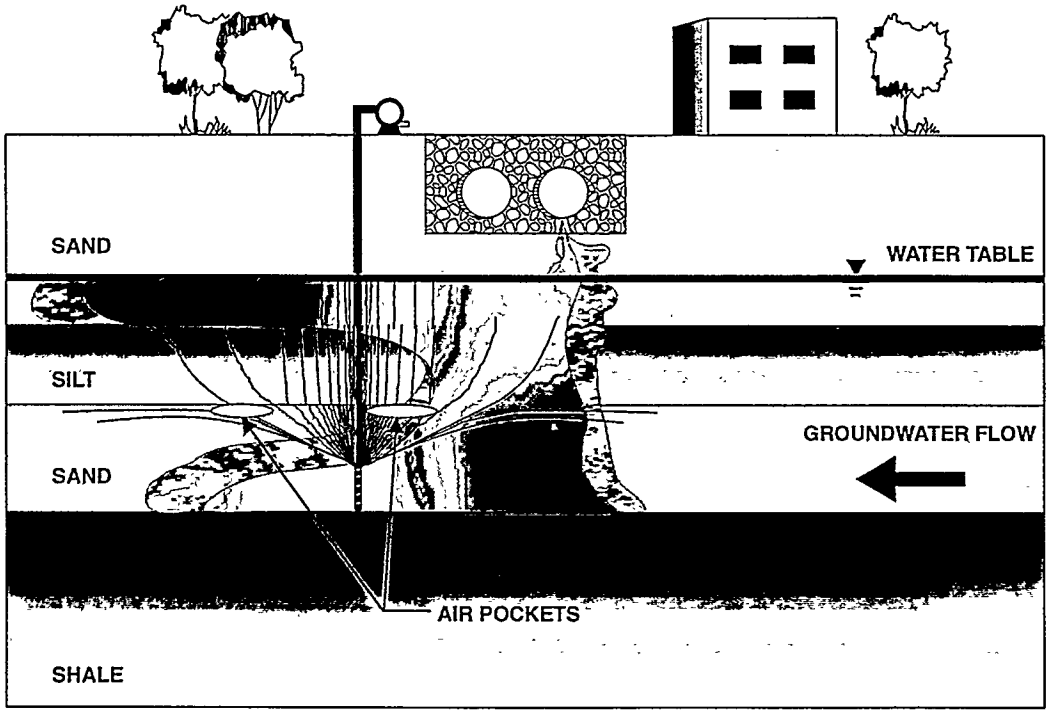
a) Was the site characterization sufficiently detailed such that it is very likely that the site is true layered and that the permeability increases with depth? Or alternately, are there any heterogeneities which could inhibit the effectivness of sparging?

b) Could uncontrolled vapor migration produce safety and/or health hazards?

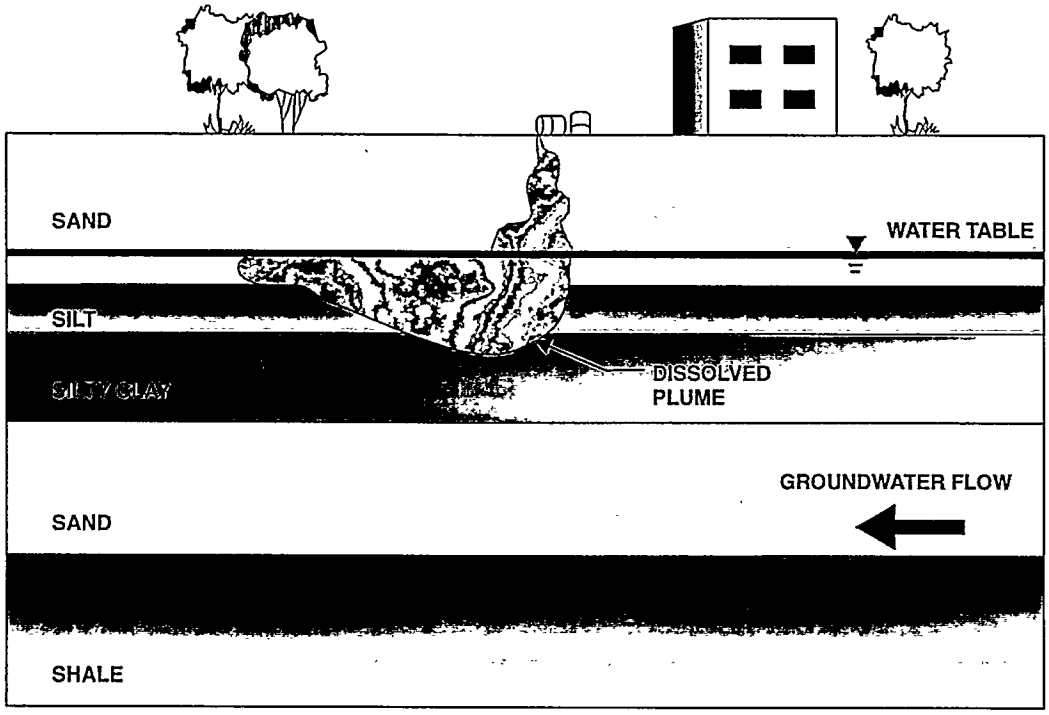
c) Is it economical to install a system, taking into account the depth to the zones of contamination and density of sparge wells?

d) If a source is targeted, how will the practitioner insure that sparging does not spread DNAPL?

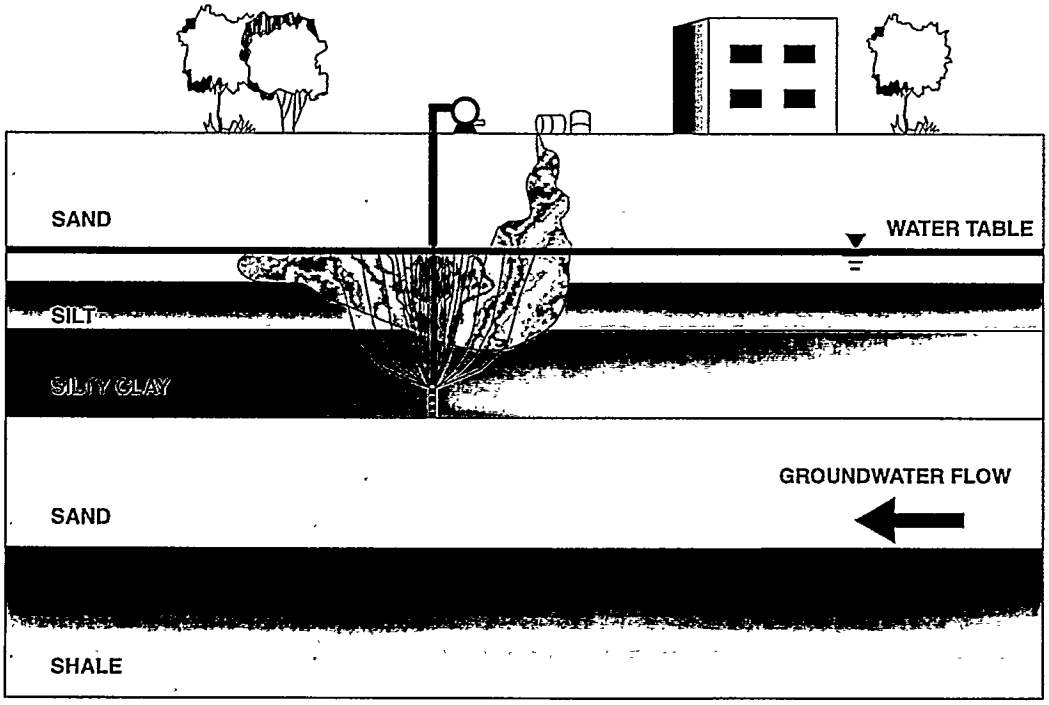
CONCEPTUAL AIR DISTRIBUTION



CHLORINATED HYDROCARBON - LAYERED FORMATION

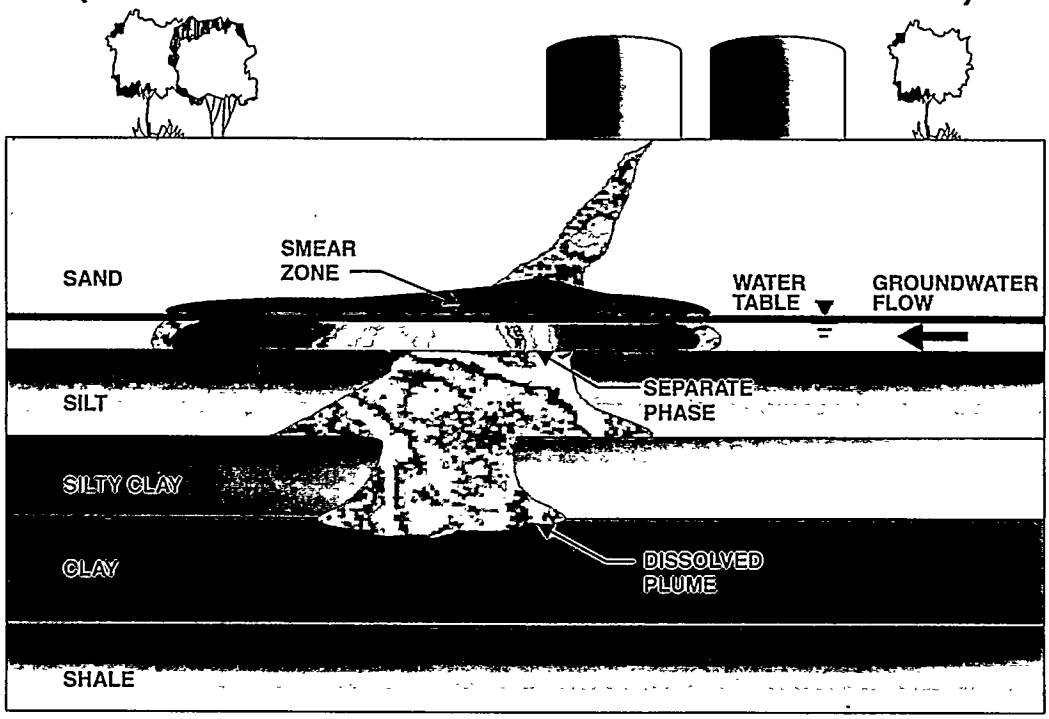


CONCEPTUAL AIR DISTRIBUTION



SCENARIO 4:

PETROLEUM HYDROCARBON - LAYERED FORMATION (DECREASING PERMEABILITY WITH DEPTH)



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively permeable materials which were deposited in discrete layers. The permeability of the layers decreases with depth. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate that the subsurface layers have the characteristics of "gravels", "sands", or "silts"

Here the water-bearing unit has been impacted by a release of petroleum hydrocarbons that are less dense than water (LNAPLs, e.g., gasoline, jet fuel, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) hydrocarbons floating on the groundwater table and/or residual hydrocarbons trapped beneath the water table in a "smear zone".

Dissolved contaminants of concern in such settings are often aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX).

EXPERIENCE - AIR SPARGING APPLICATIONS

This scenario has no case studies in the current technical literature. Results are suspected to be promising as most petroleum hydrocarbons of concern are relatively volatile and/or aerobically degradable and the geologic setting allows for air sparging of specific areas by injecting air below the impacted zone. Thus, air sparging affects removal through both volatilization and enhanced oxygenation (and subsequent biodegradation).

The effects of the site geology of this scenario on sparging are mainly favorable. The decreasing permeability of the sediments with depth would allow for the uninhibited upward movement of air. This would reduce the probability of production of "fugitive vapors" or air pocket formations. In addition, the decreasing permeabilities of the sediments with depth would inhibit vertical contamination migration.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (++)
Good physical and technical possibility and unique target.

Plume Remediation (+)
Good physical and technical possibility, but not unique.

Containment (+)
Good physical and technical possibility, but not unique.

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. However, air sparing would both be technically and physically possible and would provide a good or unique target for air sparging in this particular conceptual scenario.

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. However, air sparging would both be technically and physically possible and might provide a good or unique target for air sparging in this particular conceptual scenario.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control system. However, air sparging would both be technically and physically possible and might provide a good or unique target for air sparging in this particular conceptual scenario.

CONCERNS

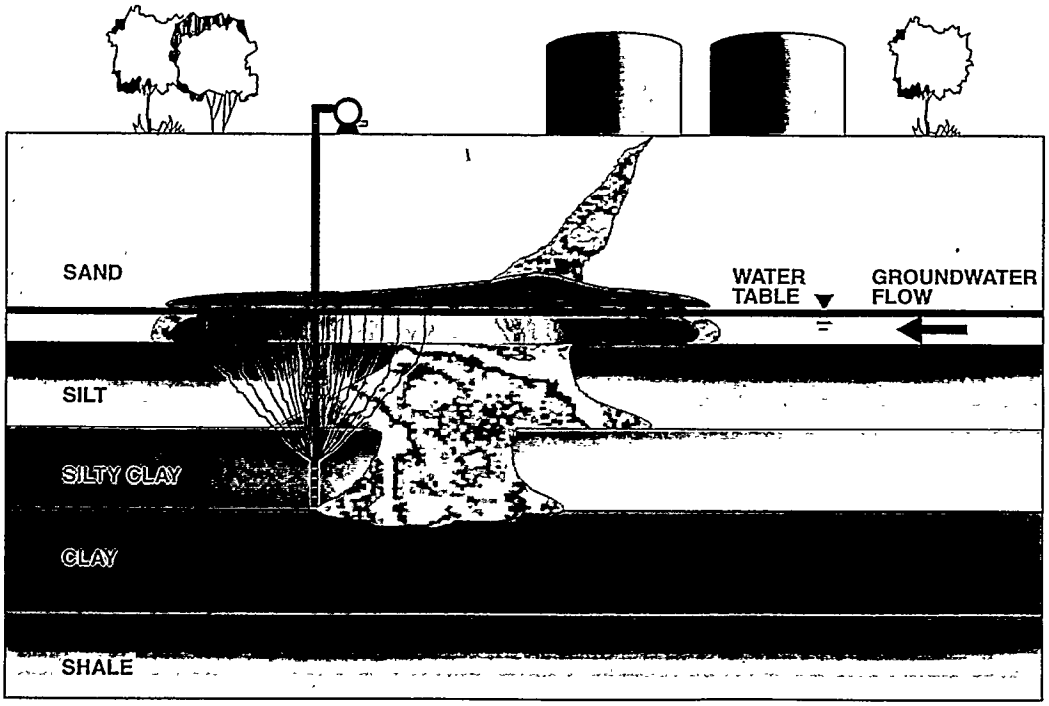
The following are issues that should be addressed by the practitioner:

a) Was the site characterization sufficiently detailed such that it is very likely that the site is true layered and that the permeability decreases with depth? Or alternately, are local heterogeneities (i.e. thin confining layers or discontinuities) present?

b) Could uncontrolled vapor migration produce safety and/or health hazards?

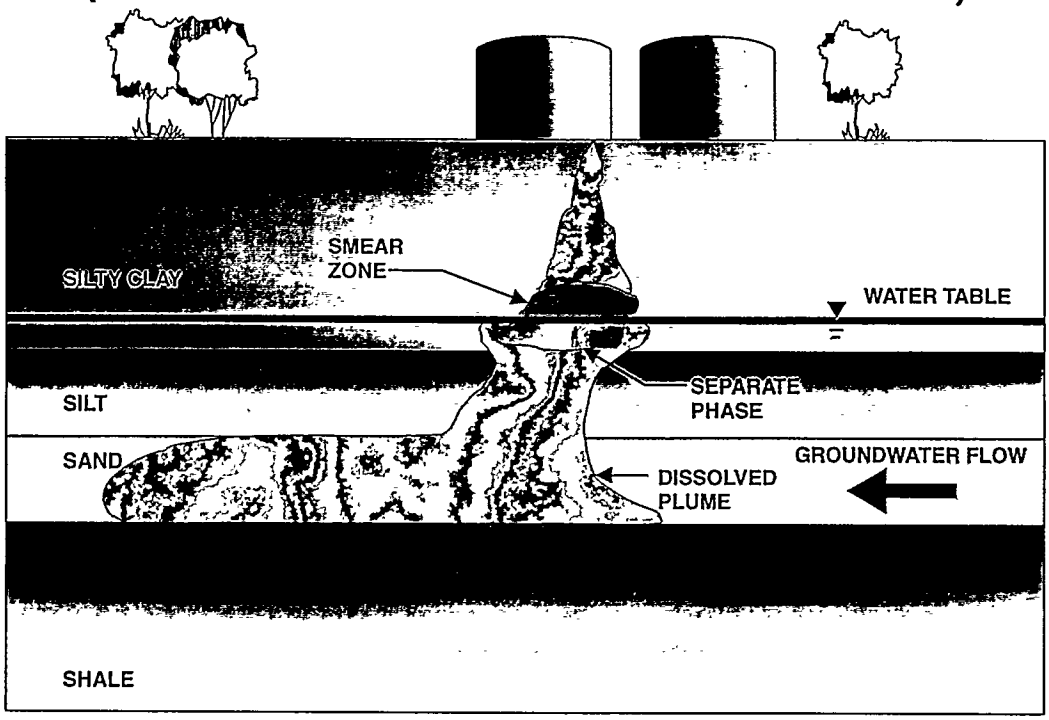
c) Does the depth to groundwater prohibit the installation of the system due to cost considerations, especially if a high density of wells is required?

CONCEPTUAL AIR DISTRIBUTION



SCENARIO 5:

PETROLEUM HYDROCARBON - LAYERED FORMATION (INCREASING PERMEABILITY WITH DEPTH)



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively permeable materials which were deposited in discrete layers. The permeability of the layers increases with depth. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate that the subsurface layers have the characteristics of "gravels", "sands", or "silts".

Here the water-bearing unit has been impacted by a release of petroleum hydrocarbons that are less dense than water (LNAPLs, e.g., gasoline, jet fuel, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) hydrocarbons floating on the groundwater table and/or residual hydrocarbons trapped beneath the water table in a "smear zone".

Dissolved contaminants of concern in such settings are often aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX).

EXPERIENCE - AIR SPARGING APPLICATIONS

This scenario has no case studies in the current technical literature. Results are suspected to be less than promising as disproportionate air flow distribution patterns are expected as the result of less permeable materials overlying permeable materials. These air flow patterns would most likely not allow for specific zones in the subsurface to be specifically targeted for remediation.

The effects of the site geology of this scenario are major. The increasing permeability of sediments with depth indicates that the dissolved plume could be much more areally extensive at depth (in the sand layer than in the overlying silts and clays). In addition, if air sparging were used to remediate this scenario, the presence of the less permeable overlying material could inhibit upward movement of injected air, cause outward, uncontrolled air movement, and allow for the creation of subsurface air pockets at the contacts between sediment layers. This could result in "fugitive vapors" appearing in undesireable locations, such as nearby subsurface structures (i.e. basements) and possibly lead to fracturing of overlying sediment of fluidization of underlying layers..

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (-)
Unknown physical or technical possibility.

Plume Remediation (-)
Unknown physical or technical possibility.

Containment (-)
Unknown physical or technical possibility.

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. Due to the difficulty of injecting and controlling sparging air into a layered system with increasing permeabilities with depth, it is not known if air sparging is a physical/technical possibility; further investigation is required.

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. Due to the difficulty of injecting and controlling sparging air into a layered system with increasing permeabilities with depth, it is not known if air sparging is a physical/technical possibility; further investigation is required.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control system. Due to the difficulty of injecting and controlling sparging air into a layered system with increasing permeabilities with depth, it is not known if air sparging is a physical/technical possibility; further investigation is required.

CONCERNS

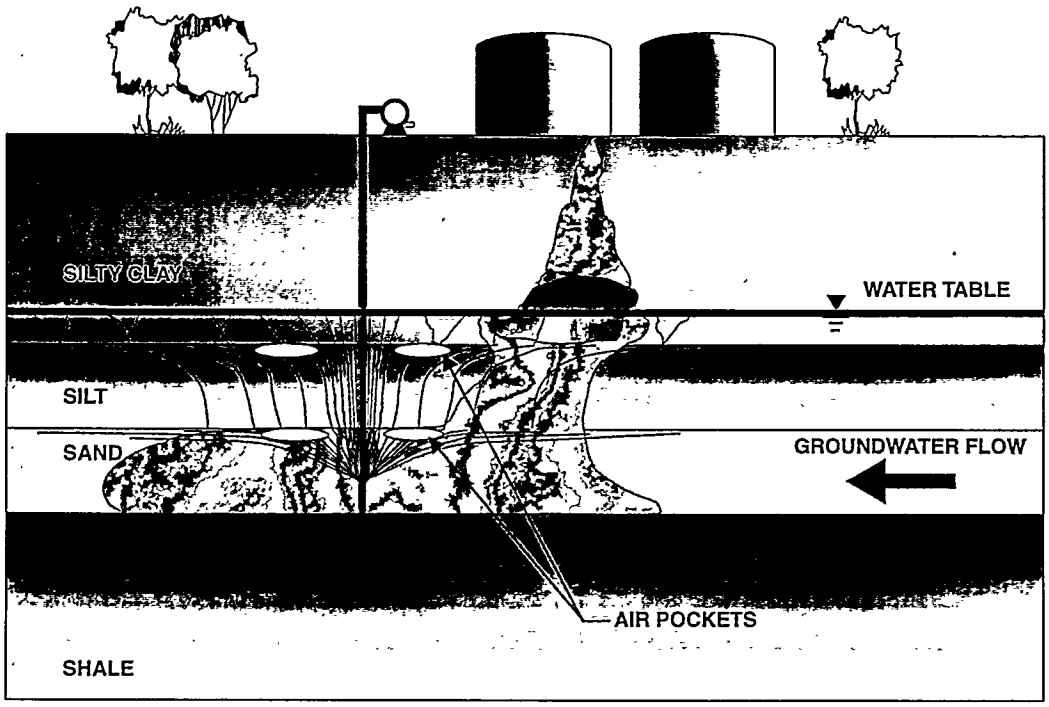
The following are issues that should be addressed by the practitioner:

a) If air sparging is employed, how will the practitioner ensure that the sparging air will be directed to the target remediation zone?

b) Could uncontrolled vapor migration, along fractures or channels of unknown orientation, produce safety and/or health hazards?

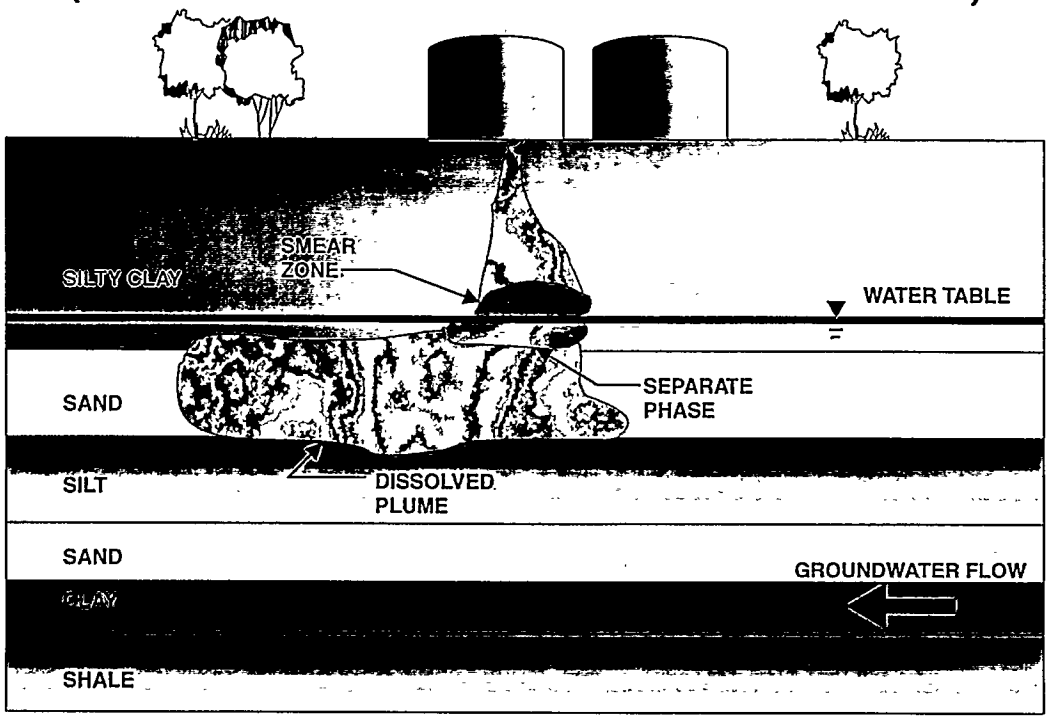
c) Is it economical to install a system?

CONCEPTUAL AIR DISTRIBUTION



SCENARIO 6:

PETROLEUM HYDROCARBON - LAYERED FORMATION (ALTERNATING PERMEABILITY WITH DEPTH)



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively permeable materials which were deposited in discreet layers. The permeability of the layers alternates with depth. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross sections should indicate that the subsurface layers have the characteristics of "gravels", "sands", or "silts".

Here the water bearing unit has been impacted by a release of petroleum hydrocarbons that are less dense than water (LNAPLs, e.g., gasoline, jet fuel, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) hydrocarbons floating on the groundwater table and/or residual hydrocarbons trapped beneath the water table in a "smear zone".

Dissolved contaminants of concern in such settings are often aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX).

EXPERIENCE - AIR SPARGING APPLICATIONS

This scenario has no case studies in the current technical literature. Results are suspected to be less than promising as disproportionate air flow distribution patterns are expected as the result of less permeable materials overlying permeable materials. These air flow patterns would most likely not allow for specific zones in the subsurface to be specifically targeted for remediation.

The effects of site geology on air flow distribution will be noticeable and crucial factor in this scenario. Obviously, one way in which site geology would impact air sparging as a remediation tool would be that the aerial extent of contamination could vary greatly depending sediment layer type. For example, in this scenario, the extent of dissolved phase in the upper sand layer would be much more extensive that the extent in the silt layer, due to groundwater flow/permeability differences.

Another major impact that the alternating sediment layers would have on the practical use of air sparging would be the effects on air distribution. In this scenario, if air sparging was used in the upper sand layer, the much lower permeability of the overlying silty clay would inhibit upward air movement, cause outward, uncontrolled air movement and allow for the creation of air pockets. This could result in "fugitive vapors", appearing in unfavorable locations (i.e. basements), if the vapors follow possible preferential pathways.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (-)
Unknown physical or technical possibility

Plume Remediation (-)
Unknown physical or technical possibility

Containment (-)
Unknown physical or technical possibility

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. Due to the difficulty of injecting and controlling sparging air into a layered system with increasing permeabilities with depth, it is not known if air sparging is a physical/technical possibility; further investigation is required. However, this scenario does not appear to be appropriate for the application of air sparging.

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. Due to the difficulty of injecting and controlling sparging air into a layered system with increasing permeabilities with depth, it is not known if air sparging is a physical/technical possibility; further investigation is required. However, this scenario does not appear to be appropriate for the application of air sparging.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control system. Due to the difficulty of injecting and controlling sparging air into a layered system with increasing permeabilities with depth, it is not known if air sparging is a physical/technical possibility; further investigation is required. However, this scenario does not appear to be appropriate for the application of air sparging.

CONCERNS

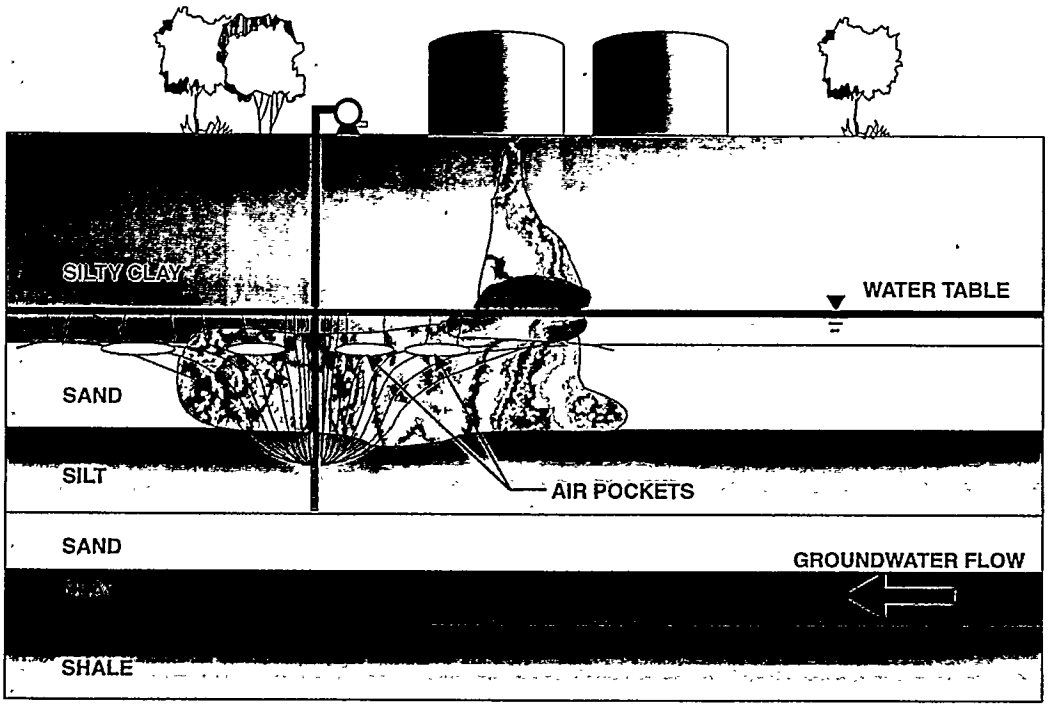
The following are issues that should be addressed by the practitioner:

a) If air sparging is employed, how will the practitioner ensure that the sparging air will be directed to the target remediation zone, and not other undesirable areas?

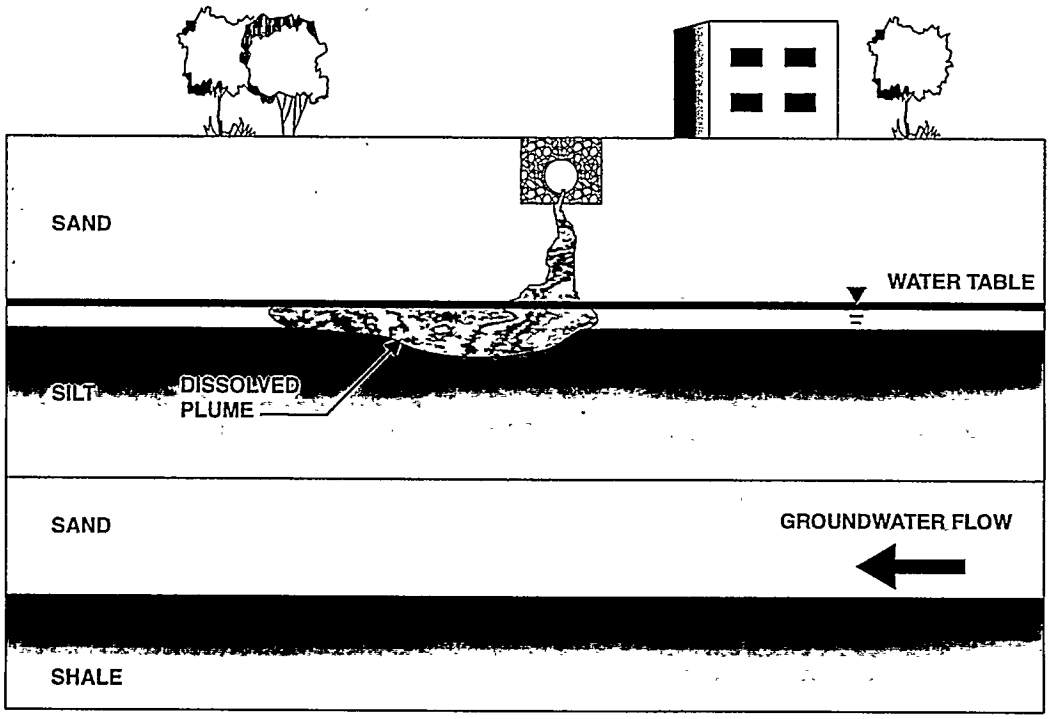
b) Could uncontrolled vapor migration, along preferential pathways (unknown fractures or channels) produce safety and/or health hazards?

c) Is it economical to install a system?

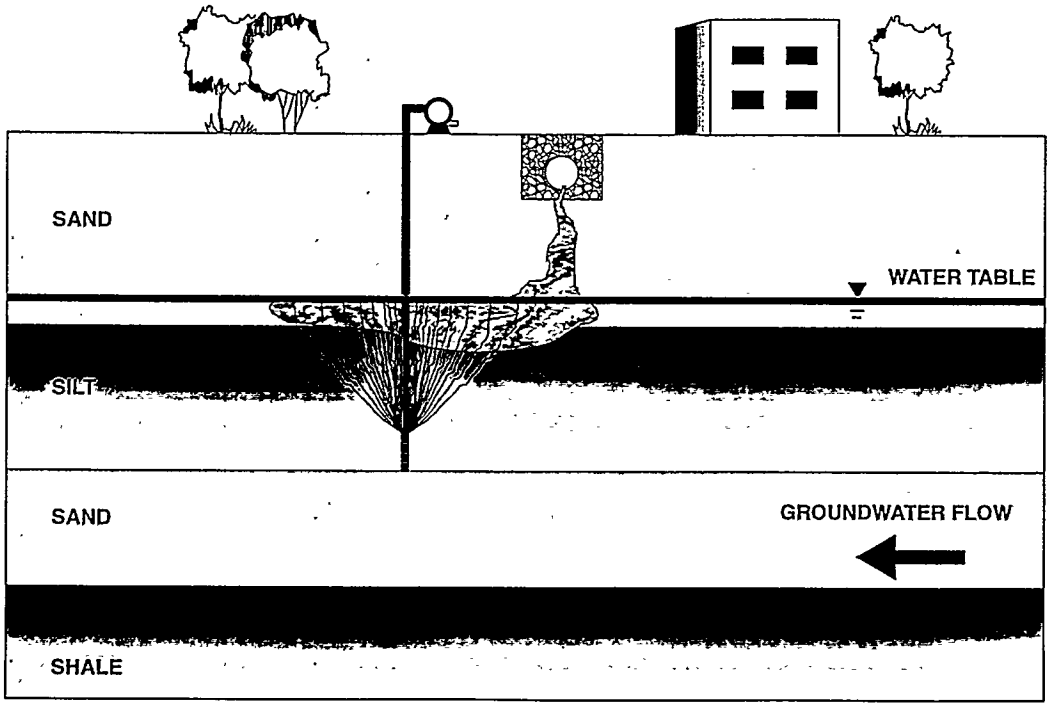
CONCEPTUAL AIR DISTRIBUTION



PETROLEUM HYDROCARBON - LAYERED FORMATION

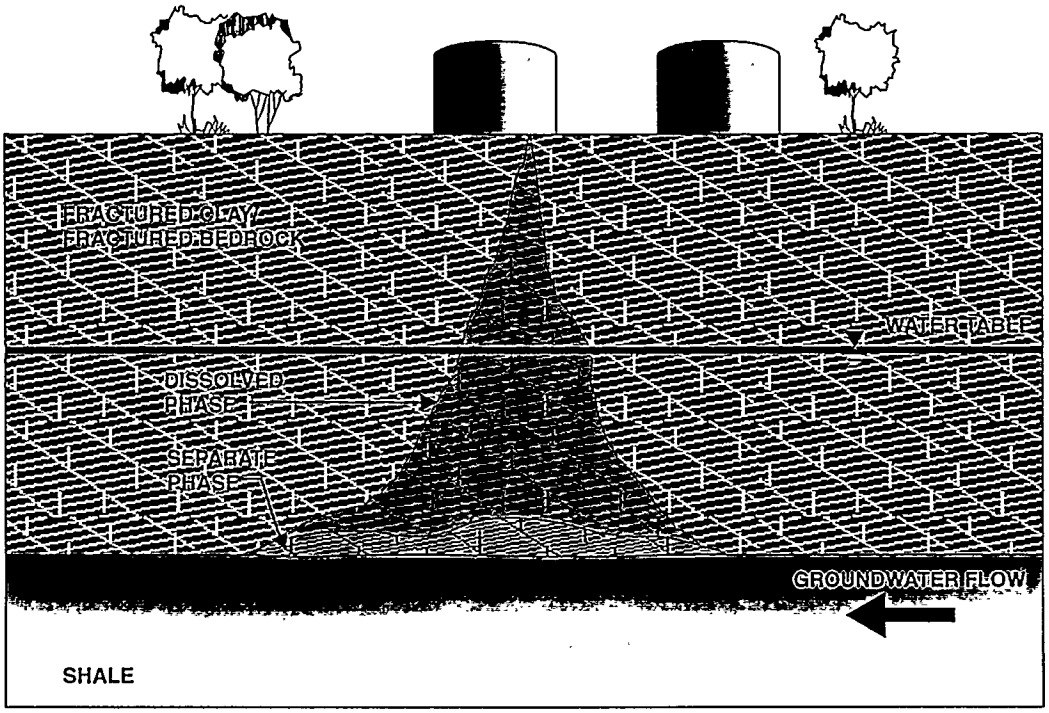


CONCEPTUAL AIR DISTRIBUTION



SCENARIO 7:

CHLORINATED HYDROCARBON - FRACTURED/TIGHT FORMATION



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by clay (or other fine grained soils) or bedrock. For the zone of interest (the zone to be impacted by potential remedial activities), boring logs or geologic cross-sections should indicate if the bedrock or clay is fractured or unfractured.

Here the water-bearing unit has been impacted by a release of chlorinated hydrocarbons that are denser than water (DNAPLs, e.g., trichloroethene, tetrachloroethene, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) chlorinated hydrocarbons which reside in the fractures, at a confining unit, or within the pore space of the matrix.

Dissolved contaminants of concern in such settings are often trichloroethene, tetrachloroethene and/or vinyl chloride.

EXPERIENCE - AIR SPARGING APPLICATIONS

This scenario has no case studies in the current technical literature. Although chlorinated hydrocarbons may be volatilized, this is a scenario for which practitioners can not confidently anticipate air distribution following injection into the aquifer. As depicted above, the air distribution patterns are controlled by the location, orientation, number, and size of the fractures.

The absence of fractures in the subsurface media at this site would ensure that sparging could not be used, since there would be no practical way to inject air into the formation, without artificial fracturing. The presence of fractures, in either the bedrock or clay, could allow for air movement through preferential pathways, which may or may not contain chlorinated solvents, In addition, if the air injected did volatilize chlorinated solvents, the movement of the vapors could become uncontrolled, and as such may appear in distant and undesirable locations (i.e. basements).

The characteristics of the media underlying this site make sparging very unattractive as a remedial option. Chlorinated solvents present in the fractures could migrate in any direction following the fracture traces/orientations. Due to this effect of geology, it would be very difficult to determine the extent, let alone mitigate the presence of the chlorinated solvents in this media with air sparging.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (--)	Plume Remediation (--)	Containment (--)
Not physically or technically possible.	Not physically or technically possible.	Not physically or technically possible.

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. Due to the inherent uncertainty of air flow caused by the fractured media (or nonexistent air flow in unfractured media) and the concern for uncontrolled chlorinated hydrocarbons migration, air sparging is not considered to be a viable remedial technology for source zones.

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. Due to the inherent uncertainty of air flow in the fractured media (or nonexistent air flow in unfractured media) and the concern for uncontrolled chlorinated hydrocarbons migration, air sparging is not considered to be a viable remedial technology for dissolved plumes.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control systems. Due to the inherent uncertainty of air flow in the fractured media (or nonexistent air flow in unfractured media) and the concern for uncontrolled chlorinated hydrocarbons migration, air sparging is not considered to be a viable remedial technology for barrier control.

CONCERNS

The following are issues that should be addressed by the practitioner:

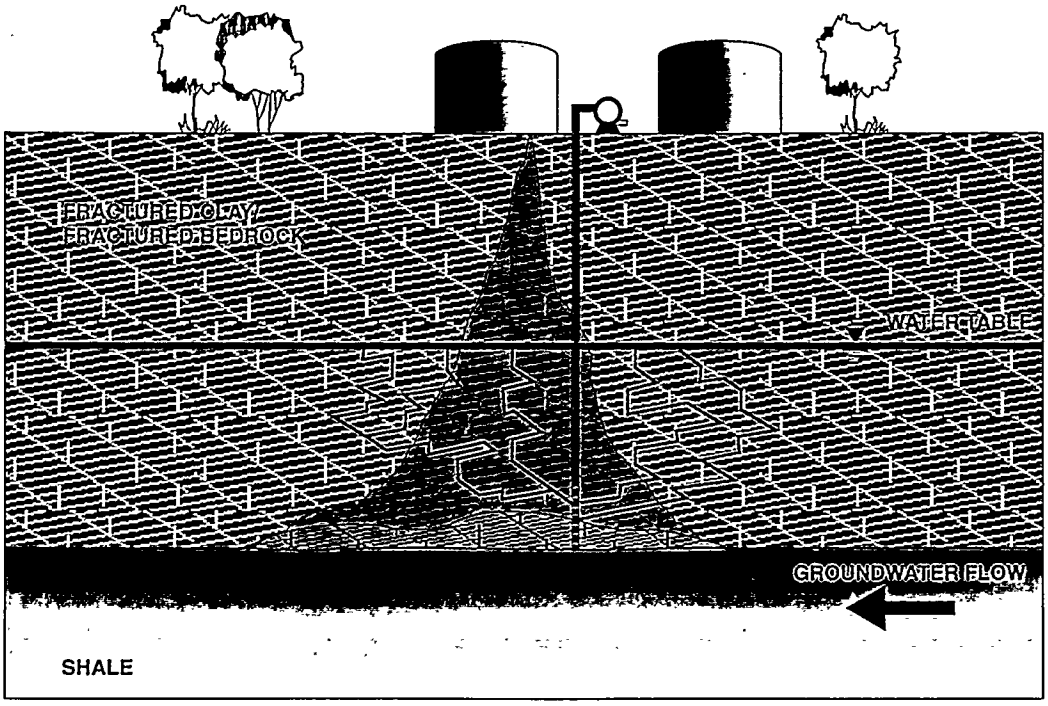
a) If air sparging is employed, how will the practitioner ensure that the sparging air will be directed to the target remediation zone?

b) If a source area is targeted, how will the practitioner insure that sparging does not spread DNAPL?

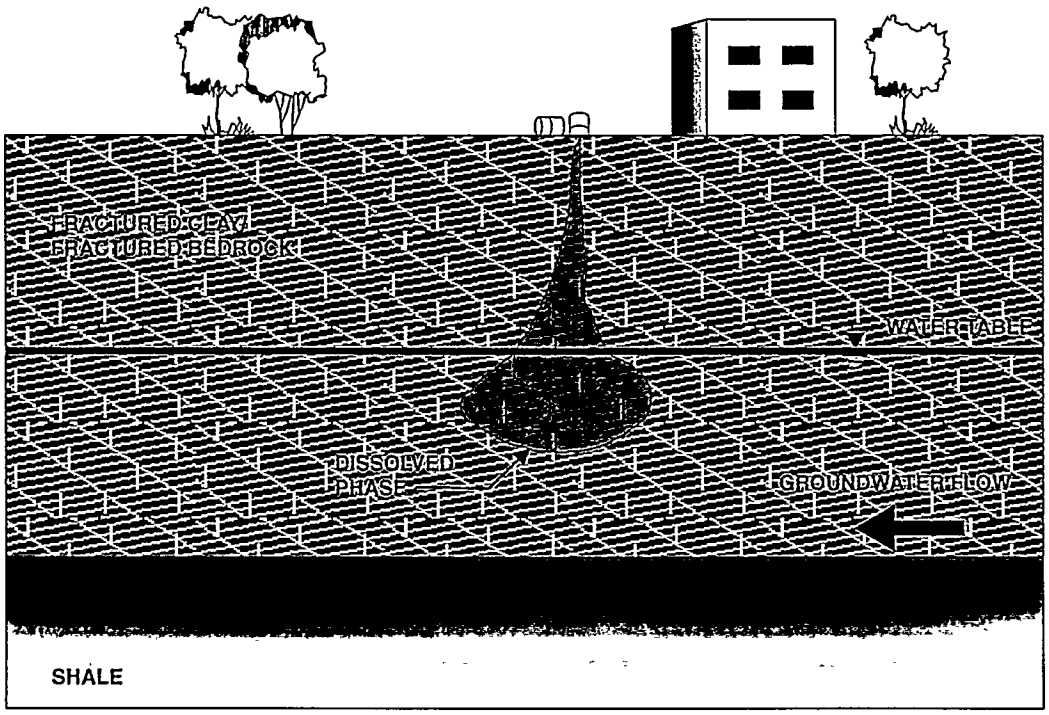
c) Could uncontrolled vapor migration to undesirable locations (i.e. basements) produce safety and/or health hazardous?

d) Is it economical to install a system, especially if remediation targets are at great depths or if artificial fracturing is required?

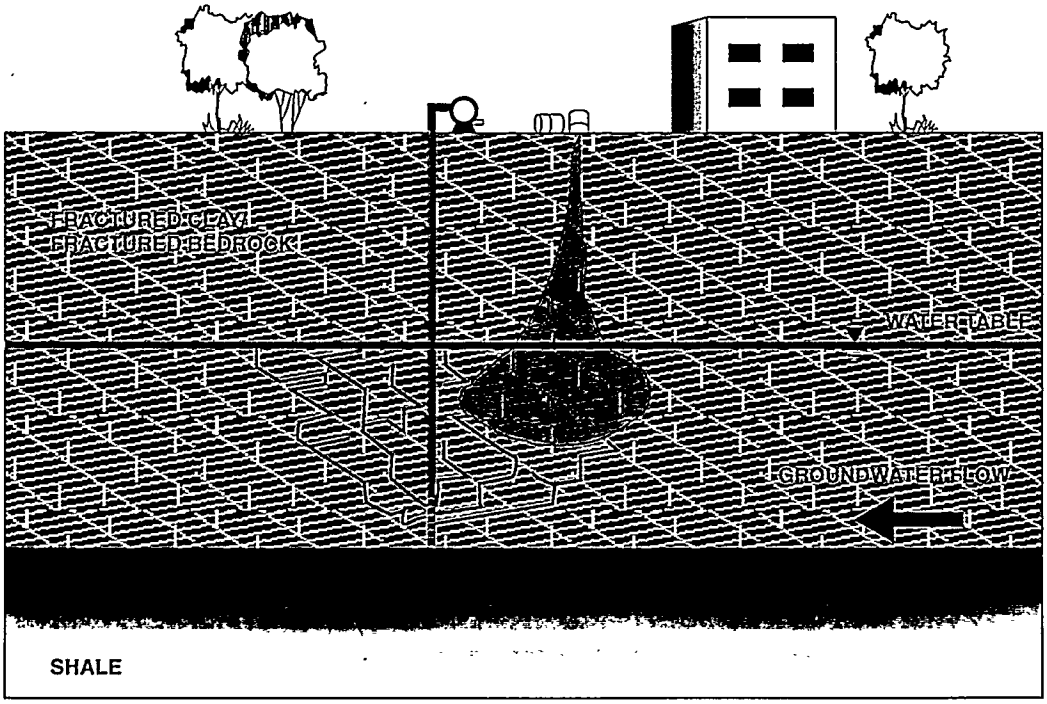
CONCEPTUAL AIR DISTRIBUTION



CHLORINATED HYDROCARBON - FRACTURED/TIGHT FORMATION

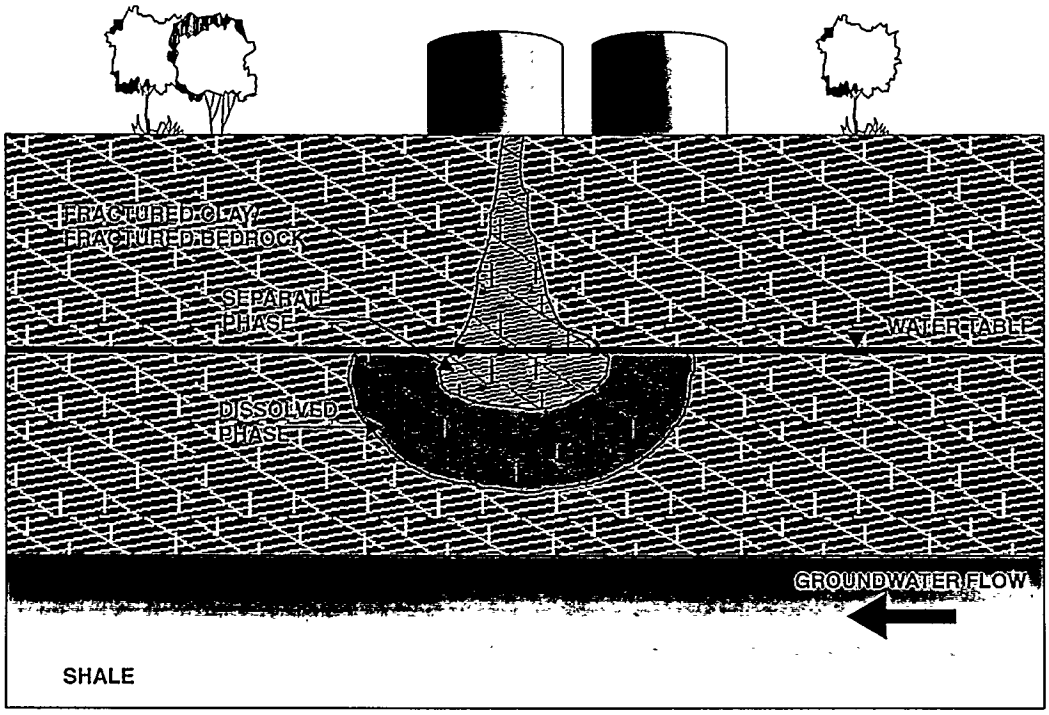


CONCEPTUAL AIR DISTRIBUTION



SCENARIO 8:

PETROLEUM HYDROCARBON - FRACTURED/TIGHT FORMATION



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by clay (or other fine grained soils) or bedrock. For the zone of interest (the zone to be impacted by potential remedial activities), boring logs or geologic cross-sections should indicate whether the bedrock or clay is fractured or unfractured.

Here the water-bearing unit has been impacted by a release of petroleum hydrocarbons that are less dense than water (LNAPLs, e.g., gasoline, jet fuel, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) hydrocarbons floating on the groundwater table and/or residual hydrocarbons trapped beneath the water table in a "smear zone".

Dissolved contaminants of concern in such settings are often aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX).

EXPERIENCE - AIR SPARGING APPLICATIONS

This exact scenario has no case studies in the current technical literature. However, limited sucess has been reported using air sparging to remediate naturally fractured clay, glacial tills and saprolite matricies (Fairbanks, P.E., etal., 1993 and Aelion, C.M., 1995). Research and large scale physical modeling results suggest that air sparging may be appropriate in sites with massive clays or tills, with natural fracturing (Johnson, R.L., 1993).

Although petroleum hydrocarbons are relatively volatile and/or aerobically degradable, in this scenario the practitioners cannot confidently anticipate air distribution patterns, following injection into the aquifer. As depicted above, the air distribution patterns are controlled by the presence, number, size, and orientation of the fractures.

The absence of fractures ensures that air sparging cannot be used, since there would be no practical way to inject air into the formation, without artificial fracturing. The presence of fractures in the subsurface media also has major effects on the usage of air sparging. The presence and orientation of the fractures could make it very difficult to limit air injection to only the impacted zones. In addition, since fractures are difficult to trace or follow, the injected air could appear in distant and undesirable locations, such as subsurface structures (i.e. basements).

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (--)	Plume Remediation (--)	Containment (--)
Not technically or physically possible.	Not technically or physically possible.	Not technically or physically possible.

SOURCE ZONES

No data exist yet in the literature documenting the effectiveness of air sparging on source zones. Due to the inherent uncertainty of air flow due to the fractured media, air sparging is not considered to be a viable remedial technology for source zones in this exact matrix. However, research and large scale physical modeling results suggest that air sparging may be appropriate in sites with massive clays or tills, with natural fracturing (Johnson, R.L., 1993).

DISSOLVED PLUMES

No data exist yet in the literature documenting the effectiveness of air sparging on dissolved plumes. Due to the inherent uncertainty of air flow due to the fractured media, air sparging is not considered to be a viable remedial technology for dissolved plumes.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control systems. Due to the inherent uncertainty of air flow due to the fractured media, air sparging is not considered to be a viable remedial technology for barrier control.

CONCERNS

The following are issues that should be addressed by the practitioner:

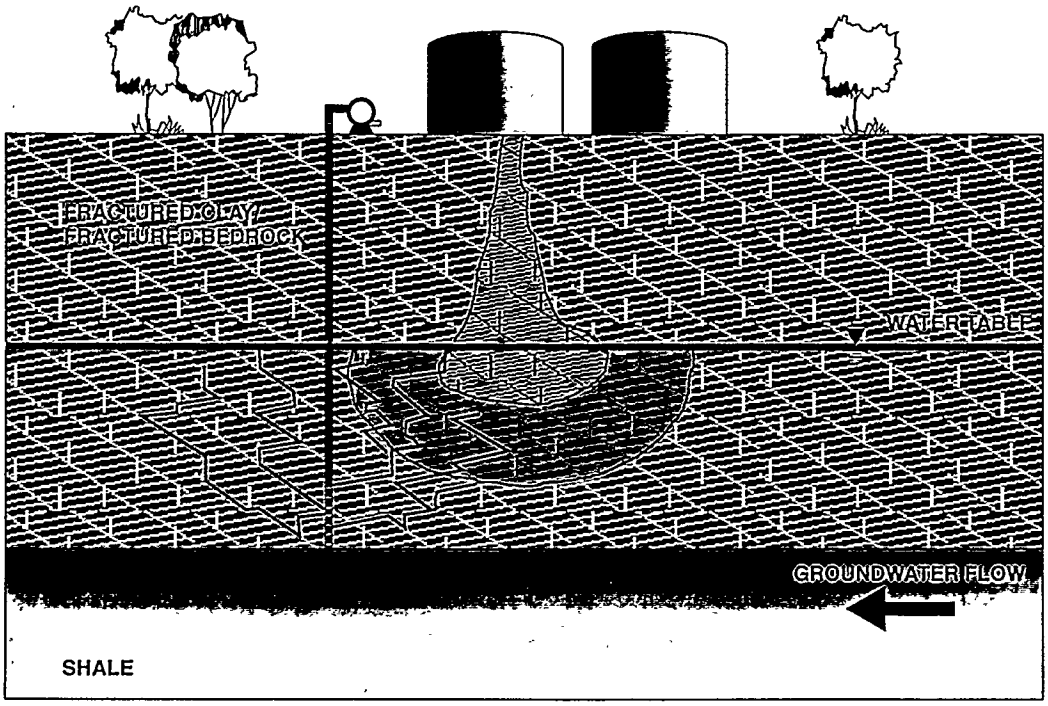
a) If air sparging is employed, how will the practitioner ensure that the sparging air will be directed to the target remediation zone?

b) If the remediation target is a source zone, how will the practitioner insure that sparging does not spread LNAPL?

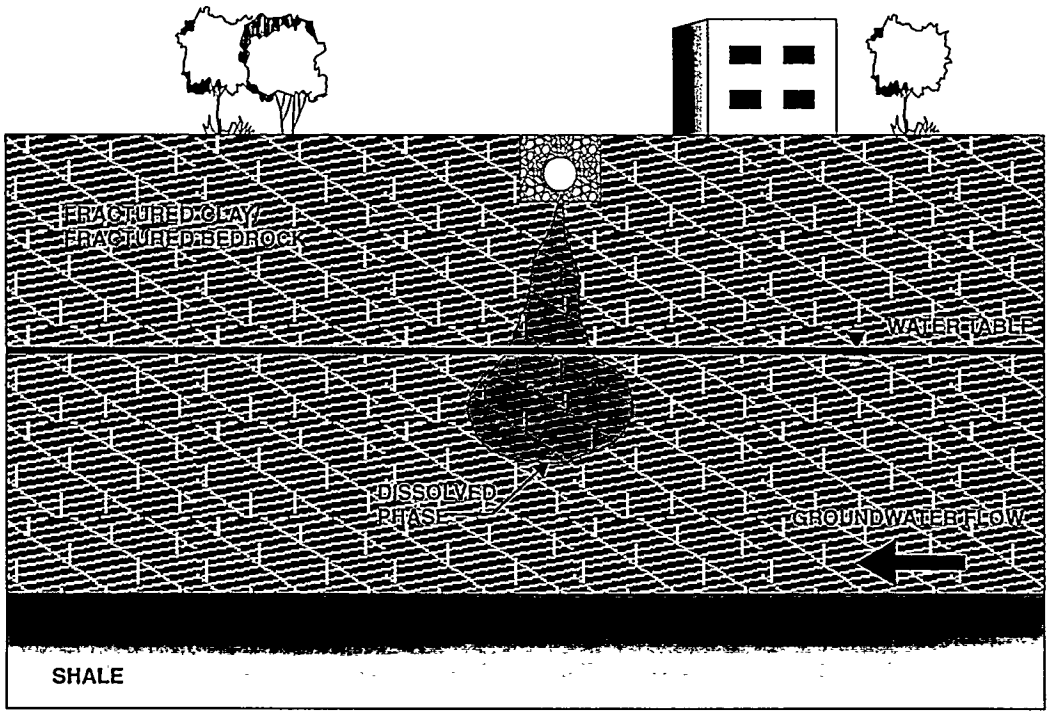
c) Could uncontrolled vapor migration, due to unknown fracture distribution and orientations, produce safety and/or health hazardous?

d) Is it economical to install a system, especially in bedrock or unfractured sediment which may require artificial fracturing?

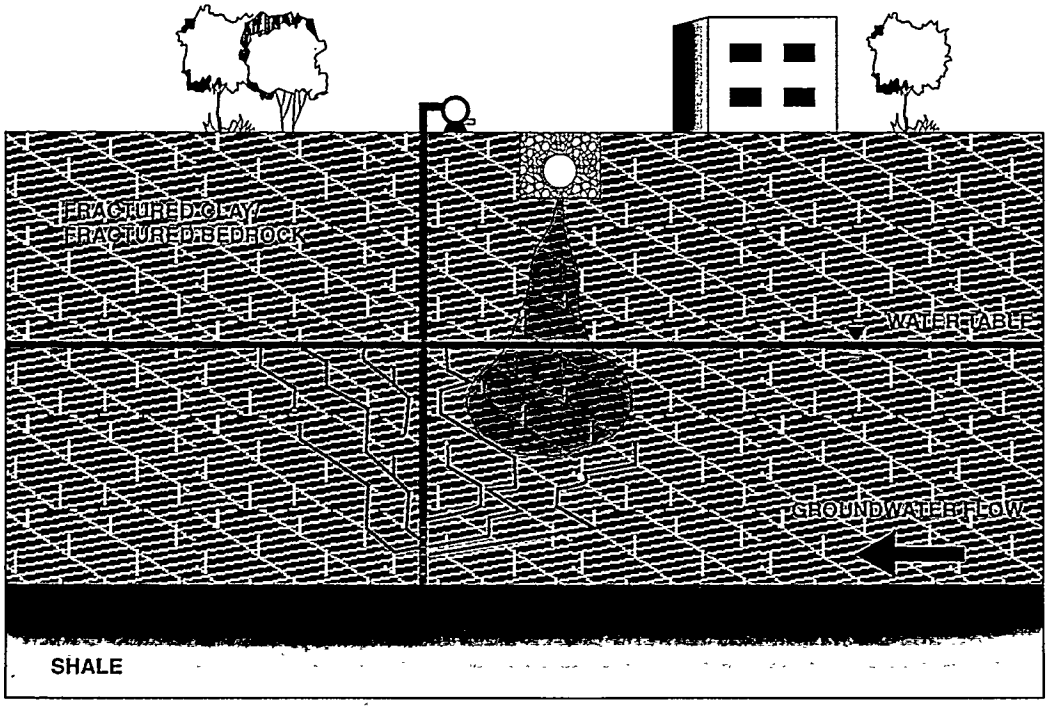
CONCEPTUAL AIR DISTRIBUTION



PETROLEUM HYDROCARBON - FRACTURED/TIGHT FORMATION

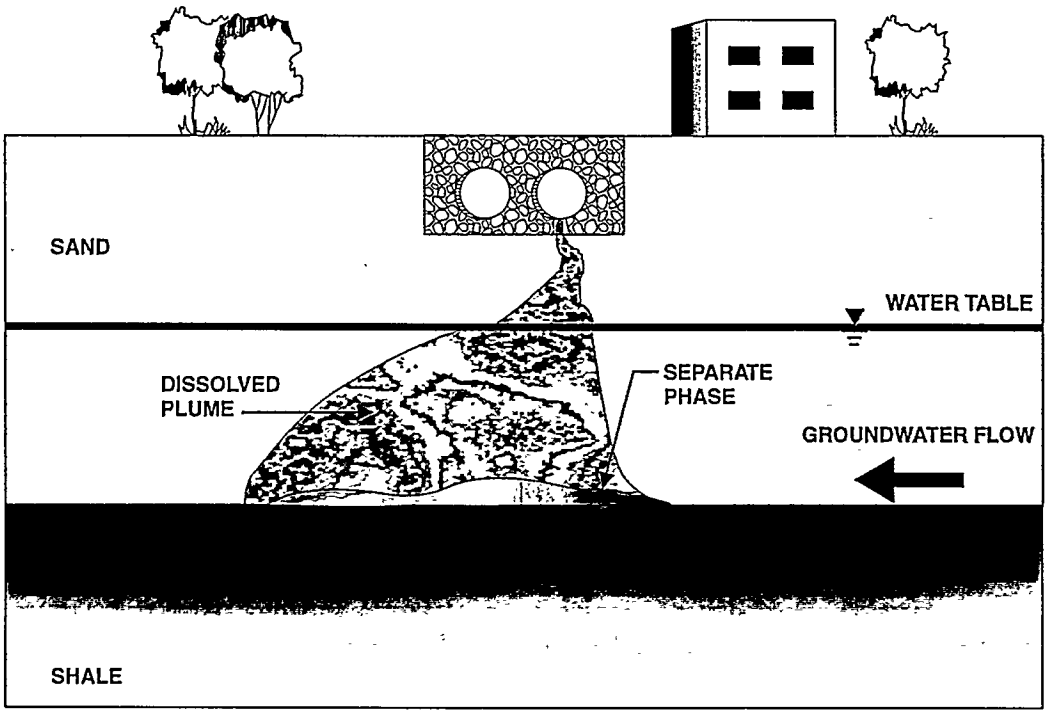


CONCEPTUAL AIR DISTRIBUTION



SCENARIO 9:

CHLORINATED HYDROCARBON - HOMOGENEOUS FORMATION



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively homogeneous and permeable materials. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate uniformly distributed "gravels", "sands", or "silts".

Here the water-bearing unit has been impacted by a release of chlorinated hydrocarbons that are denser than water (DNAPLs e.g., trichloroethene, tetrachloroethene, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) chlorinated hydrocarbons which have migrated downward and collected at a confining layer.

Typical dissolved contaminants of concern in such settings are trichloroethene, tetrachloroethene, and/or vinyl chloride.

EXPERIENCE - AIR SPARGING APPLICATIONS

This is a scenario with some case studies reported in the current technical literature. Results are promising as most chlorinated hydrocarbons are relatively volatile. Biodegradation may also contribute to contaminant removal, but typically rates are very low.

This is also the one scenario for which practitioners can confidently project the pattern of air distribution, following injection into the aquifer. As depicted above, the air distribution is expected to be roughly symmetrical about the injection point, regardless of which sediment type present. The treatment zone radius will approximately equal the depth below groundwater to the top of the injection well screen, within certain limitations (i.e. if depth exceeds 10 to 15 feet, this projection tends to be less accurate). Readers are referred to the field study of Lundegard (1994), where the air flow distribution was measured to extend about 7 feet away from an air injection point located approximately 10 feet below the water table.

The effects of site geology on the air flow will be noticeable in the different sediments discussed in this scenario. Generally, the more fine-grained the sediment, the greater the injection pressure (and therefore less air volume) required to obtain and maintain the optimal radius of air distribution.

The other effects of site geology on the use of air sparging would tend to be favorable. Since the sediments underlying the site are homogeneous, the formation of air pockets and uncontrolled vapor migration would not be of great concern.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (-)
Unknown technical or physical possibility

Plume Remediation (+)
Possibly a good physical or technical possibility, but not unique.

Contaminant (+)
Possibly a good physical or technical possibility, but not unique.

SOURCE ZONES

Although practitioners are confident that they can anticipate air flow in a homogeneous setting, the difficulty of injecting air below the source limits the effectiveness of air sparging in this case. Further, the possible spread of DNAPL to areas previously not contaminated (e.g. underlying aquifers, especially if confining layers are not extensive) is a potential concern.

DISSOLVED PLUMES

Limited data suggest that air sparging would be both technically and physically possible and might provide a good or unique target for air sparging in this particular conceptual scenario. Demonstration projects at Savannah River provide examples of case histories in which air sparging enjoyed success in remediating heavily contaminated chlorinated hydrocarbon plumes (Looney, etal., 1991).

BARRIER CONTROL SETTINGS

Limited data suggest that air sparging would be both technically and physically possible and might provide a good or unique target for air sparging in this particular conceptual scenario (Pankow, etal., 1993).

CONCERNS

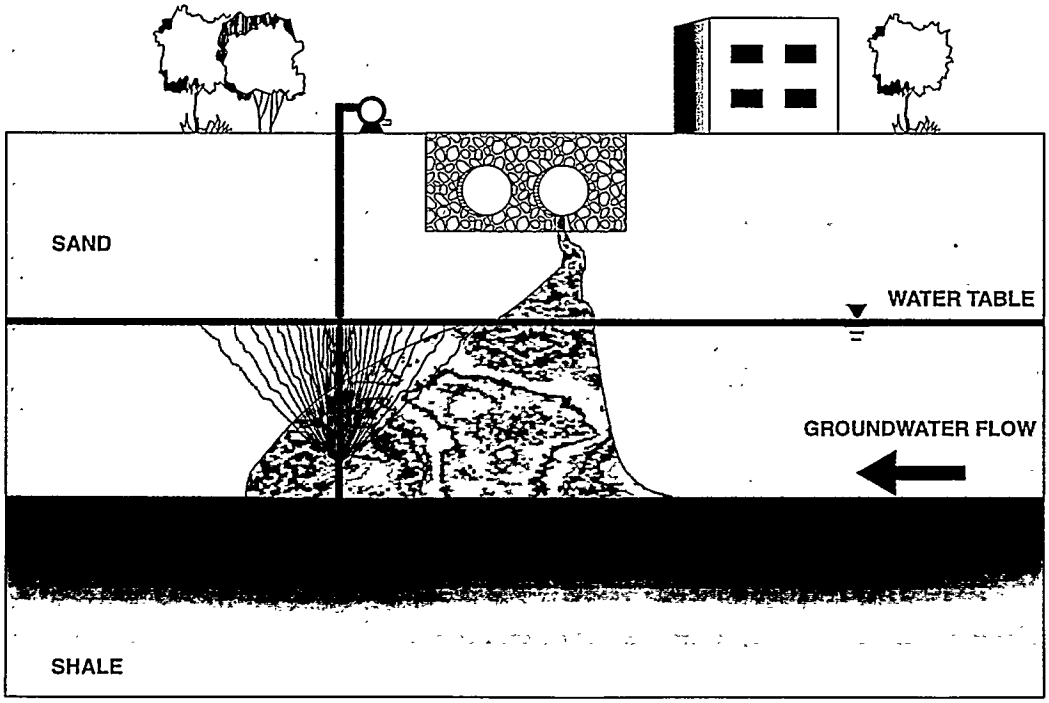
The following are issues that should be addressed by the practitioner:

a) Was the site characterization sufficiently detailed such that it is very likely that the site is truly "homogeneous"? Or, alternately, are local heterogeneities (i.e. thin confining layers or discontinuities, etc) present?

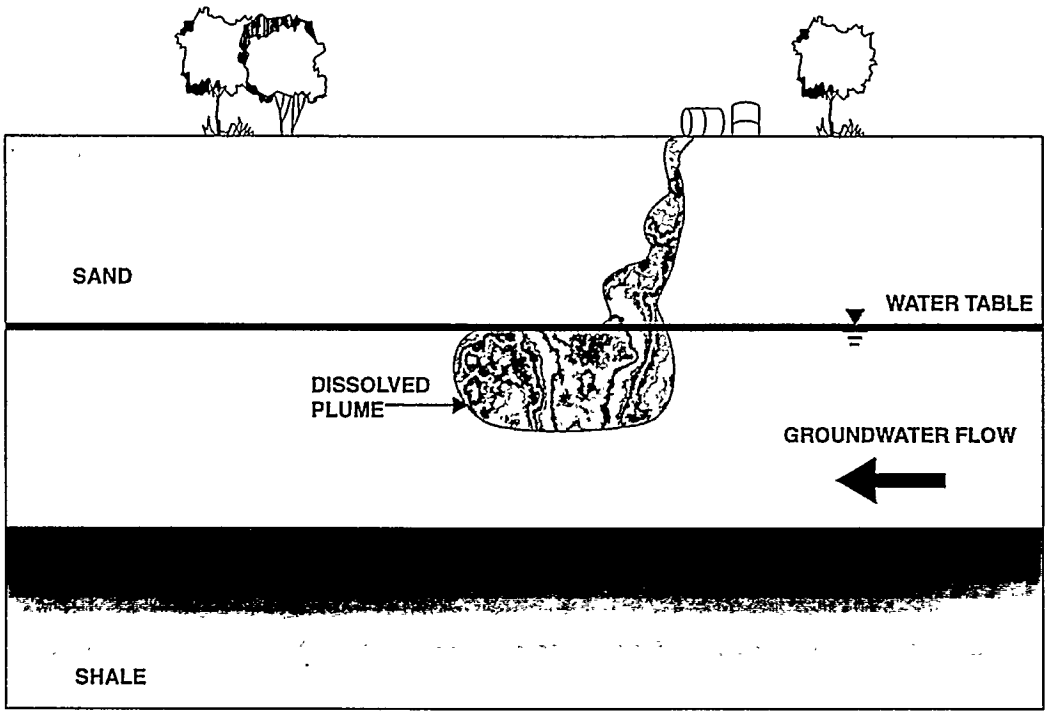
b) Could uncontrolled vapor migration produce safety and/or health hazards?

c) Is it economical to install a system? Typically, many air sparging wells may be required. If the DNAPL pool or resulting plumes are very deep (>50 feet) costs will likely become prohibitive.

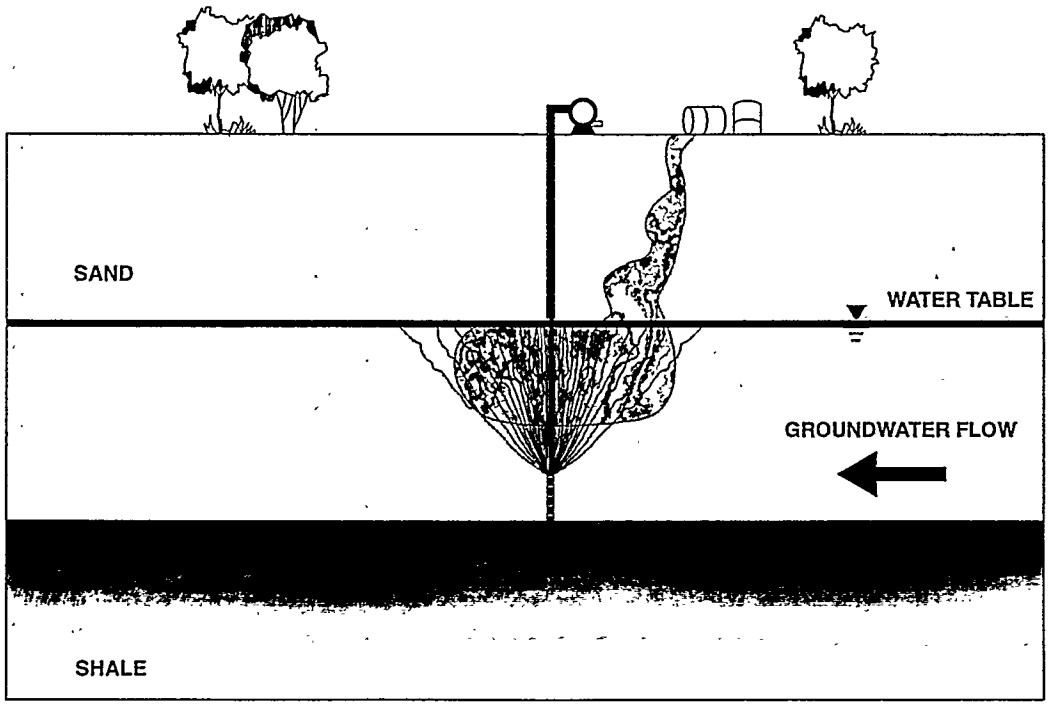
CONCEPTUAL AIR DISTRIBUTION



CHLORINATED HYDROCARBON - HOMOGENEOUS FORMATION

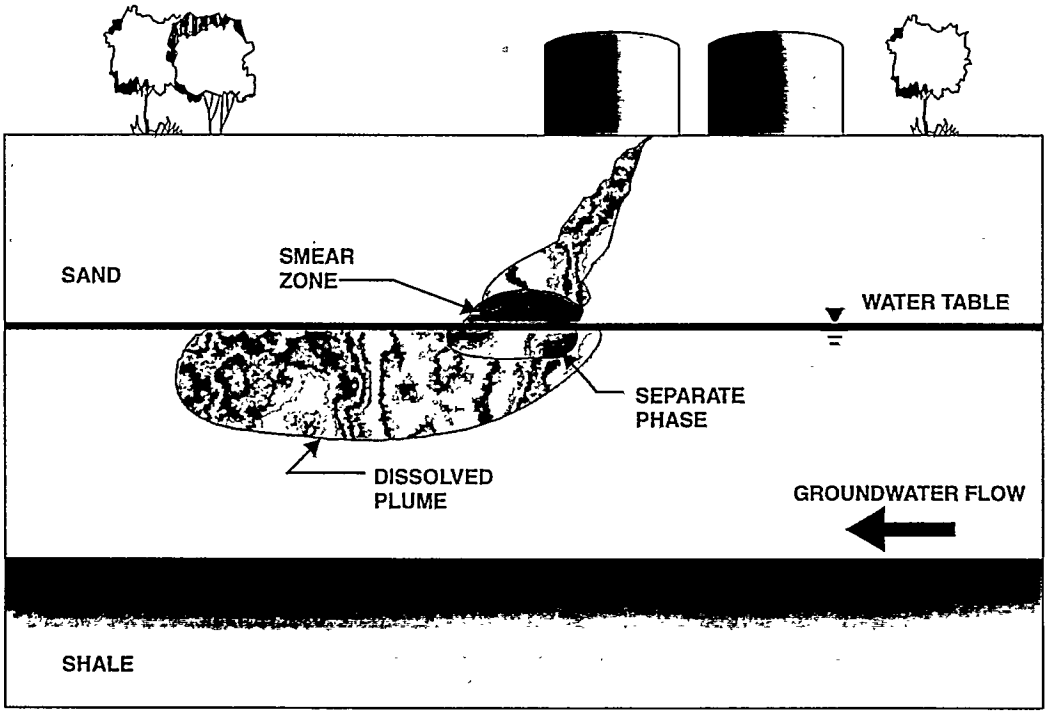


CONCEPTUAL AIR DISTRIBUTION



SCENARIO 10:

PETROLEUM HYDROCARBON - HOMOGENEOUS FORMATION



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively homogeneous and permeable materials. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate uniformly distributed "gravels", "sands", or "silts".

Here the water-bearing unit has been impacted by a release of petroleum hydrocarbons that are less dense than water (LNAPLs, e.g., gasoline, jet fuel, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) hydrocarbons floating on the groundwater table and/or residual hydrocarbons trapped beneath the water table in a "smear zone".

Dissolved contaminants of concern in such settings are often aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX).

EXPERIENCE - AIR SPARGING APPLICATIONS

This is the scenario most commonly associated with case studies reported in the current technical literature. Results are promising as most petroleum hydrocarbons of concern are relatively volatile and/or aerobically degradable. Thus, air sparging can affect removal through both volatilization and enhanced oxygenation (and subsequently biodegradation).

This is also the one scenario for which practitioners can more confidently project the pattern of air distrbuition following injection into the aquifer. As depicted above, the air distribution is expected to be roughly symmetrical about the injection point, regardless of the sediment type present. The treatment zone radius will approximately equal the depth below groundwater to the top of the injection well screen, within certain limitations (i.e. if depth exceeds 10 to 15 feet, this projection tends to be less accurate). Readers are referred to the field study of Lundegard (1994), where the air flow distribution was measured to extend about 7 feet away from an air injection point located approximately 10 feet below the water table.

The effects of site geology on the air flow will be noticeable in the different sediments discussed in this scenario. Generally, the more fine-grained the sediment, the greater the injection pressure (and therefore less air volume) required to maintain the optimal radius of air distribution.

Other effects of site geology would likely be favorable. Since the scenario indicates that geology is homogeneous, uncontrolled vapor migration and formation of air pockets would not be a major concern.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (++)	Plume Remediation (+)	Containment (+)
Good physical/technical possibility, a unique target	Good physical/technical possibility, but not unique.	Good physical/technical possibility, but not unique.

SOURCE ZONES

Limited data available to date suggests that it is possible to achieve source zone remediation to the degree that dissolved concentrations may be reduced from approximately 10 mg/L to 0.01-0.10 mg/L. Few, if any, case studies report reducing source zone dissolved concentrations to levels less than 0.01 mg/L. To achieve removal to target levels below these concentrations, it will probably be more cost-effective to allow natural attenuation processes to complete the remediation. The introduction of air into the capillary fringe and vadose zone may also enhance national biodegradation via bioventing.

DISSOLVED PLUMES

Limited data available to-date suggests that properly designed in-situ air sparging systems may quickly (less than 1 year) remediate dissolved hydrocarbon plumes. Others contend that, once a source zone is removed, natural attenuation processes will rapidly and more cost-effectively remediate the dissolved petroleum hydrocarbons. Caution must be used if practitioners planning to use air sparging for very large plume areas; due to density of sparge point considerations, costs may become excessive, especially if compared with other technologies.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control systems. Practitioners believe, however, that air sparging migration barriers are likely to be effective, as air sparging seems to be effective at remediating dissolved plumes, the air flow distribution is easily characterized and systems can be designed with more confidence than in any other geologic setting. However, due to the relative small size of typical treatment zone radii, critics suggest that the process may prove to be economical only in shallow groundwater settings given that a high linear density of wells will be necessary (approximately 20 foot spacings).

CONCERNS

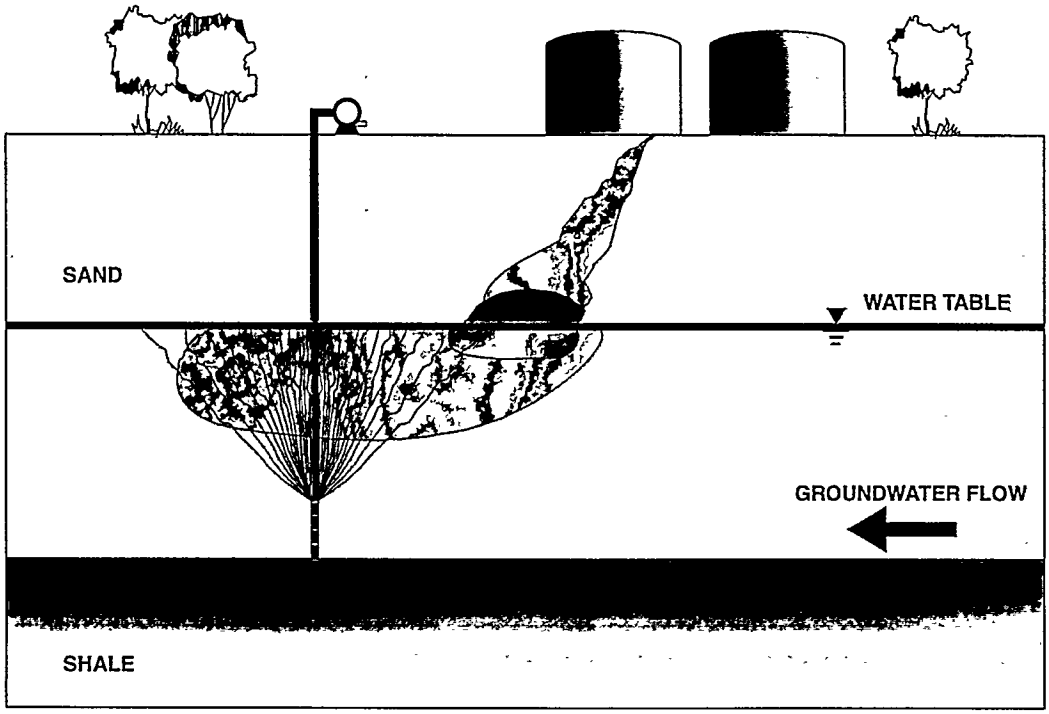
The following are issues that should be addressed by the practitioner:

a) Was the site characterization sufficiently detailed such that it is very likely that the site is truly "homogeneous"? Or alternately, are the local heterogeneities (i.e. thin confining layers which can render sparging ineffective) present?

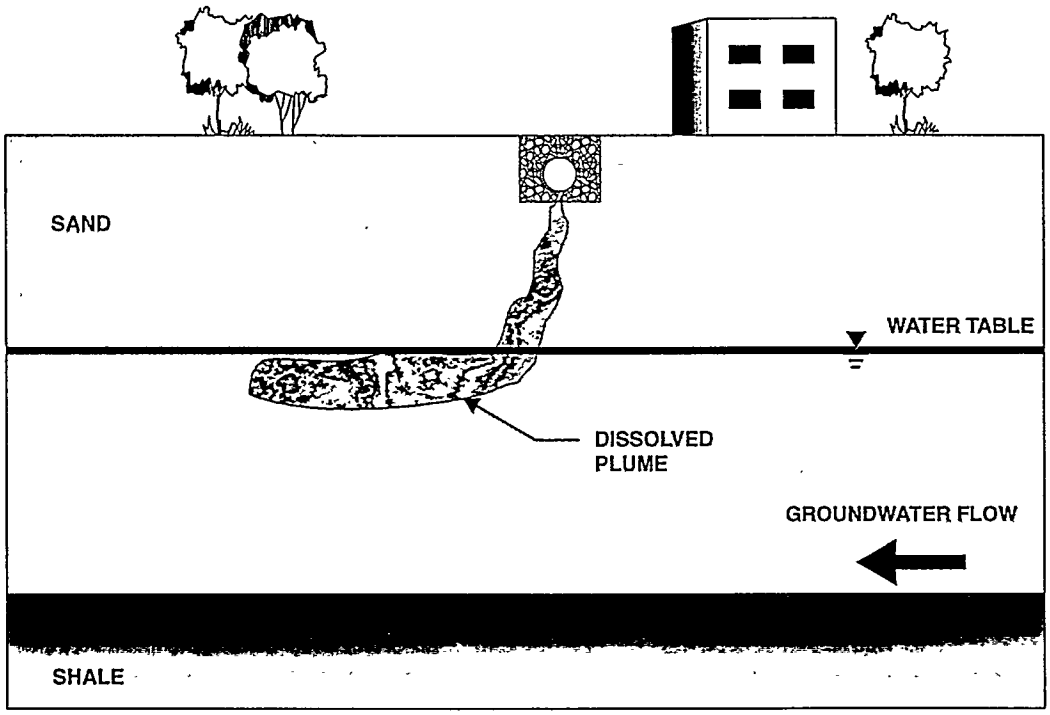
b) Could uncontrolled vapor migration produce safety and/or health hazards?

c) Is it economical to install a system that will require a relatively high well density?

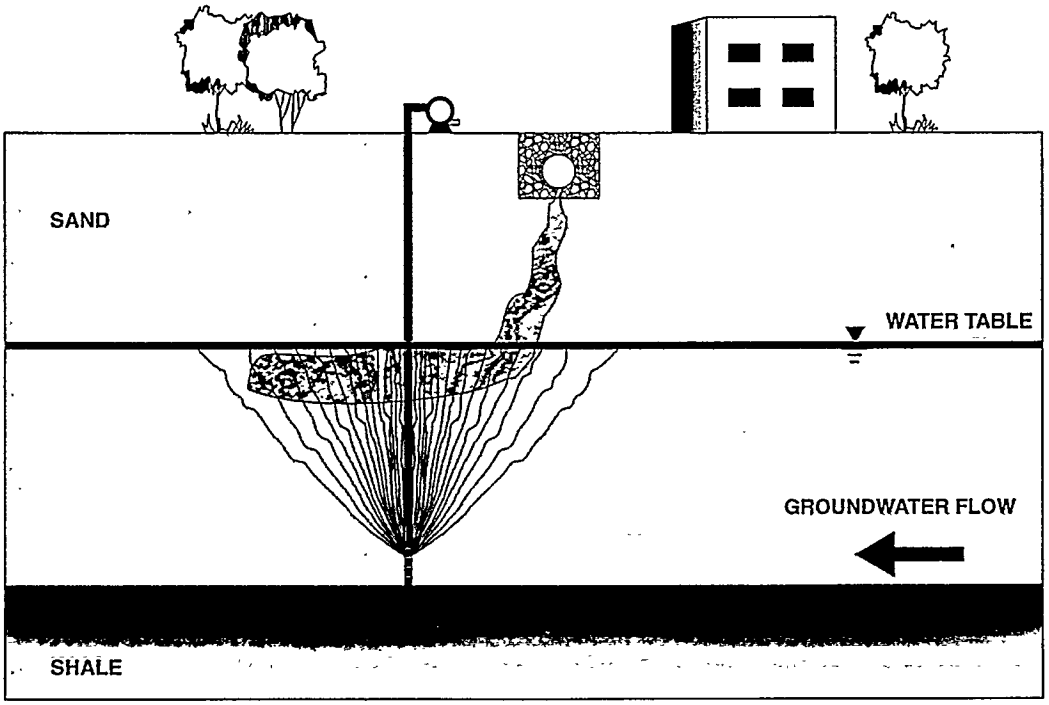
CONCEPTUAL AIR DISTRIBUTION



PETROLEUM HYDROCARBON - HOMOGENEOUS FORMATION



CONCEPTUAL AIR DISTRIBUTION



REFERENCES

SCENARIO 1: Martin, L.M., et al., 1992.

SCENARIO 2: Middleton, A.C., et al., 1990; Barrera, J.A., 1993b.

SCENARIO 3: Middleton, A.C., et al., 1990; Brown, R.A., Henry, E., et al., 1991.

SCENARIO 4: Marley, M.C., et al, 1990b; Marley M.C., 1991m.

SCENARIO 5: Barrera, J.A., 1993b.

SCENARIO 6: Swinford, G.L., 1993; Brown, R., et al., 1993c; Weymann, D.F.

Alternative Scenario: Swinford, G.L., 1993; Hu, S., et al.

SCENARIO 7: None identified.

SCENARIO 8: Fairbanks, P.E., et al., 1993; Aelion, C.M., 1995; Johnson, R.L., 1993; Miller, R.N., et al., 1991

Alternative Scenario: Miller, R.N., et al., 1991.

SCENARIO 9: Looney, et al., 1991; Pankow, et al., 1993; Anjell, K.G.; Hackett, B.H., et al 1995b

Alternative Scenario: Hackett, B.H., et al., 1995b; Martin, L.M., et al., 1992.

SCENARIO 10: Lundegard, 1994.

APPENDIX C

TABLE OF CONTENTS

	Page
INTRODUCTION	C-1
EXAMPLE SITE Decision Tree Narrative	C-2
EXHIBITS	C-23

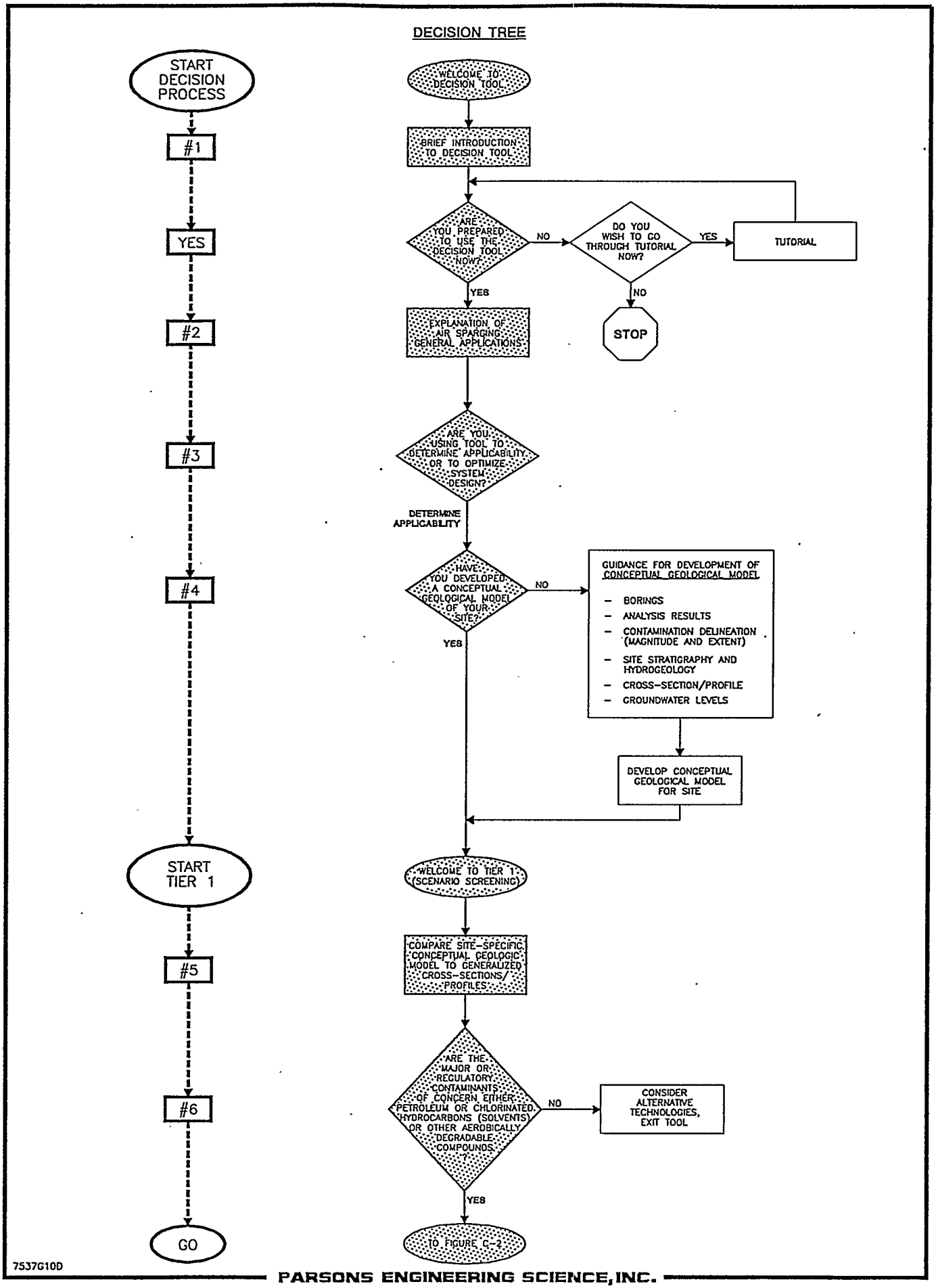
EXAMPLE SITE

DECISION TREE

AND

NARRATIVE

FIGURE C-1



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1 *Required Action:* Read Introduction.

The Conceptual Decision Tool has been developed to provide a simple yet comprehensive process for accurate and expedited decision-making with respect to the applicability of air sparging at a particular site. Use of the Tool is not intended for detailed design applications or for fate and transport modelling of specific sites. The Tool is not intended to model physical systems; instead it provides a "model" of the decision-making process.

Text Reference: Section 1.2

2 *Required Action:* Read Air Sparging Background.

Text Reference: Section 1.4

3 *Required Action:* Identify intended use of Tool.

Decision: Determine Applicability

Reason: The example site is being evaluated for the potential application of air sparging as a remediation technology.

4 *Required Action:* Determine if Conceptual Geologic Model is ready.

Decision: Yes

Reason: There is existing site assessment information for the example site being evaluated, refer to EXHIBIT-A.

Text Reference: Section 2.2

5 *Required Action:* Compare Conceptual Geologic Model to Generalized Cross-Sections of Site Conceptual Models.

Appendix B of the Conceptual Decision Tool provides a number of Site Conceptual Models. During the progression through the next several blocks of this Decision Tree, the example site (using information from EXHIBIT-A) will be compared to the models; the model most representative of the example site will be selected.

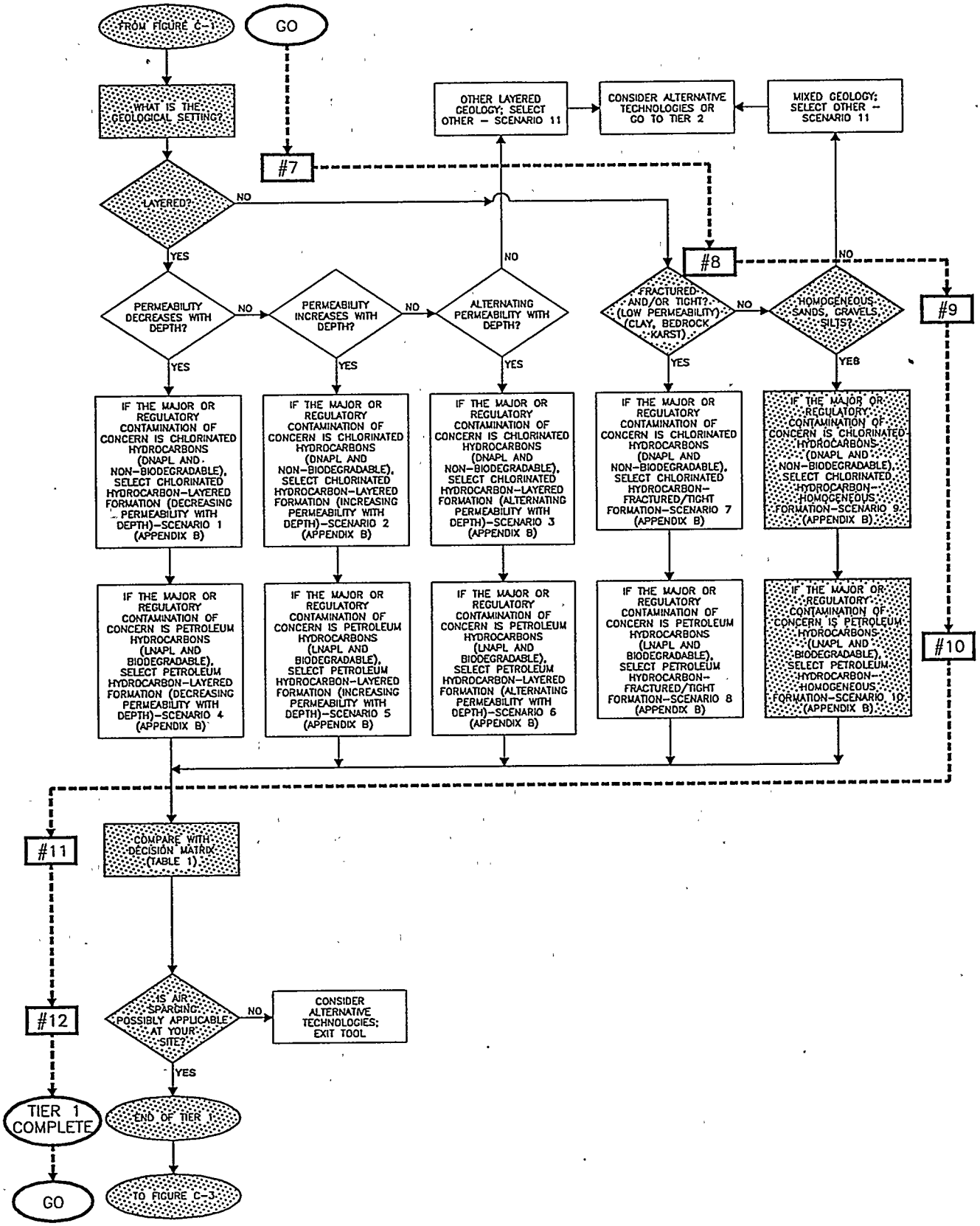
6 *Required Action:* Determine if Major Contaminants are Petroleum or Chlorinated Hydrocarbons.

Decision: Yes

Reason: The contaminants of concern for the example site are petroleum hydrocarbon compounds (EXHIBIT-A).

Text Reference: Section 2.2.1

FIGURE C-2



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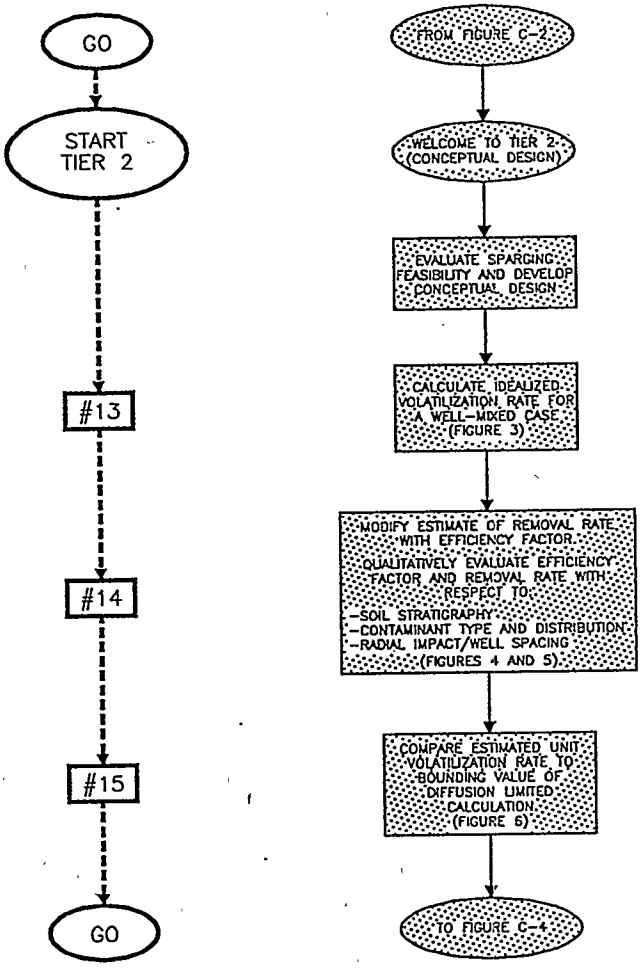
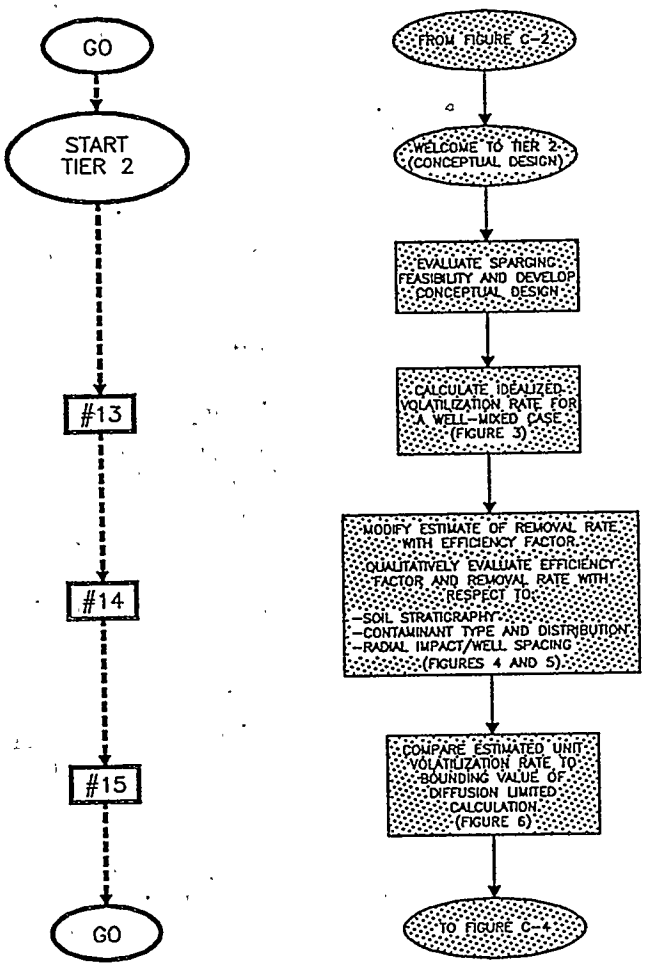
# 7	*Required Action:*	Determine if Geologic Setting is Layered.
	Decision:	No
	Reason:	The example site geology is not layered (EXHIBIT-A).
	Text Reference:	Section 2.2.2
# 8	*Required Action:*	Determine if Geologic Setting is Fractured of Tight.
	Decision:	No
	Reason:	The example site geology is not fractured and/or tight (EXHIBIT-A).
	Text Reference:	Section 2.2.2
# 9	*Required Action:*	Determine if Geologic Setting is Homogeneous.
	Decision:	Yes
	Reason:	The example site geology is homogeneous (EXHIBIT-A).
	Text Reference:	Section 2.2.2
# 10	*Required Action:*	Confirm Scenario selection.
	Decision:	Hydrocarbon-Homogeneous Formation-Scenario 10, refer to EXHIBIT-B.
	Reason:	The contaminant of concern for the example site is petroleum hydrocarbons (EXHIBIT-A).
	Text Reference:	Section 2.2.2
# 11	*Required Action:*	Use Decision Matrix.

Refer to EXHIBIT-C, enter the table at Scenario Number 10 and remediation objective, and obtain applicability rating or scale. For the example site, plume remediation is the objective because no LNAPL is present and the horizontal extent of the plume has been defined (EXHIBIT-A). Using EXHIBIT-C, the applicability rating or scale for the example site is "+".

	Text Reference:	Section 2.2.3 and Section 2.3
# 12	*Required Action:*	Determine if air sparging is applicable.
	Decision:	Yes
	Reason:	From #12 and EXHIBIT-C, a "+" was determined for the example site. A "+" means "determined to be a good physical of technical possibility and a justifiable (but not unique) target for sparging".
	Text Reference:	Section 2.3


GO
START TIER 2
#13
#14
#15
GO
FROM FIGURE C-2
WELCOME TO TIER 2 (CONCEPTUAL DESIGN)
EVALUATE SPARGING FEASIBILITY AND DEVELOP CONCEPTUAL DESIGN
CALCULATE IDEALIZED VOLATILIZATION RATE FOR A WELL-MIXED CASE (FIGURE 3)
MODIFY ESTIMATE OF REMOVAL RATE WITH EFFICIENCY FACTOR. QUALITATIVELY EVALUATE EFFICIENCY FACTOR AND REMOVAL RATE WITH RESPECT TO:
-SOIL STRATIGRAPHY
-CONTAMINANT TYPE AND DISTRIBUTION
-RADIAL IMPACT/WELL SPACING
(FIGURES 4 AND 5)
COMPARE ESTIMATED UNIT VOLATILIZATION RATE TO BOUNDING VALUE OF DIFFUSION LIMITED CALCULATION (FIGURE 6)
TO FIGURE C-4

# 13	*Required Action:*	Calculate "optimal" unit removal rate for volatilization based on an idealized "well-mixed" case.
	Result:	Removal Rate for Volatilization equals 0.18 kg/day, refer to EXHIBIT-D. (Note: At this point, the user must complete a portion of the calculation; then, the user must retrieve the flowrate value from #18 to complete the calculation in #13. After #13 is complete, the value must be entered into #14 and #15.)
	Text Reference:	Sections 3.1.1 and 3.2.1
# 14	*Required Action:*	Determine Efficiency Factor to Modify the "optimal" unit removal rate for volatilization, yielding an estimate for the maximum unit removal rate for volatilization under site-specific conditions.
	Intermediate:	a) Action: Adjust efficiency factor based on contaminant type and distribution. Using the applicability rating "+" (from EXHIBIT-C) enter the graph in EXHIBIT-E. Denoted by "#a" on EXHIBIT-E. Reason: The site has no free product and the dissolved plume originates from LNAPL concentrations. Result: No adjustment up or down the curve of EXHIBIT-E is required, still at "#a". b). Action: Adjust efficiency factor based on well spacing. Working with EXHIBIT-F, a Potential Air Saturation Level of 15% was selected along with a value of 7 feet for the distance from the injection point (i.e., radius of influence). The intersection point (denoted "#b") on EXHIBIT-F falls within the "optimal zone". Reason: 15% is mid-level of the recommended Theoretical Maximum and Minimum Values and 7 feet radius of influence was assumed for the initial estimate for the example site. Result: No adjustment up or down the curve of EXHIBIT-E is required, still at "#a". c). Action: Adjust efficiency factor based on soil stratigraphy. Reason: The example site is comprised of porous sediments (EXHIBIT-A) and should be conducive to air flow.


GO
START TIER 2
#13
#14
#15
GO
FROM FIGURE C-2
WELCOME TO TIER 2 (CONCEPTUAL DESIGN)
EVALUATE SPARGING FEASIBILITY AND DEVELOP CONCEPTUAL DESIGN
CALCULATE IDEALIZED VOLATILIZATION RATE FOR A WELL-MIXED CASE (FIGURE 3)
MODIFY ESTIMATE OF REMOVAL RATE WITH EFFICIENCY FACTOR. QUALITATIVELY EVALUATE EFFICIENCY FACTOR AND REMOVAL RATE WITH RESPECT TO: -SOIL STRATIGRAPHY -CONTAMINANT TYPE AND DISTRIBUTION -RADIAL IMPACT/WELL SPACING (FIGURES 4 AND 5)
COMPARE ESTIMATED UNIT VOLATILIZATION RATE TO BOUNDING VALUE OF DIFFUSION LIMITED CALCULATION (FIGURE 6)
TO FIGURE C-4

Result: Make an adjustment up the curve of one-half of an interval, denoted by "#c" on EXHIBIT-E.

Final Result: Based on the intermediate results, the efficiency factor for the example site is 0.4, refer to EXHIBIT-E. Therefore, an estimate for the maximum unit removal rate for volatilization (Removal $Rate_{V\text{-}max}$) is equal to the "optimal" removal rate (Removal $Rate_V$, from EXHIBIT-D) multiplied by the Efficiency Factor (F, from EXHIBIT-E).

That is;

Removal $Rate_{V\text{-}max}$ = Removal $Rate_V$ * F

Therefore, for the example site;

Removal $Rate_{V\text{-}max}$ = (0.18 kg/day) (0.4) = 0.07 kg/day

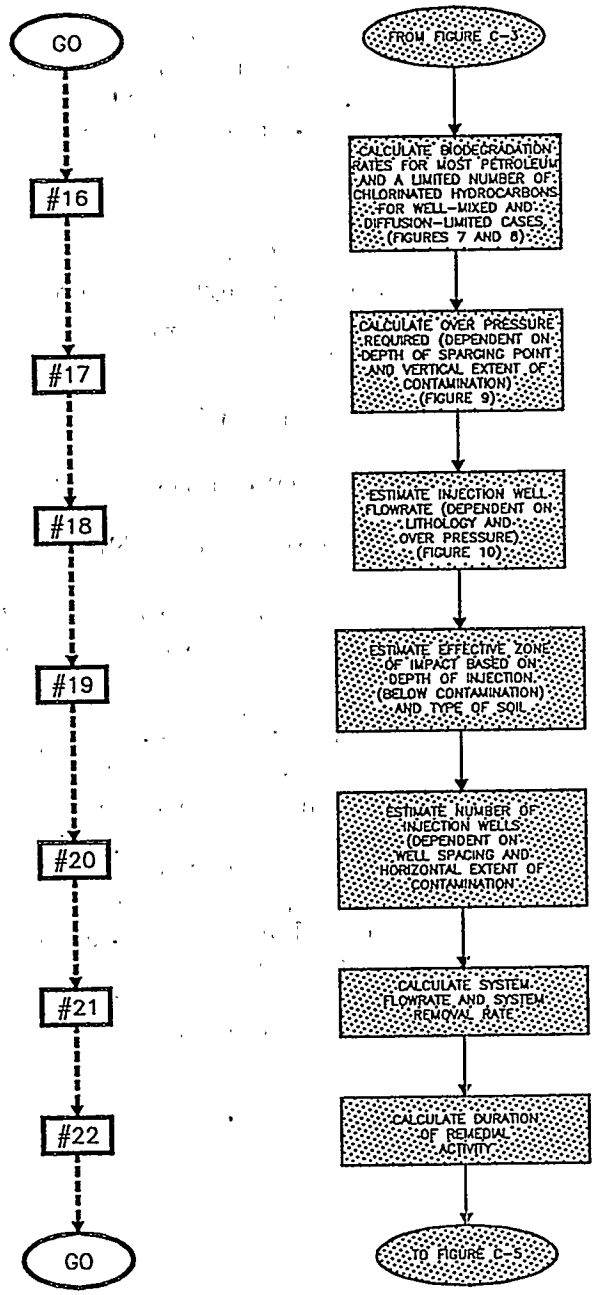
Text Reference: Sections 3.1.1 and 3.2.1

15 *Required Action:* Compare the estimated maximum unit removal rate for volatilization (from #14) to the unit removal rate for volatilization based on "diffusion-limited" case.

Result: Unit removal rate for volatilization (lower bounding level) equals 1,500 mg/day (=0.0015 kg/day), refer to EXHIBIT-G. Compare 0.0015 kg/day (lower bounding level or minimum from EXHIBIT-G) to 0.07 kg/day (estimated maximum from #14). The applicability evaluation for the example site may proceed because the value from #14 is much greater than the value from #15.

(Note: If the value from #14 was comparable to (or less than) the value from #15, then the user might have a "diffusion-limited" situation and need to re-check the site characteristics.

Text Reference: Sections 3.1.1 and 3.2.1


GO
#16
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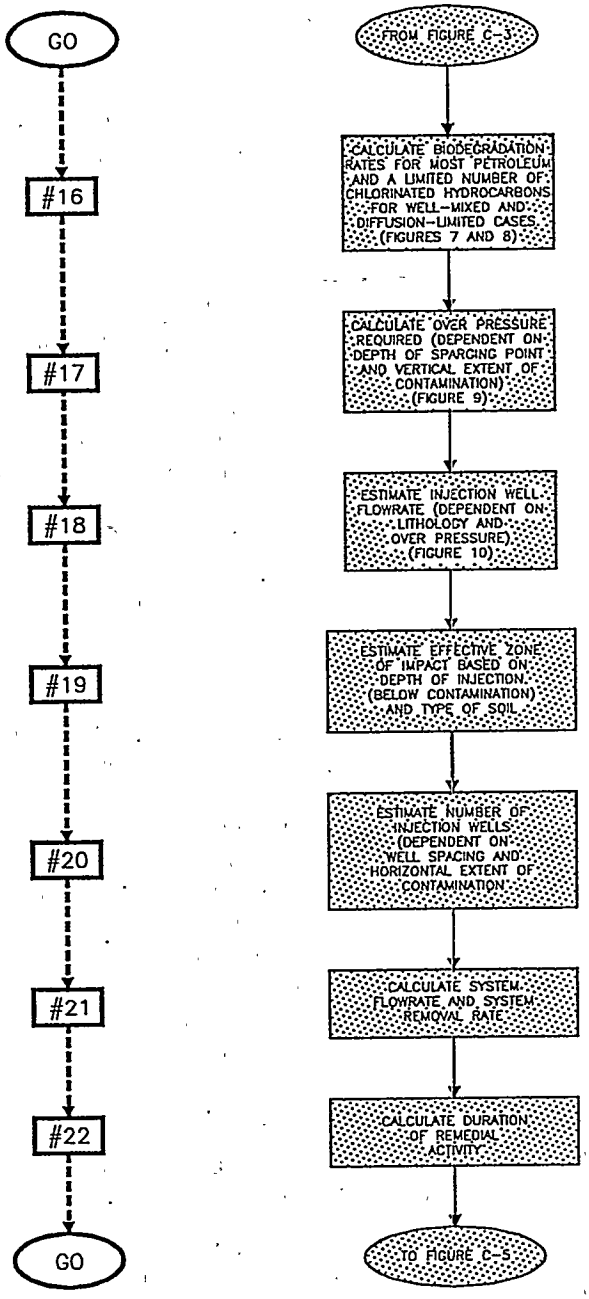
FROM FIGURE C-3
CALCULATE BIODEGRADATION RATES FOR MOST PETROLEUM AND A LIMITED NUMBER OF CHLORINATED HYDROCARBONS FOR WELL-MIXED AND DIFFUSION-LIMITED CASES (FIGURES 7 AND 8)
CALCULATE OVER PRESSURE REQUIRED (DEPENDENT ON DEPTH OF SPARGING POINT AND VERTICAL EXTENT OF CONTAMINATION) (FIGURE 9)
ESTIMATE INJECTION WELL FLOWRATE (DEPENDENT ON LITHOLOGY AND OVER PRESSURE) (FIGURE 10)
ESTIMATE EFFECTIVE ZONE OF IMPACT BASED ON DEPTH OF INJECTION (BELOW CONTAMINATION) AND TYPE OF SOIL
ESTIMATE NUMBER OF INJECTION WELLS (DEPENDENT ON WELL SPACING AND HORIZONTAL EXTENT OF CONTAMINATION
CALCULATE SYSTEM FLOWRATE AND SYSTEM REMOVAL RATE
CALCULATE DURATION OF REMEDIAL ACTIVITY
TO FIGURE C-5

# 16	*Required Action:*	Evaluate the unit removal rate for biodegradation based on "well-mixed" and "diffusion-limited" cases.
	Result:	For the example site, the contaminants of concern (BTEX) lend themselves well to both volatilization and biodegradation, refer to EXHIBIT-H. In general, the removal rates for biodegradation resemble the graph of EXHIBIT-I. At the start of injection with an excess quantity of hydrocarbons (food source), the rate remains relatively constant. As the hydrocarbons are consumed and the quantity decreases, the rate starts to decline. For the example site, there is no free product; only dissolved plume remediation is required. Therefore, assume the average biodegradation rate for the site would be 1%/day of petroleum hydrocarbons, refer to EXHIBIT-I (Continued). As the quantity of hydrocarbons decreases, the rate will also decrease.
	Text Reference:	Sections 3.1.1 and 3.2.2
# 17	*Required Action:*	Calculate minimum injection conceptual system operating and over pressures.
	Result:	For the example site, the minimum injection pressure (i.e., the lower bound which must be exceeded to inject the first air bubble) is 5 psi. Similarly, the over pressure (i.e., or upper bound, which if exceeded will result in secondary fracturing or fluidization) is 15 psi (with safety factor applied). Finally, the conceptual operating pressure, which must be within the range bounded by the minimum injection pressure and over pressure, is flowrate dependent and determined through application of Darcy's Law as depicted in Figure 10 of the Text. Refer to EXHIBITS J, J.1 and K. For the example site, the conceptual operating pressure is 15 psi.
	Text Reference:	Section 3.2.3. Figures 9 and 10 and Table 8
#18	*Required Action:*	Estimate injection well flowrate based on lithology and over pressure.
	Result:	Using the graph of EXHIBIT-K, enter the x-axis at the appropriate soil permeability (from EXHIBIT-K.1) and move vertically up the graph until the line representing 15 psi (from EXHIBIT-J) is encountered, then move horizontally to the left to determine the air flowrate. For the example site, the air flowrate equals 2 cfm, refer to EXHIBIT-K. (Note: Remember, the flowrate value must be taken back to complete the calculations in #13, #14 and #15.)
	Text Reference:	Section 3.2.3


GO
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GO
FROM FIGURE C-3
CALCULATE BIODEGRADATION RATES FOR MOST PETROLEUM AND A LIMITED NUMBER OF CHLORINATED HYDROCARBONS FOR WELL-MIXED AND DIFFUSION-LIMITED CASES. (FIGURES 7 AND 8)
CALCULATE OVER PRESSURE REQUIRED (DEPENDENT ON DEPTH OF SPARGING POINT AND VERTICAL EXTENT OF CONTAMINATION) (FIGURE 9)
ESTIMATE INJECTION WELL FLOWRATE (DEPENDENT ON LITHOLOGY AND OVER PRESSURE) (FIGURE 10)
ESTIMATE EFFECTIVE ZONE OF IMPACT BASED ON DEPTH OF INJECTION (BELOW CONTAMINATION) AND TYPE OF SOIL
ESTIMATE NUMBER OF INJECTION WELLS (DEPENDENT ON WELL SPACING AND HORIZONTAL EXTENT OF CONTAMINATION
CALCULATE SYSTEM FLOWRATE AND SYSTEM REMOVAL RATE
CALCULATE DURATION OF REMEDIAL ACTIVITY
TO FIGURE C-5

#19	*Required Action:*	Estimate the effective zone of impact.
	Result:	For the example site, the estimated radius of influence for each injection well equals 7 feet. In addition, the estimated zone of impact for each injection well equals 14 feet. Refer to EXHIBIT-L.
	Text Reference:	Section 3.2.4
# 20	*Required Action:*	Estimate the number of injection wells.
	Result:	Using the effective zone of impact determined in #19 (i.e., 14 feet), the number of injection wells required for the example site is equal to eight. This is determined by overlying the diagram depicting the extent of contamination with the estimated effective zone of impact for each of the eight wells, refer to EXHIBIT-M.
	Text Reference:	Section 3.2.4
# 21	*Required Action:*	Calculate system flowrate and system removal rate.
	Result:	The system flow rate is determined by multiplying the flowrate for an individual air sparging well times the number of wells. In the example, the result is 2 ft^3/min/well (from EXHIBIT-K) times 8 wells (from EXHIBIT-M), which equals 16 ft^3/min. Refer to EXHIBIT-N.

The system removal rate is determined by considering the contaminant removal rates for volatilization and biodegradation, i.e., 0.56 kg/day and 1%/day, respectively. As will be seen in the next step, for this example, the volatilization rate greatly exceeds the biodegradation rate (by two orders of magnitude); hence, the bioremediation rate may be ignored as negligible in this calculation. (NOTE: This will not necessarily be appropriate for other situations).

Text Reference: Sections 3.2.4 and 3.2.5

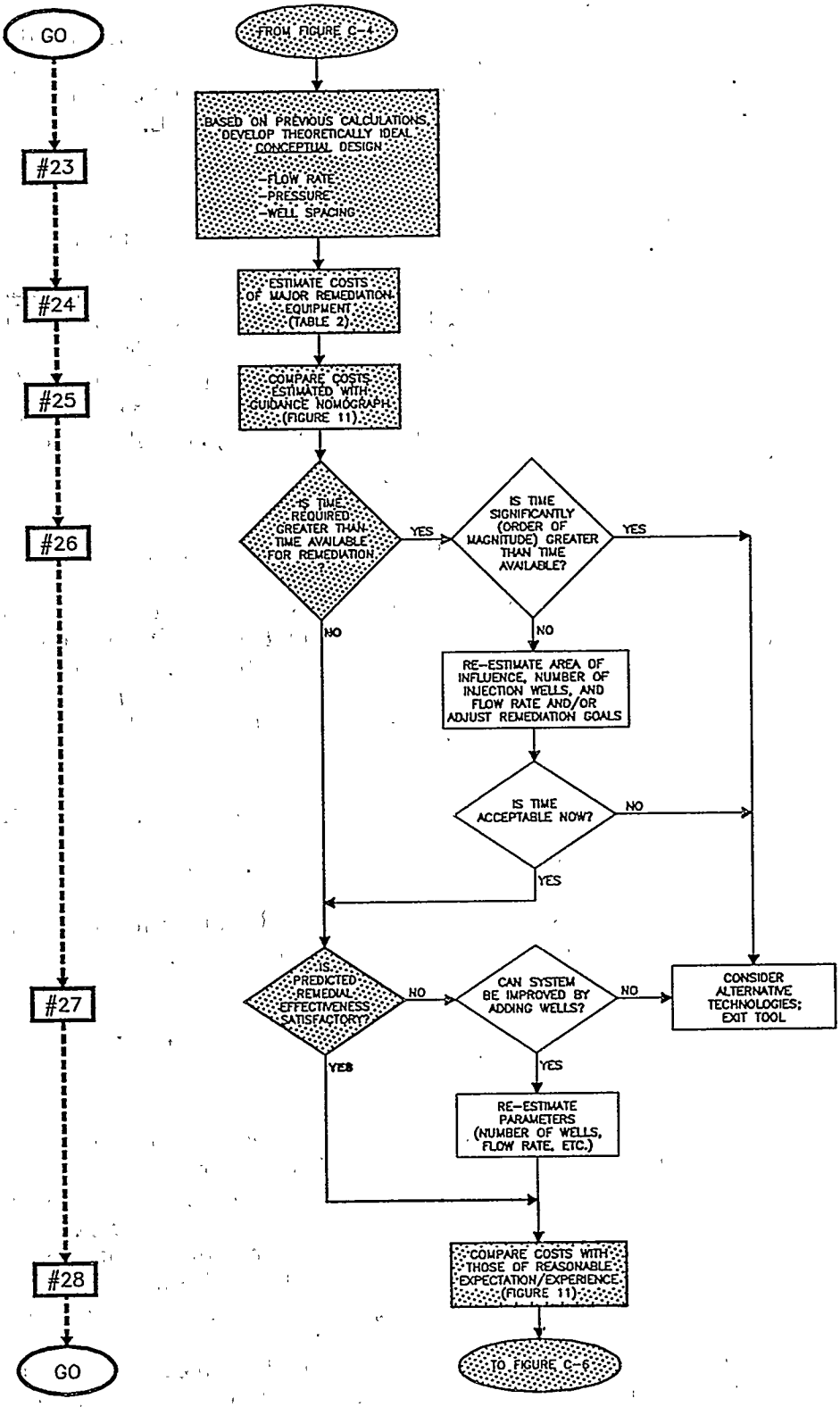
22 *Required Action:* Calculate duration of remedial activity.

Result:

To calculate the duration of remedial activity, in principle, the level of site contamination may be divided by the removal rate determined in #21. If volatilization prevails (as in the example case), the total contaminant mass must be determined first. This is estimated by multiplying the average contaminant concentration (i.e., 10 mg/L of benzene) by the volume of the zone of contamination, resulting in about 3.6 Kg. [NOTE: if biodegradation prevails, apply the second equation in Figure 8 (i.e., $C_p=C_oE^{-0.01t}$) to the initial and desired contaminant concentrations, solving for time (i.e., t). In the example, this calculation suggests that 750 days are required for biodegradation alone.] Using the volatilization removal rate only suggests that remediation with the conceptual design proposed would be accomplished within about 7 days. Refer to EXHIBIT-N.

Text Reference: Sections 3.2.4 and 3.2.5

FIGURE C-5



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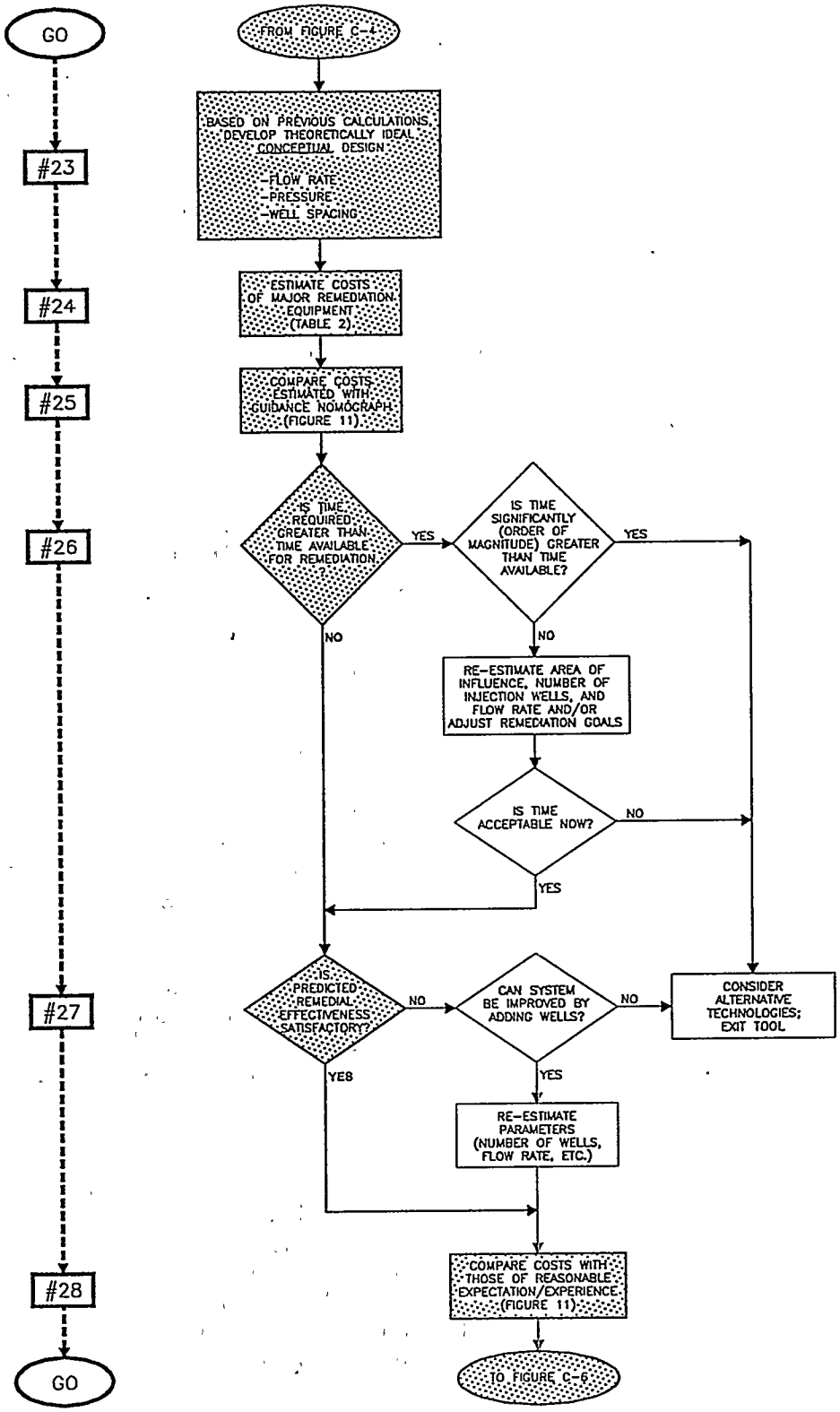
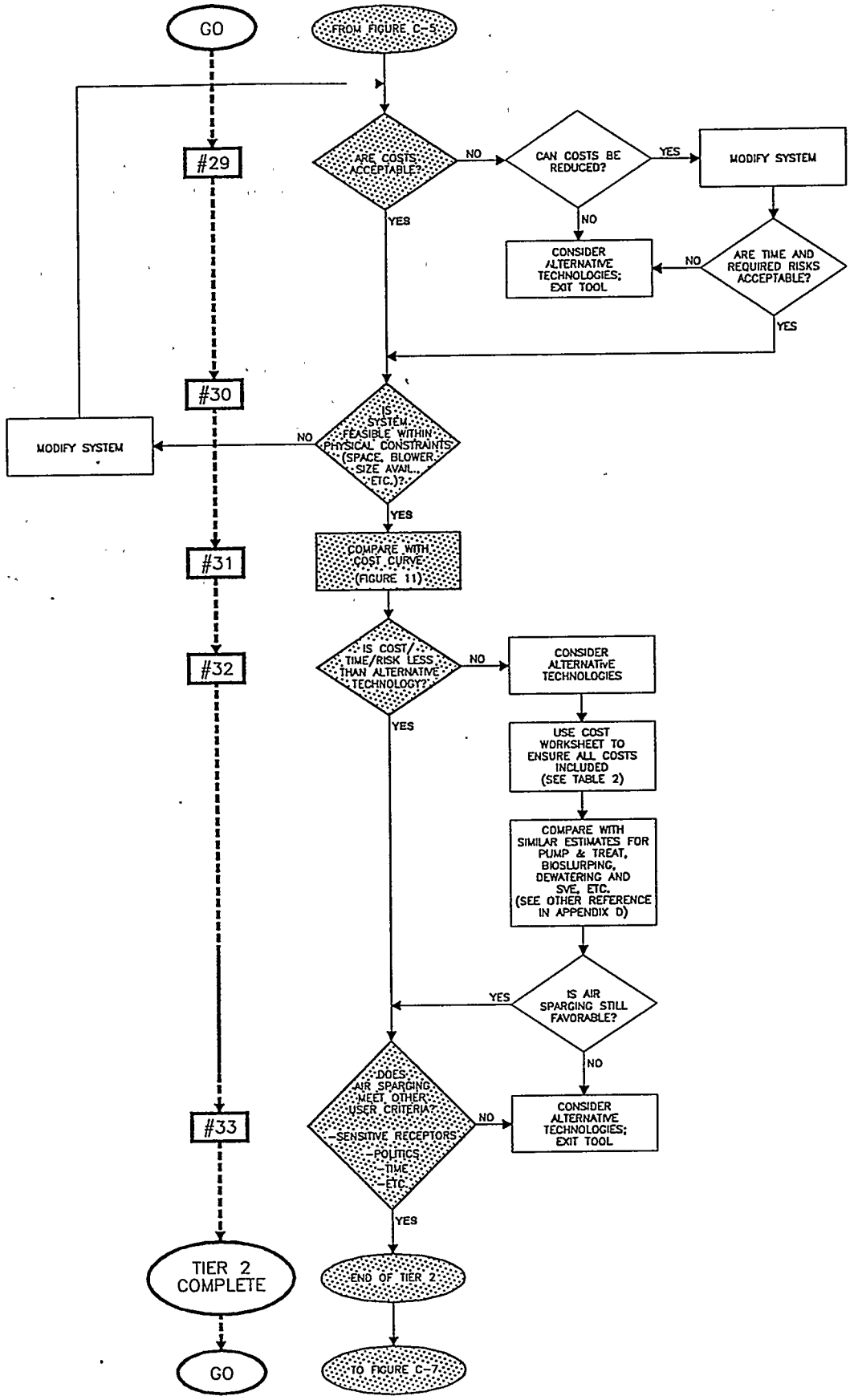
#23	*Required Action:*	Develop conceptual design.
	Result:	For example site: - Well Injection Pressure = 15 psi (from EXHIBIT-J) - Well Flowrate = 2 cfm (from EXHIBIT-K) - System Flowrate = 16 cfm (from EXHIBIT-N) - For conceptual design layout based on the above parameters, refer to EXHIBIT-O.
	Text Reference:	Sections 3.2.4 and 3.2.5
# 24	*Required Action:*	Estimate costs for major remediation equipment.
	Result:	For example site, based on conceptual design layout, the total estimated cost for installation of the system equals $935,000 and the total well footage to be installed equals 1,100 feet, refer to EXHIBIT-P.
	Text Reference:	Section 3.2.6
# 25	*Required Action:*	Compare estimated costs for system installation with guidance nomograph.
	Result:	The estimated cost for installation (from EXHIBIT-P) divided by the total well footage (from EXHIBIT-P) equals the estimated cost per foot of well ($850/foot). Entering the graph in EXHIBIT-Q with the above values, the estimate for the example site compares to the guidance values (i.e., the example site estimate falls within the cost zone). (Note: The user could have determined a rough estimate for the system installation cost without generating the cost worksheet, EXHIBIT-P. To accomplish this, the user would determine the total well footage (air sparging wells, soil vapor extraction wells, monitoring points, etc.) from the conceptual design. The user would enter the graph of EXHIBIT-Q, with the associated total well footage value, along the x-axis; then, move up the graph until the curve is intersected. Moving horizontally, the user could determine a value or range of values for the estimated cost per foot of well. The cost per foot of well multiplied by the total well footage would equal a rough estimated cost or range of estimated costs for the installation of the system.)
	Text Reference:	Section 3.2.6


GO
#23
#24
#25
#26
#27
#28
GO
FROM FIGURE C-4
BASED ON PREVIOUS CALCULATIONS, DEVELOP THEORETICALLY IDEAL CONCEPTUAL DESIGN
-FLOW RATE
-PRESSURE
-WELL SPACING
ESTIMATE COSTS OF MAJOR REMEDIATION EQUIPMENT (TABLE 2)
COMPARE COSTS ESTIMATED WITH GUIDANCE NOMOGRAPH (FIGURE 11)
IS TIME REQUIRED GREATER THAN TIME AVAILABLE FOR REMEDIATION?
YES
IS TIME SIGNIFICANTLY (ORDER OF MAGNITUDE) GREATER THAN TIME AVAILABLE?
YES
NO
NO
RE-ESTIMATE AREA OF INFLUENCE, NUMBER OF INJECTION WELLS, AND FLOW RATE AND/OR ADJUST REMEDIATION GOALS
IS TIME ACCEPTABLE NOW?
NO
YES
IS PREDICTED REMEDIAL EFFECTIVENESS SATISFACTORY?
NO
CAN SYSTEM BE IMPROVED BY ADDING WELLS?
NO
CONSIDER ALTERNATIVE TECHNOLOGIES; EXIT TOOL
YES
YES
RE-ESTIMATE PARAMETERS (NUMBER OF WELLS, FLOW RATE, ETC.)
COMPARE COSTS WITH THOSE OF REASONABLE EXPECTATION/EXPERIENCE (FIGURE 11)
TO FIGURE C-6

# 26	*Required Action:*	Determine if time required is greater than that available for remediation.
	Decision:	No
	Reason:	The duration of remedial activity (EXHIBIT-N) is acceptable (e.g., within regulatory requirements or expectations).
# 27	*Required Action:*	Determine if remedial effectiveness is satisfactory.
	Decision:	Yes
	Reason:	The removal rates (for volatilization and biodegradation) (EXHIBIT-N) will satisfy the desired cleanup requirements (EXHIBIT-A).
# 28	*Required Action:*	Re-compare estimated costs.
	Result:	For the example site, the decisions made in #26 and #27 did not result in any revisions to the conceptual system design; therefore, the re-comparison of costs is not required at this time.

FIGURE C-6



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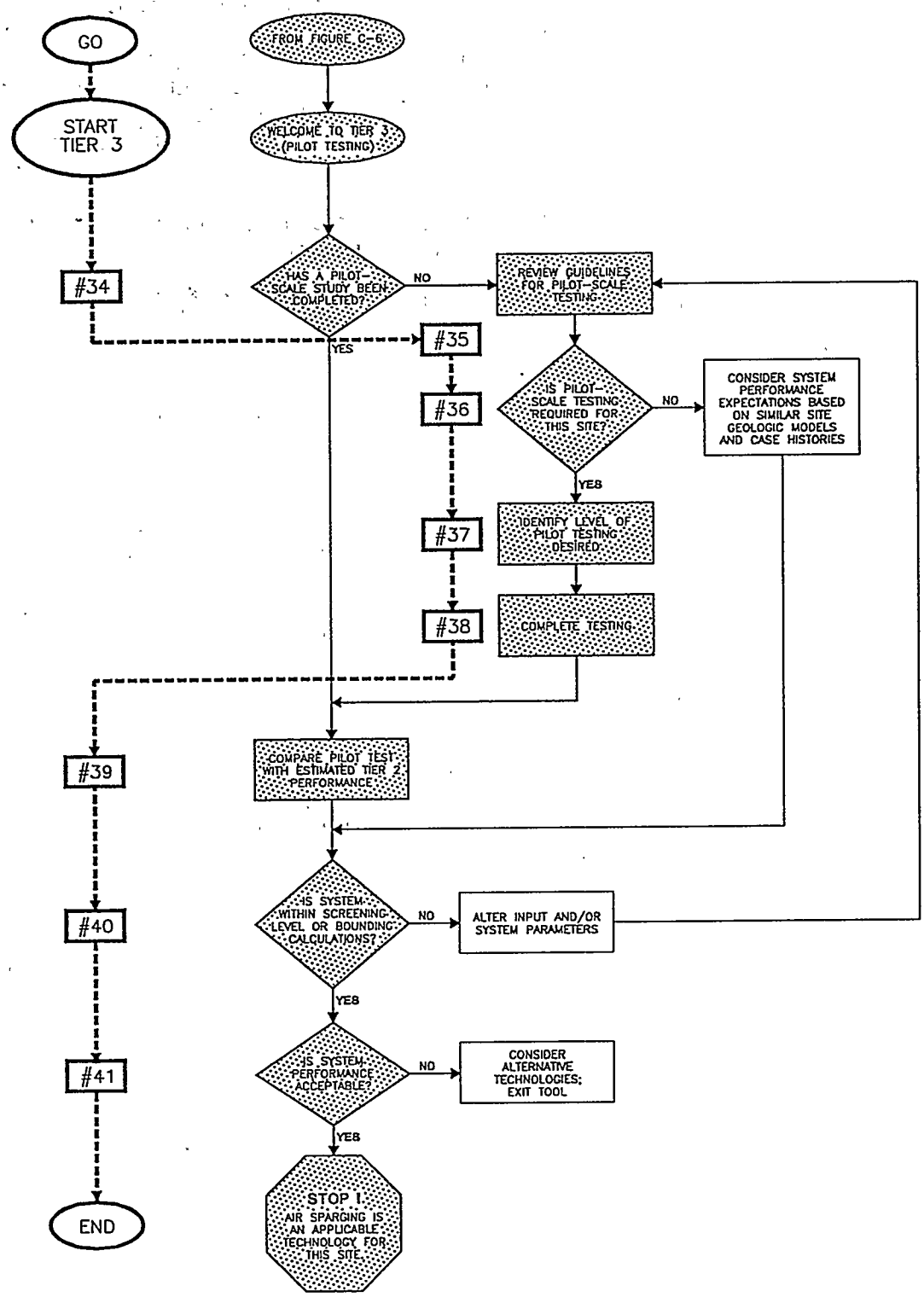
# 29	*Required Action:*	Determine if costs are acceptable.
	Decision:	Yes. However, if a longer remediation time is acceptable and/or preferred, the conceptual design could be re-configured and optimized, resulting in a much lower cost for installation. Concurrently, the duration of remedial activity would increase exponentially because parts of the contaminated zone would become diffusion-limited.
	Reason:	No revisions have been made to the conceptual design at this time. See #41 below.
# 30	*Required Action:*	Determine if system installation is feasible.
	Decision:	Yes
	Reason:	The system is feasible and has no special requirements.
# 31	*Required Action:*	Re-compare estimated costs.
	Result:	No revisions have been made to the conceptual design at this time. Hence, re-comparison is not required.
# 32	*Required Action:*	Determine if costs/time/risks incurred are less than alternative technologies.
	Decision:	Yes; however, see comments at #41 below regarding optimization.
	Reason:	The system is still feasible and applicable at this time.
# 33	*Required Action:*	Determine if air sparging meets other criteria.
	Decision:	Yes
	Reason:	The example site meets the criteria set (e.g., political and regulatory as well as safety, operational, etc., requirements).
	Text Reference:	Section 3.4

FIGURE C-7



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# 34	*Required Action:*	Determine if pilot study has been completed.
	Decision:	No
	Reason:	The example site background information (EXHIBIT-A) does not include any previous pilot testing data.
# 35	*Required Action:*	Review guidelines for pilot-scale testing.
	Result:	Review Section 4.0 and Table 3 of Text.
# 36	*Required Action:*	Determine if pilot testing is required for site.
	Decision:	Yes
	Reason:	For the example site, there is no background pilot testing data and it appears the site is a good candidate for the application of air sparging. Therefore, pilot testing would provide data required for development of the site conceptual design.
	Text Reference:	Section 4.0
# 37	*Required Action:*	Identify level of testing.
	Result:	For the level selected for the example site, refer to EXHIBIT-R. In the example site, pilot testing is used to refine system performance values estimated in the conceptual design process and to provide the basis for optimization of the conceptual design.
	Text Reference:	Section 4.0
# 38	*Required Action:*	Complete testing.
	Result:	Perform pilot study testing in accordance with the information provided in Text (Section 4.0). Field testing startup parameters for air sparging (e.g., injection pressure and air flowrate) may be based on the conceptual design values (EXHIBIT-O).
	Text Reference:	Section 4.0
# 39	*Required Action:*	Compare pilot test data to conceptual design.
	Result:	For the example site, the pilot testing data and the conceptual design values were comparable.
	Text Reference:	Section 4.0
# 40	*Required Action:*	Determine if system is within screening or bounding levels.
	Decision:	Yes
	Reason:	Based on the results of #39, the conceptual system design is still feasible.
# 41	*Required Action:*	Determine if system performance is acceptable.
	Decision:	Yes
	Reason:	Based on the results of #39, the conceptual system design performance is still acceptable.

The conceptual design may, however, be optimized, significantly increasing the time required for remediation. For example, the conceptual design may be revised to include only two wells, assuming a 15-foot radius of influence with 5% air saturation at the "edge" of the effective treatment zone. This will impact the conceptual system costs significantly (reducing total costs to less than $300,000). Similarly, remediation time will be increased to approximately one year, since at the edges of the effective treatment zone, removal rates tend toward the diffusion-limited scenario. Even so, air sparging will still be an applicable technology for this site, depending on other criteria (ie., regulatory, political, etc.

END: AIR SPARGING IS APPLICABLE !

EXHIBITS

EXHIBIT - A

SITE CONCEPTUAL GEOLOGIC MODEL

(Information obtained from previously completed site assessments.)
(See Exhibit - L for graphical description.)

Contaminant Source:

- Leaking Above Ground Storage Tank, Gasoline

Analysis Results:

- Benzene, Toluene, Ethylbenzene, Xylenes (BTEX) in soil and groundwater.

Contamination Delineation:

- No observation of LNAPL
- Dissolved Benzene in groundwater - 10 mg/L
- Horizontal extent has been defined in both soil and groundwater.

Site Stratigraphy and Hydrogeology:

- The site is underlain by relatively homogeneous and permeable sandy gravel materials to a depth of approximately 30 feet below grade. Beneath 30 feet, the formation is shale. The depth to water is 15 feet below surface grade.

Cleanup Requirement:

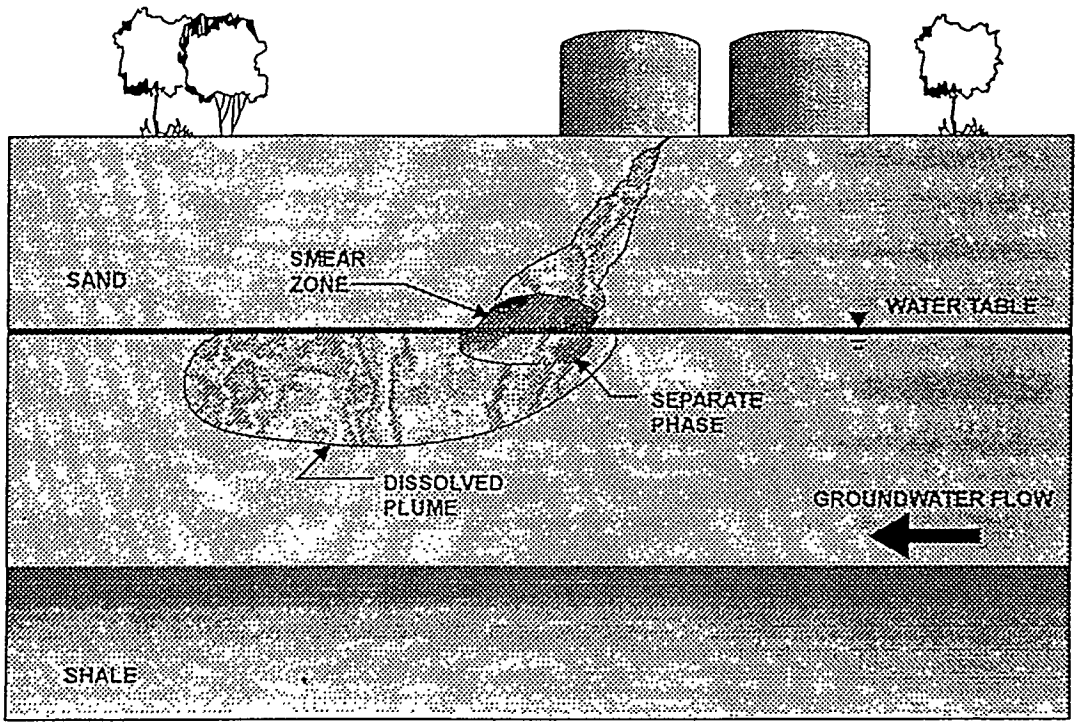
- Benzene in groundwater - 0.005 mg/L

SCENARIO 10:

EXHIBIT –B

PETROLEUM HYDROCARBON - HOMOGENEOUS FORMATION

(from Appendix B)



CONCEPTUAL SCENARIO DESCRIPTION

As depicted above, the site is underlain by relatively homogeneous and permeable materials. For the zone of interest (the zone to be impacted by remedial activities), boring logs or geologic cross-sections should indicate uniformly distributed "gravels", "sands", or "silts".

Here the water-bearing unit has been impacted by a release of petroleum hydrocarbons that are less dense than water (LNAPLs, e.g., gasoline, jet fuel, etc.). If a "source zone" still remains, it may contain mobile liquid (separate phase) hydrocarbons floating on the groundwater table and/or residual hydrocarbons trapped beneath the water table in a "smear zone".

Dissolved contaminants of concern in such settings are often aromatic hydrocarbons, such as benzene, toluene, ethylbenzene, and xylenes (BTEX).

EXPERIENCE - AIR SPARGING APPLICATIONS

This is the scenario most commonly associated with case studies reported in the current technical literature. Results are promising as most petroleum hydrocarbons of concern are relatively volatile and/or aerobically degradable. Thus, air sparging can affect removal through both volatilization and enhanced oxygenation (and subsequently biodegradation).

This is also the one scenario for which practitioners can more confidently project the pattern of air distrbuition following injection into the aquifer. As depicted above, the air distribution is expected to be roughly symmetrical about the injection point, regardless of the sediment type present. The treatment zone radius will approximately equal the depth below groundwater to the top of the injection well screen, within certain limitations (i.e. if depth exceeds 10 to 15 feet, this projection tends to be less accurate). Readers are referred to the field study of Lundegard (1994), where the air flow distribution was measured to extend about 7 feet away from an air injection point located approximately 10 feet below the water table.

The effects of site geology on the air flow will be noticeable in the different sediments discussed in this scenario. Generally, the more fine-grained the sediment, the greater the injection pressure (and therefore less air volume) required to maintain the optimal radius of air distribution.

Other effects of site geology would likely be favorable. Since the scenario indicates that geology is homogeneous, uncontrolled vapor migration and formation of air pockets would not be a major concern.

REMEDIATION OBJECTIVES AND RATINGS

Source Remediation (++)	Plume Remediation (+)	Containment (+)
Good physical/technical possibility, a unique target	Good physical/technical possibility, but not unique.	Good physical/technical possibility, but not unique.

SOURCE ZONES

Limited data available to date suggests that it is possible to achieve source zone remediation to the degree that dissolved concentrations may be reduced from approximately 10 mg/L to 0.01-0.10 mg/L. Few, if any, case studies report reducing source zone dissolved concentrations to levels less than 0.01 mg/L. To achieve removal to target levels below these concentrations, it will probably be more cost-effective to allow natural attenuation processes to complete the remediation. The introduction of air into the capillary fringe and vadose zone may also enhance national biodegradation via bioventing.

DISSOLVED PLUMES

Limited data available to-date suggests that properly designed in-situ air sparging systems may quickly (less than 1 year) remediate dissolved hydrocarbon plumes. Others contend that, once a source zone is removed, natural attenuation processes will rapidly and more cost-effectively remediate the dissolved petroleum hydrocarbons. Caution must be used if practitioners planning to use air sparging for very large plume areas; due to density of sparge point considerations, costs may become excessive, especially if compared with other technologies.

BARRIER CONTROL SETTINGS

No data exist yet in the literature documenting the effectiveness of air sparging migration barrier control systems. Practitioners believe, however, that air sparging migration barriers are likely to be effective, as air sparging seems to be effective at remediating dissolved plumes, the air flow distribution is easily characterized and systems can be designed with more confidence than in any other geologic setting. However, due to the relative small size of typical treatment zone radii, critics suggest that the process may prove to be economical only in shallow groundwater settings given that a high linear density of wells will be necessary (approximately 20 foot spacings).

CONCERNS

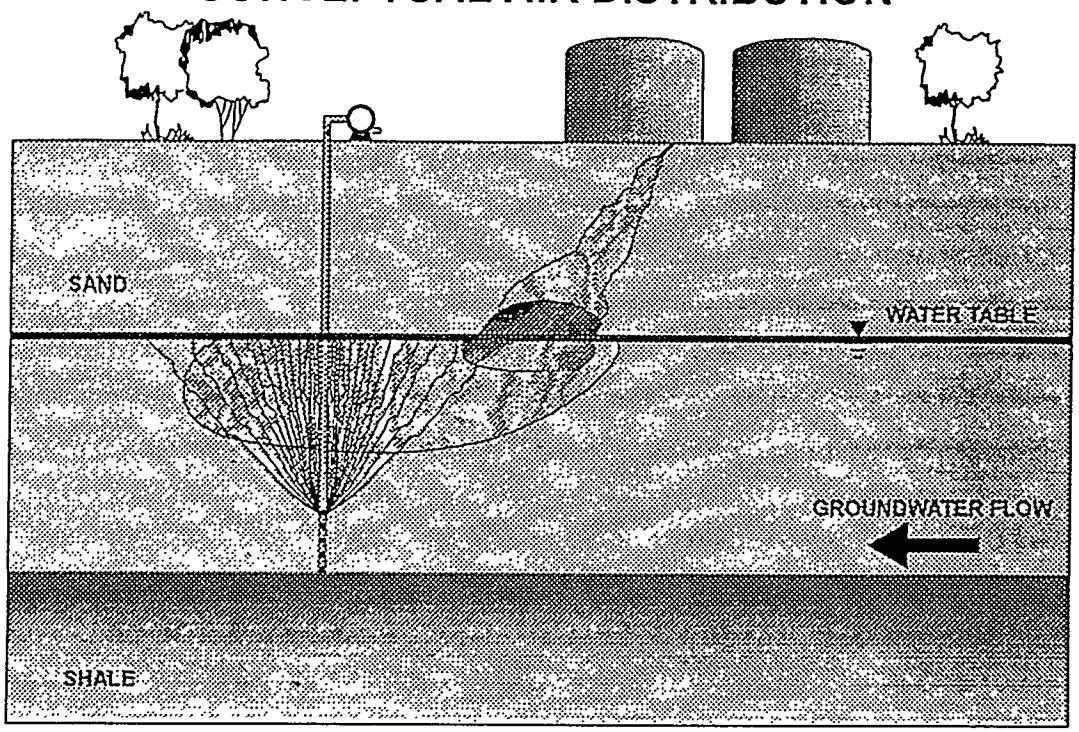
The following are issues that should be addressed by the practitioner:

a) Was the site characterization sufficiently detailed such that it is very likely that the site is truly "homogeneous"? Or alternately, are the local heterogeneities (i.e. thin confining layers which can render sparging ineffective) present?

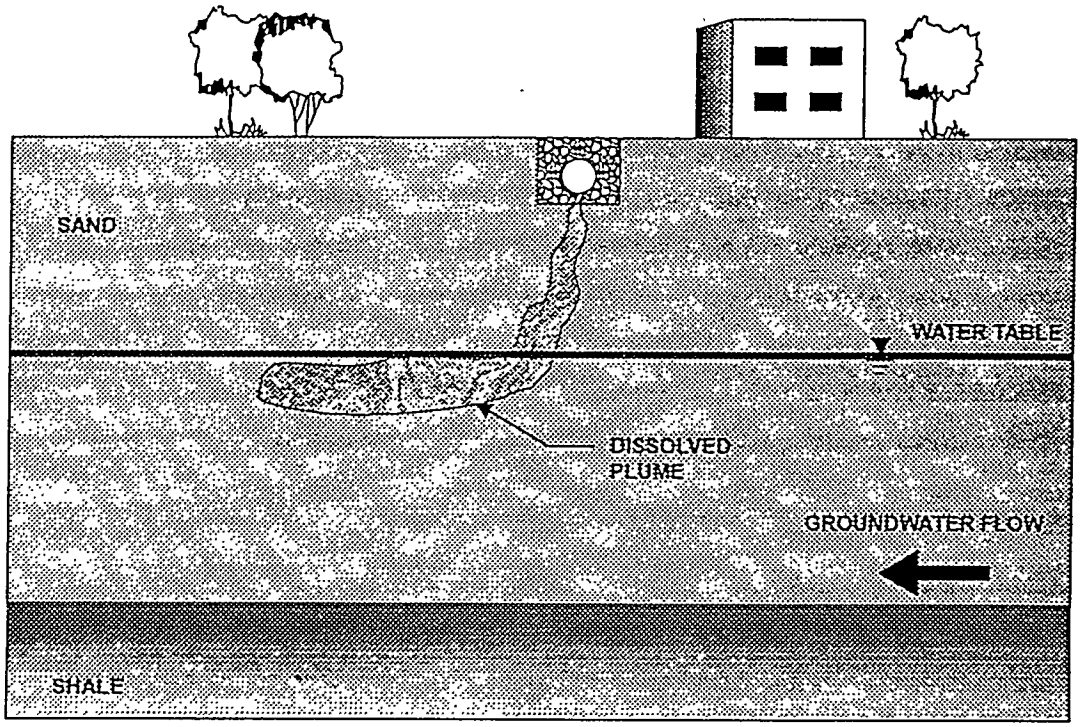
b) Could uncontrolled vapor migration produce safety and/or health hazards?

c) Is it economical to install a system that will require a relatively high well density?

CONCEPTUAL AIR DISTRIBUTION



PETROLEUM HYDROCARBON - HOMOGENEOUS FORMATION



CONCEPTUAL AIR DISTRIBUTION

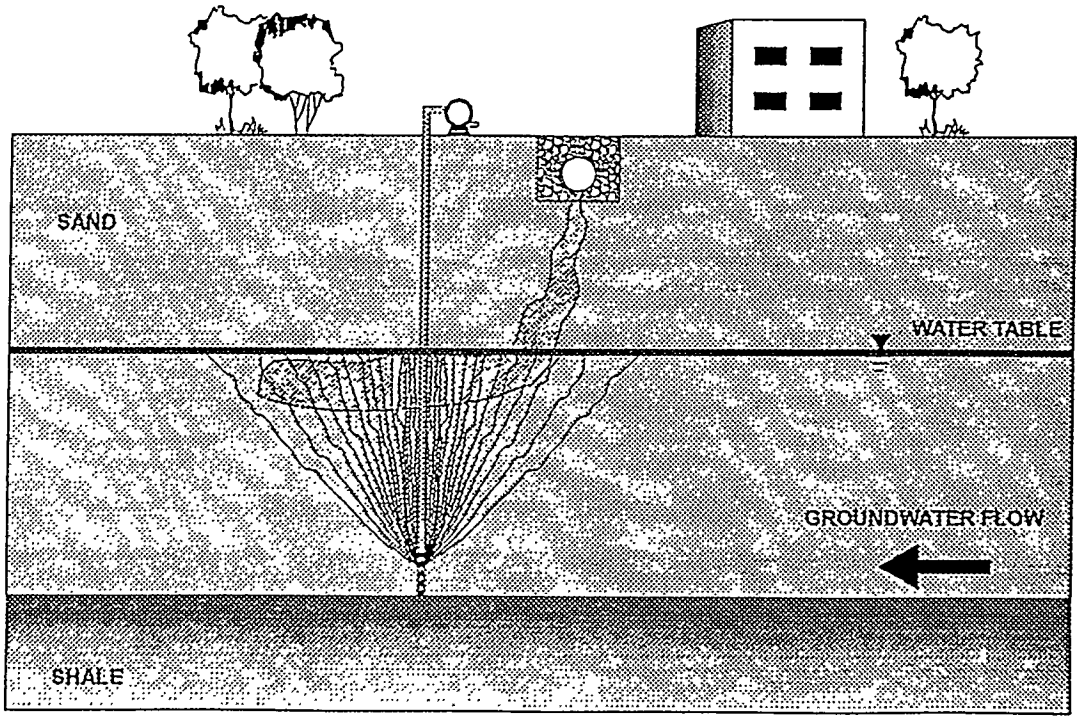


EXHIBIT - C

TABLE 1
AIR SPARGING OPTIMIZATION DECISION TOOL
SUMMARY OF DECISION TOOL SCENARIOS

Scenario Number	Description of Scenarios	Objectives: Source Remediation	Objectives: Plume Remediation	Objectives: Containment
1	Chlorinated Hydrocarbon - Layered Formation (Decreasing Permeability with Depth)	-	+	+
2	Chlorinated Hydrocarbon - Layered Formation (Increasing Permeability with Depth)	--	-	-
3	Chlorinated Hydrocarbon - Layered Formation (Alternating Permeability with Depth)	--	-	-
4	Petroleum Hydrocarbon - Layered Formation (Decreasing Permeability with Depth)	++	+	+
5	Petroleum Hydrocarbon - Layered Formation (Increasing Permeability with Depth)	-	-	-
6	Petroleum Hydrocarbon - Layered Formation (Alternating Permeability with Depth)	-	-	-
7	Chlorinated Hydrocarbon - Fractured/Tight Formation	--	--	--
8	Petroleum Hydrocarbon - Fractured/Tight Formation	--	--	--
9	Chlorinated Hydrocarbon - Homogeneous Formation	-	+	+
10	Petroleum Hydrocarbon - Homogeneous Formation	++	+	+
11	Other	?	?	?

Legend:

++ = Determined to be a good physical or technical possibility and a good/unique target for sparging.
+ = Determined to be a good physical or technical possibility and a justifiable (but not unique) target for sparging.
- = Determined to be an unknown physical or technical possibility.
-- = Determined to be not physically or technically possible.

EXHIBIT - D

FIGURE 3
Evaluation of Removal Rate for Volatilization (Well-Mixed Case)

Removal Rate for Volatilization Calculation

Removal $Rate_v$ (mg/day) = C_{est} x Flowrate (ft^3/min)

Where:

Removal $Rate_v$ = Removal Rate for Volatilization (mg/day)

$C_{est} = C_{iw} H_i$

Flowrate (ft^3/min) determined from Figure 10

Where:

C_{est} = Estimate of contaminant vapor concentration (mg/L)

C_{iw} = dissolved concentration of compound i (mg/L)

H_i = Henry's Law constant for compound i (unitless) (from Table 6)

Example:

Known:
C_{iw} = 10 mg/L (from Exhibit - A)
H_i = 0.221 (from Exhibit - D.1)
Flow Rate = 2 ft^3/min (from Exhibit - K)

Therefore:
C_{est} = (10 mg/L)(0.221) = 2.21 mg/L

Then:
Removal $Rate_v$ = (2.21 mg/L)(2 ft^3/min)(28.32 L/ft^3)(1,440 min/day)
= 180,000 mg/day
= 0.18 kg/day

EXHIBIT - D.1

TABLE 6
AIR SPARGING OPTIMIZATION DECISION TOOL

HENRY'S CONSTANTS

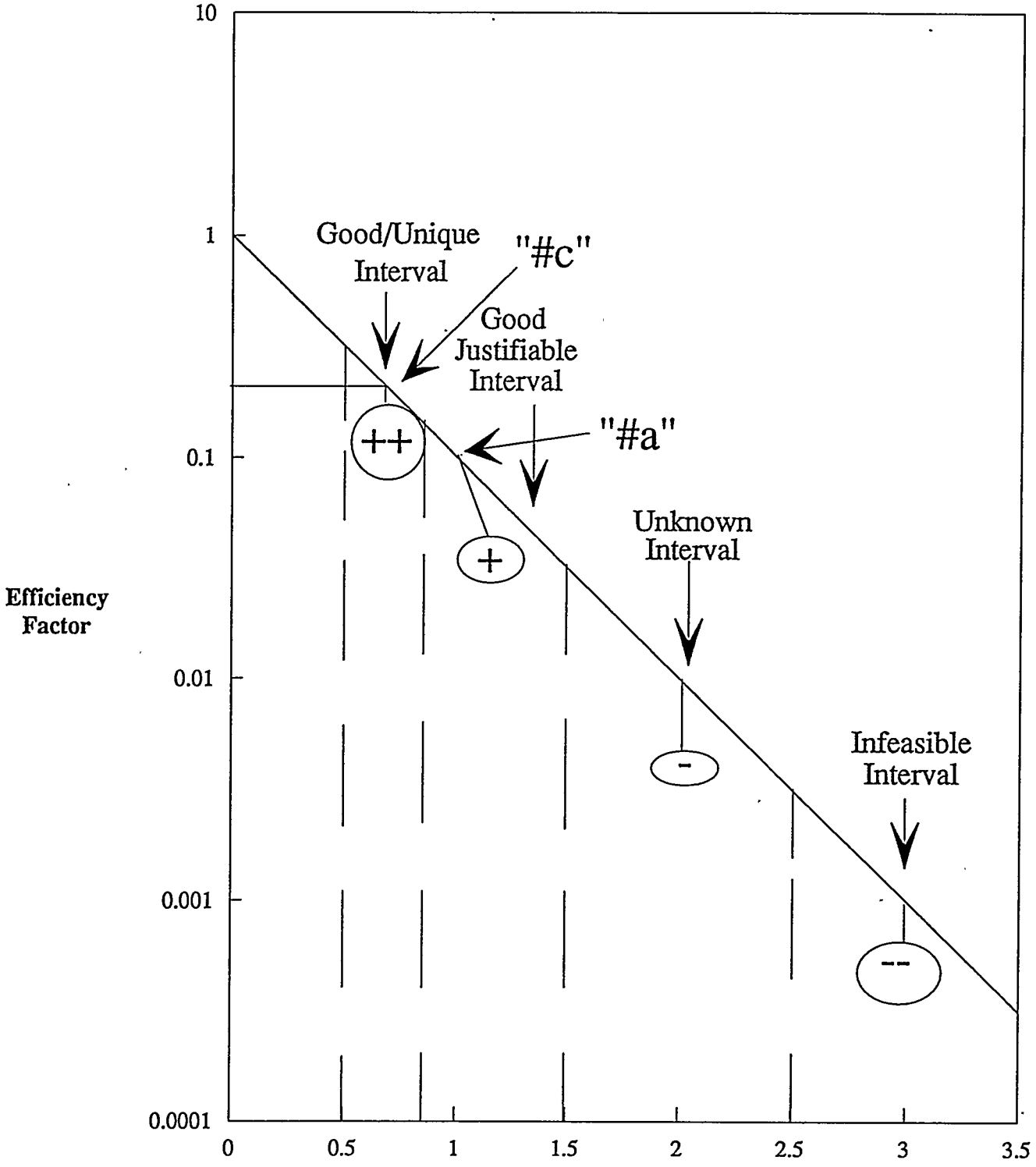
Chemical	Henry's Constant (atm x m^3/mole)	Henry's Constant (unitless)
Benzene	0.00543	0.221 *
Carbon Tetrachloride	0.02	0.813
Chlorobenzene	0.00346	0.141
Chloroethane	0.011	0.447
Chloroform	0.00375	0.152
Cis-1,2-dichloroethene	0.0075	0.305
1,1-Dichloroethane	0.0057	0.232
1,2-Dichloroethane	0.0011	0.0447
1,1-Dichloroethene	0.154	6.26
1,2-Dichloropropane	0.0036	0.146
Ethylbenzene	0.0079	0.321
Methylene Chloride	0.00257	0.104
Styrene	0.00228	0.0927
1,1,2,2-Tetrachloroethane	0.0005	0.0203
Tetrachloroethene	0.0227	0.923
Toluene	0.00661	0.269
Trans-1,2-dichloroethene	0.0066	0.268
1,1,1-Trichloroethane	0.00276	0.112
1,1,2-Trichloroethane	0.00117	0.0476
Trichloroethene	0.00892	0.363
Vinyl Chloride	0.695	2.83
Xylene	0.0054	0.22

* = used benzene value in the calculations of Exhibit D (to provide a conservative estimate).

EXHIBIT - E

FIGURE 4

Efficiency Factor Based on Soil Stratigraphy and Rating From Tier 1



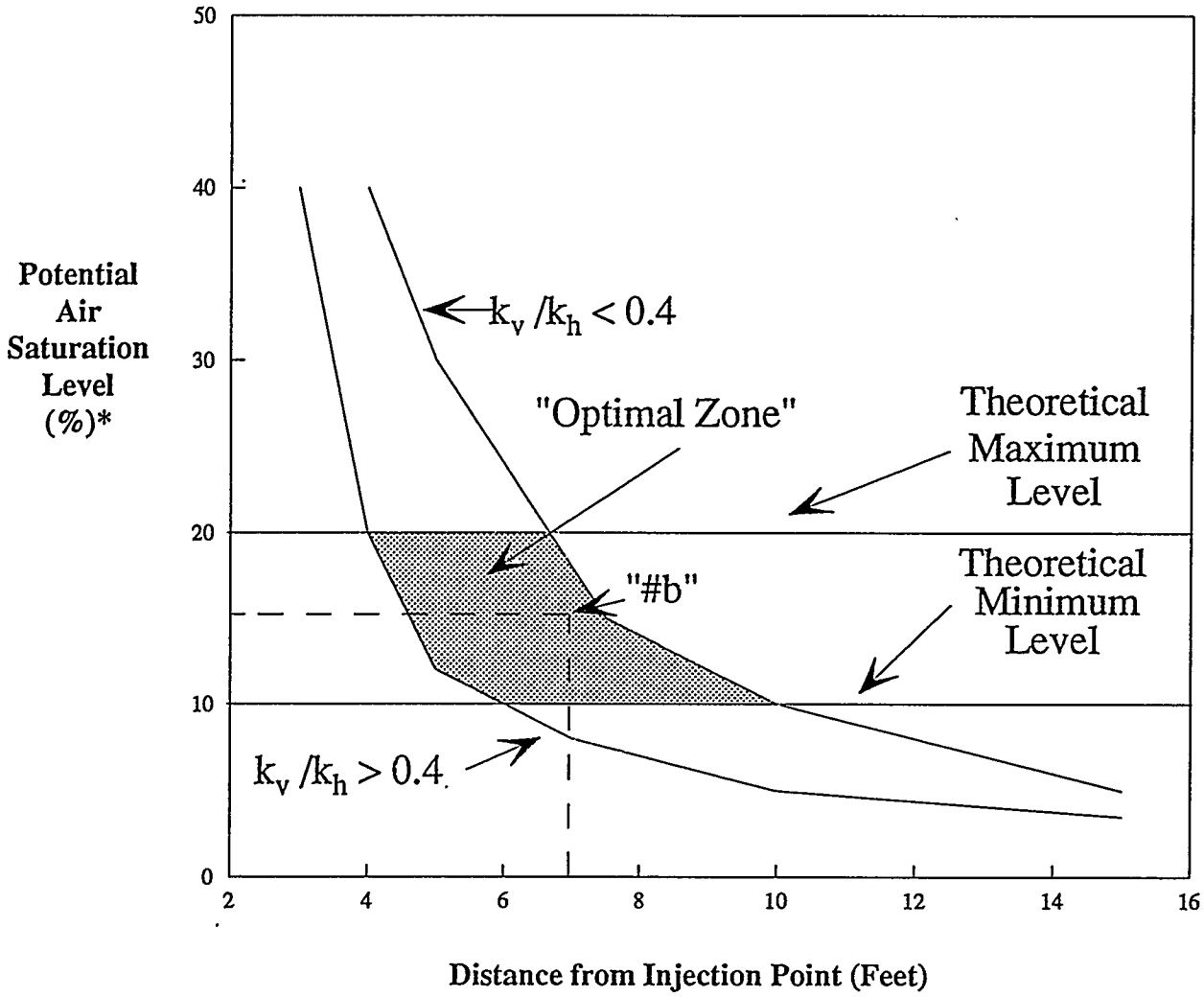
++ = determined to be a good physical or technical possiblity and a good/unique target for sparging.
+ = determined to be a good physical or technical possiblity and a justifiable (but not unique) target for sparging.
- = Determined to be an unknown physical or technical possibility
- = Determined to be not physically or technically possible.

Note: Based on contaminant type and distribution, well spacing, and soil stratrigraphy.

EXHIBIT - F

FIGURE 5

Radial Efficiency of Air Sparging Well



* indicates percentage of available pores which are potentially saturated.
k_v/k_v = Vertical Hydraulic Conductivity/Horizontal Hydraulic Conductivity.
References: (Lundegard, 1994; Acomb, et.al, 1995)

EXHIBIT - G

FIGURE 6
Evaluation of Removal Rate for Volatilization (Diffusion-Limited Case)

Removal Rate for Volatilization Calculation

To derive the graph:

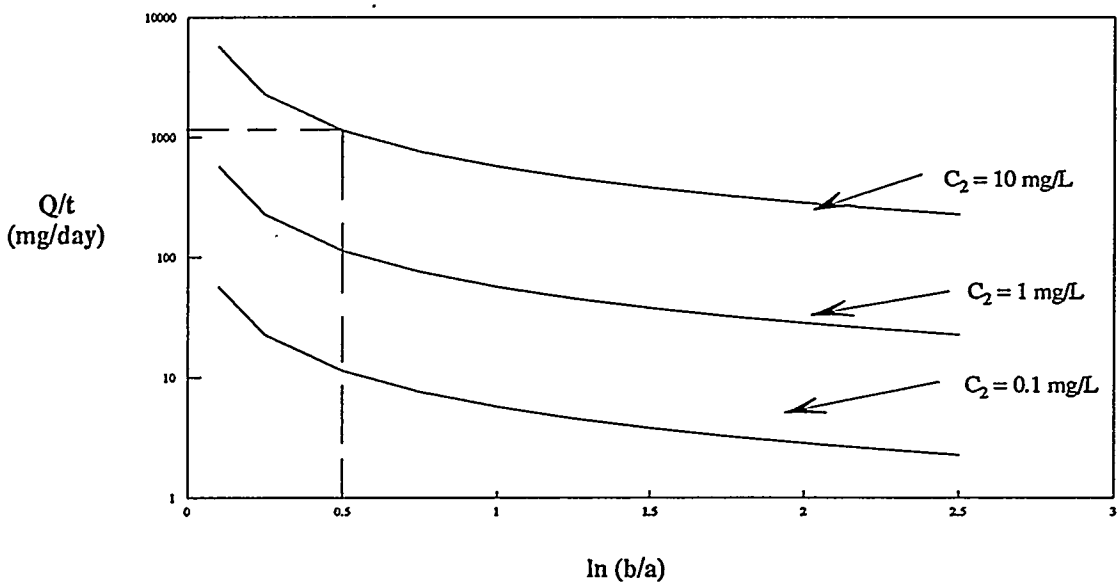
$$(Q_t / t) = \text{mass loss per time} = \frac{(2 \times 3.1415 \times 86{,}400 \text{ sec} \times D \times L \times (C_2 - C_1))}{\ln (b/a)}$$

Where:

- (Q_t / t) = mass loss per time (mg/day) = Removal Rate
- D = Effective diffusion coefficient = $0.00001 \times 0.33^{1.33}$ (cm^2/sec)
- L = Length of channel = number of channels (between 10 and 100)* and depth below water table (cm)
- b = thickness of diffusion zone (measured from edge of channel)(cm)
- a = channel radius (cm)
- C_2 = average dissolved concentration (mg/L)

Assume $C_2 >> C_1$, where C_2 equals the average dissolved concentration in bulk water/channel interface and C_1 is concentration at the air/water interface:

$C_1 = 0$



EXAMPLE:

Known:

C_2 = 10 mg/L (from Exhibit - A)

Assume:

ln (b/a) = 0.5 (worst case)

Then:

Enter graph at ln (b/a) = 0.5; move vertically until intercept curve for C_2 = 10 mg/L;
Move horizontally and obtain Removal Rate (Q/t) = 1,500 mg/day = 0.0015 kg/day.

REFERENCE:

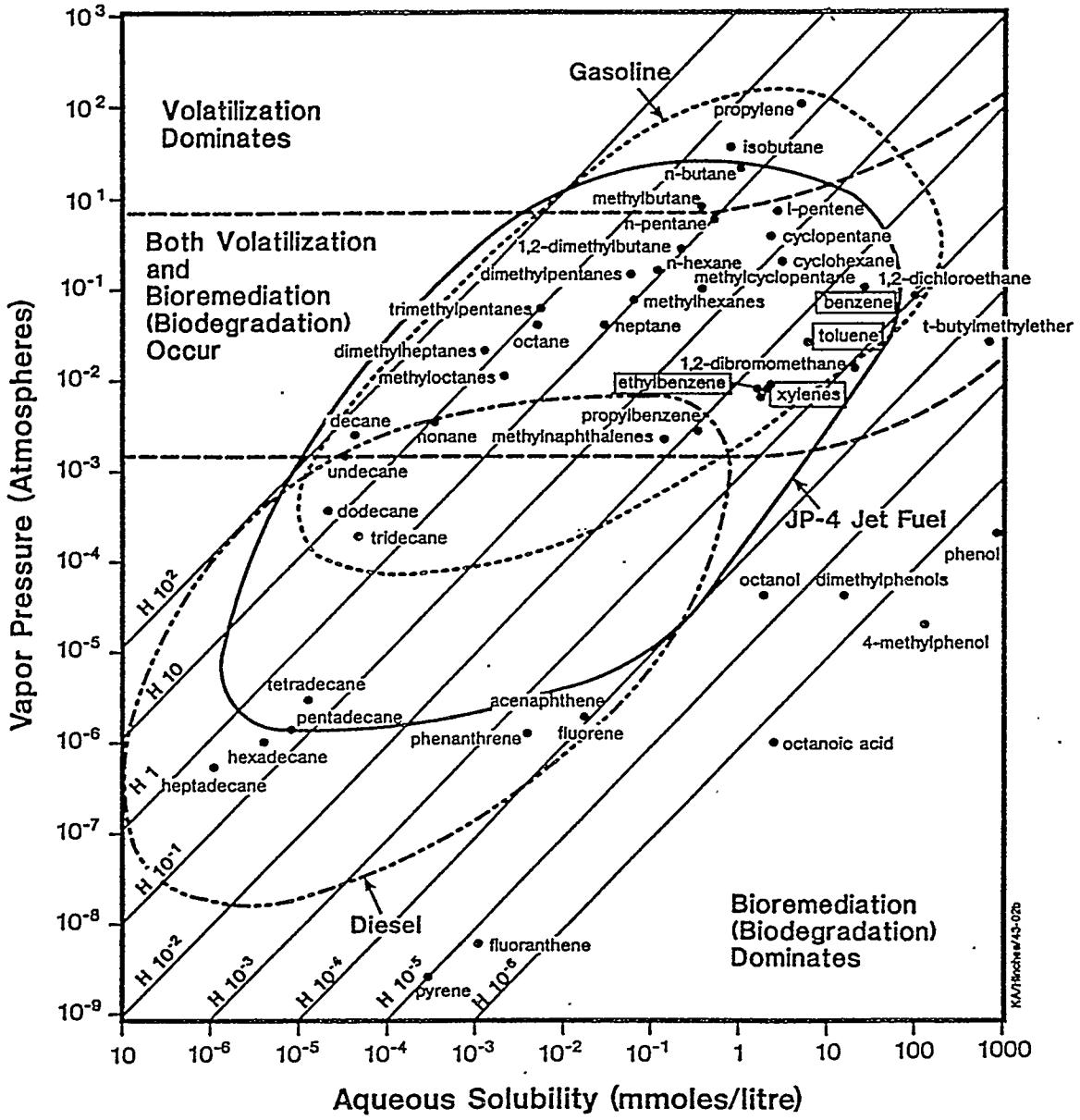
(Johnson, R. L. etal, 1994, Johnson, P. C., personal communication, 6 September 1995)

*For this example, the number of channels used is 100 and the depth below water is 457 cm.

EXHIBIT - H

FIGURE 7

RELATIONSHIP BETWEEN CONTAMINANT PHYSIOCHEMICAL PROPERTIES AND POTENTIAL FOR VOLATILIZATION AND/OR BIOREMEDIATION



H = Henry's Law Coefficient (atm • m³/mole)

[1] Note: This figure should only be utilized for conceptual purposes. In practice, air sparging feasibility is very much dependent on site-specific conditions.

Adapted from "Bioventing" by R.E. Hinchee, R.N. Miller, and C. Vogel, presented at and included in Proceeding of Air Force Center of Environmental Excellence (AFCEE), Technology Transfer Symposium, San Antonio, May 1991.

EXHIBIT - I

FIGURE 8
EVALUATION OF REMOVAL RATES FOR BIODEGRADATION

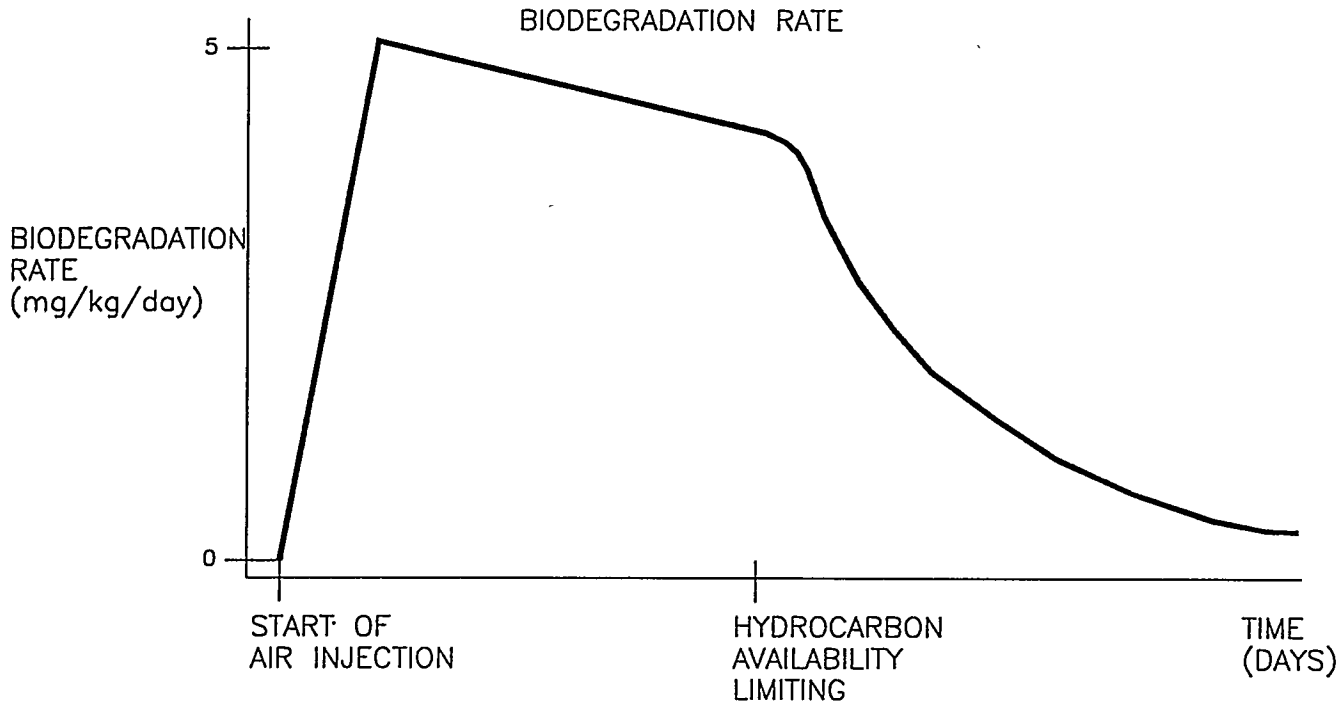


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EXHIBIT - I (Continued)

FIGURE 8 CONTINUED

EVALUATION OF REMOVAL RATES FOR BIODEGRADATION

During NAPL removal, the biodegration rate is almost constant:

$C_n = C_o - 5t$ (Assume Constant Rate = 5mg/kg/day)

Where:
C_n = residual NAPL concentration (mg/kg of aquifer material)
C_o = initial contaminant concentration (mg/kg of aquifer material)
t = time (days)

Subsequent to NAPL removal (i.e., for plume remediation), the biodegration rate varies exponentially:

$C_p = C_o E^{-0.01t}$ (Rate Range = 0.3 to 2.4 %/day); Assume Rate = 1%/day

Where:
C_p = residual plume concentration (mg/L)
C_o = initial plume concentration (mg/L)
t = time (days)
E = 2.71828 (unitless)

In diffusion-limited scenarios, the biodegradation rate is:

$C_d = C_o - At$ (Rate Range = 0.02 to 0.0077 mg/kg/day)

Where:
C_d = residual contaminant concentration in diffusion-limited cases (mg/kg of aquifer material)
C_o = initial contaminant concentration (mg/kg of aquifer material)
t = time (days)
A = rate coefficient equals 0.0077 mg/kg/day or 0.02 mg/kg/day oxygen gradient; assume 0.02 mg/kg/day for very steep gradients (e.g., 10 mg/L over 1 cm) and 0.0077 mg/kg/day for reduced gradients (e.g., 10 mg/L over 10 cm).

EXAMPLE:
Known:
No NAPL removal required.
Dissolved plume remediation required.
Therefore:
Range = 0.3 to 2.4 %/day
Assume:
Removal rate for biodegradation = 1%/day

REFERENCES:
(Johnson, R. L., 1993, Hinchee, R. E., 1994, Acomb, L. J., etal 1995)

EXHIBIT - J

FIGURE 9

Evaluation of Over Pressure, Minimum Injection Pressure and Operating Pressure

Over Pressure Calculation

Step 1: Calculation of Weight of Soil

Weight of Soil (lbs/ft^2) = Depth to Top of Screen (ft) x Soil Bulk Density(lbs/ft^3)

Where: Soil Bulk Density (lbs/ft^3) is available from Table 8

Step 2: Calculation of Weight of Water

Weight of Water (lbs/ft^2) = Water Column Depth (ft) x 62.4 lb/ft^3 x effective porosity

Where: Water Column Depth (ft) = Depth to Top of Screen (ft) - Depth to Water Table (ft)
Note: Effective porosity typically varies from from <1% for tight/fractured matrices to about 30% for sand and gravel matrices

Step 3: Calculation of Total Weight

Total Weight (lbs/ft^2) = Weight of Soil (lbs/ft^2) + Weight of Water (lbs/ft^2)

Step 4: Conversion to Over Pressure

$$\text{Pressure (psig)} = \frac{\text{Total Weight } (lbs/ft^2)}{144\ in^2/ft^2}$$

Step 5: Add Safety Factor

Literature (Marley, M.C.; Btuell, C.J., Oct 94) suggests that a safety factor of 0.6 to 0.8 be applied (i.e., to minimize the chance of over pressurization). For this tool use 0.8.
Over Pressure = 0.8 Pressure (psig)

Evaluation of Minimum Injection Pressure

Step 6: Calculate Minumum Inection Pressure

Pressure (psig) = Weight of Water Column (lb/ft^2)/ (144 in^2/ft^2)

Evaluation of Operating Pressure

Step 7: Determine Operating Pressure

Based on calculations above, the operating pressure can vary between the minimum injection pressure (e.g., at no flow) and the over pressure depending on flow rate and permeability. Refer to Step #18 and and Figure 10 to determine these values.

EXAMPLE:

Known:
Soil Bulk Density = 100 lbs/ft^3 (from Exhibit - J.1)
Depth to Top of Screen = 25 ft (assumed for example)
Depth to Water Table = 15 ft (from Exhibit - A)
Effective Porosity = 0.3 (assumed for sand and gravel)

Step 1: Weight of soil = (25 ft)(100 lbs/ft^3) = 2,500 lbs/ft^2
Step 2: Weight of water = (25 ft - 15 ft)(62.4 lbs/ft^3)(0.3) = 190 lbs/ft^2
Step 3: Total weight = 2,500 lbs/ft^2 + 190 lbs/ft^2 = 2,700 lbs/ft^2
Step 4: Pressure = (2,700 lbs/ft^2)/(144 in^2/ft^2) = 19 psig
Step 5: Over Pressure = (19 psig)(0.8) = 15 psig
Step 6: Minimum Injection Pressure = (620 lb/ft^2)/($144^2/ft^2$) = 4.3 psig.
Step 7: Operating Pressure = Pinject (Exhibit - K). Select 15 psig.

REFERENCE:

(Marley, M.C.; Bruell, C.J., October 1994)

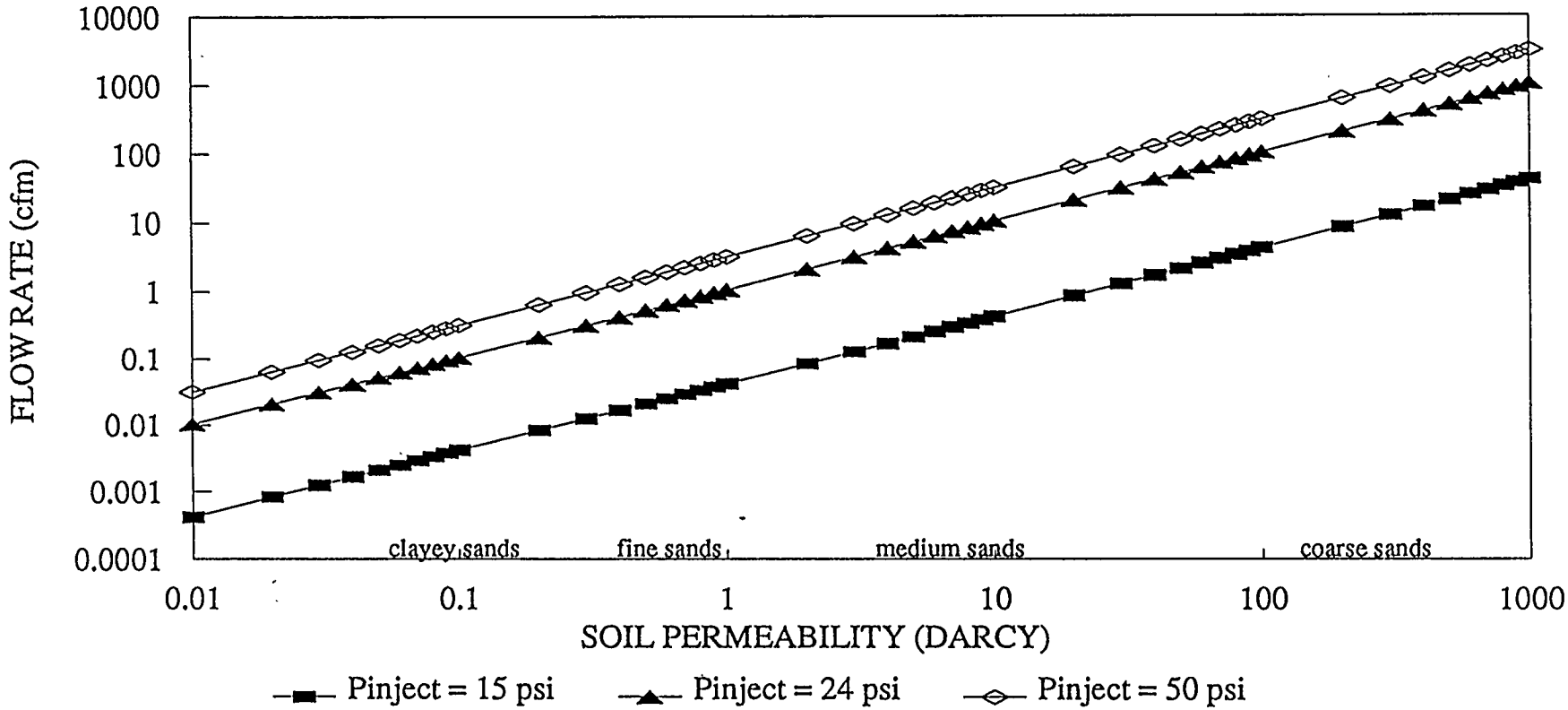
EXHIBIT - J.1

TABLE 8
AIR SPARGING OPTIMIZATION DECISION TOOL

SOIL BULK DENSITY

Material	pounds/feet^3
Sand Ottawa (dry)	92 - 110
Sand Ottawa (wet)	93 - 131
Sand, fine to medium (dry)	83 - 118
Sand, fine to medium (wet)	84 - 136
Sand and gravel (dry)	89 - 146
Sand and gravel (wet)	90 - 155
Silt (dry)	80 - 118
Silt (wet)	81 - 136
Silty Sand (dry)	87 - 127
Silty Sand (wet)	88 -142
Clay (dry)	50 - 112
Clay (wet)	94 - 133
Clay with sand or silt (dry)	60 - 135
Clay with sand or silt (wet)	100 - 147

FIGURE 10
FLOW RATE NOMOGRAPH



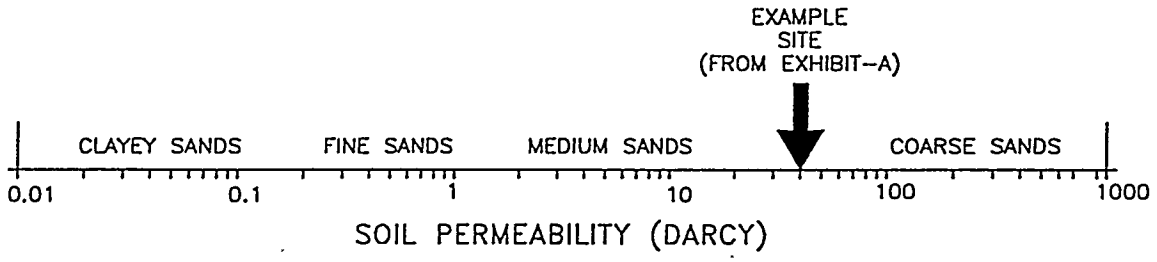
Where:
Pinject = pressure at the injection depth
L = Distance of injection point below water table = 10 feet. Different L values may be approximated by scaling.

Adapted from (Johnson, P.C., et al., 1990b) and personal communication with P.C. Johnson, September 1995.

EXHIBIT - K

EXHIBIT - K.1

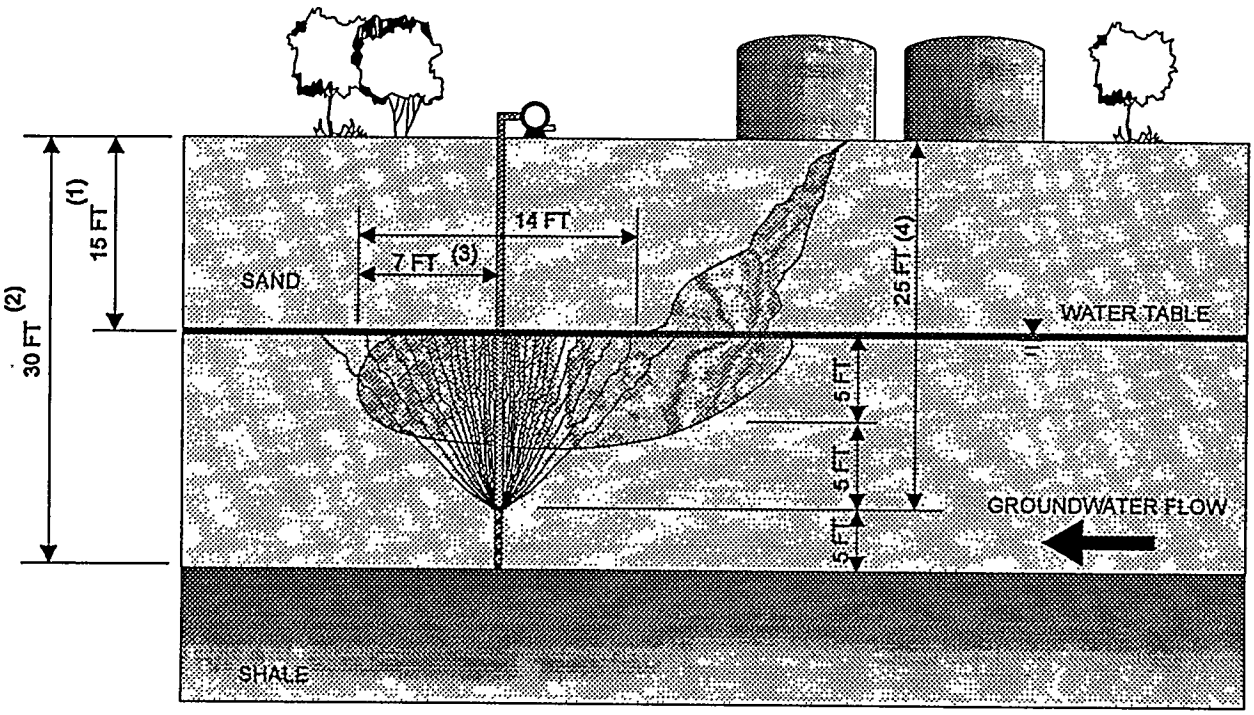
TABLE 7
AIR SPARGING OPTIMIZATION DECISION TOOL SOIL PERMEABILITY



REFERENCE: (JOHNSON, P.C., ETAL; 1990b)

EXHIBIT - L

EFFECTIVE ZONE OF IMPACT



(1) FROM EXHIBIT - A

(2) FROM EXHIBIT - A

(3) FROM EXHIBIT - F

(4) FROM EXHIBIT - J

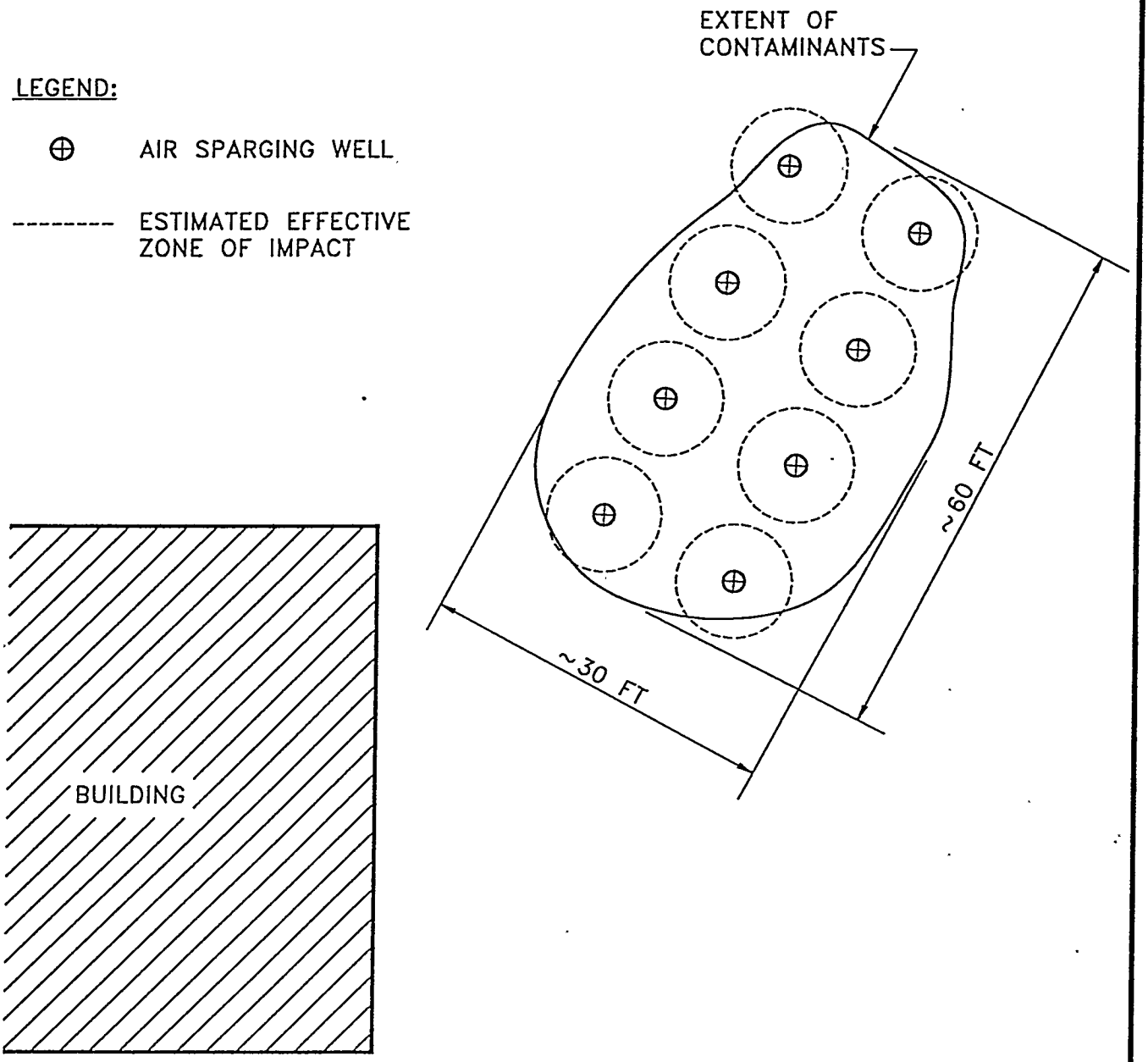
THEREFORE:

RADIUS OF INFUENCE = 7 FT

ZONE OF IMPACT = 14 FT

EXHIBIT - M

ESTIMATE NUMBER OF INJECTION WELLS



CONCEPTUAL SITE PLAN

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EXHIBIT - N

SYSTEM FLOWRATE

Flowrate for each well = 2 ft^3/min (from Exhibit K)
System flow rate = (8 wells)(2 ft^3/min) = 16 ft^3/min

SYSTEM REMOVAL RATE

Modified Removal Rate (by Volatilization) = (0.07 kg/day/well) x (8 wells)
= 0.56 kg/day (from #14)
Removal Rate (by Biodegradation) = 1%/day (from #16)
Total Removal Rate = $0.56t + e^{-0.01t}$

DURATION OF REMEDIAL ACTIVITY

System Volatilization Rate = 0.56 kg/day
System Biodegradation Rate: = 1%/day

Duration (due to Volatilization only)
= mass of contamination to be removed/system volatilization rate
= area x depth x (C_o - C_p)/system volatilization rate
= (60 ft x 30 ft x 7 ft x 28.3 L/ft^3) x (10 mg/L - 0.005 mg/L) x (1 kg/1000 mg) / 0.56 kg/day
= (356,000 L x 9.995 mg/L x 1 kg/mg) / 0.56 kg/day
= 6.4 days

Duration (due to bioremediation only)
= (ln (C_p/C_o)) / 0.01
= 100 x ln (0.005/10)
= 750 days

As a result, most removal will occur due to voltilization. Removal due to bioremediation can be ignored in this example as negligible.

EXHIBIT - O

CONCEPTUAL SYSTEM DESIGN SUMMARY

Modified Removal $Rate_v$ (by Volatilization) = 0.56 mg/day (from #21)

Removal Rate (by Biodegradation) = 1%/day (from #15)

Injection Pressure at each well = 15 psi (from Exhibit - J)

Flow Rate for Each Well = 2 ft^3/min (from Exhibit - K)

Radius of Influence for Each Well = 7 ft (from Exhibit - F)

Zone of Impact for Each Well = 14 fr (from Exhibit - L)

Depth to Water = 15 ft (from Exhibit - A)

Total Depth of Air Sparging Well = 30 ft (from Exhibit - L)

Depth to Top of Well Screen from Water Table = 10 ft (from Exhibit - L)

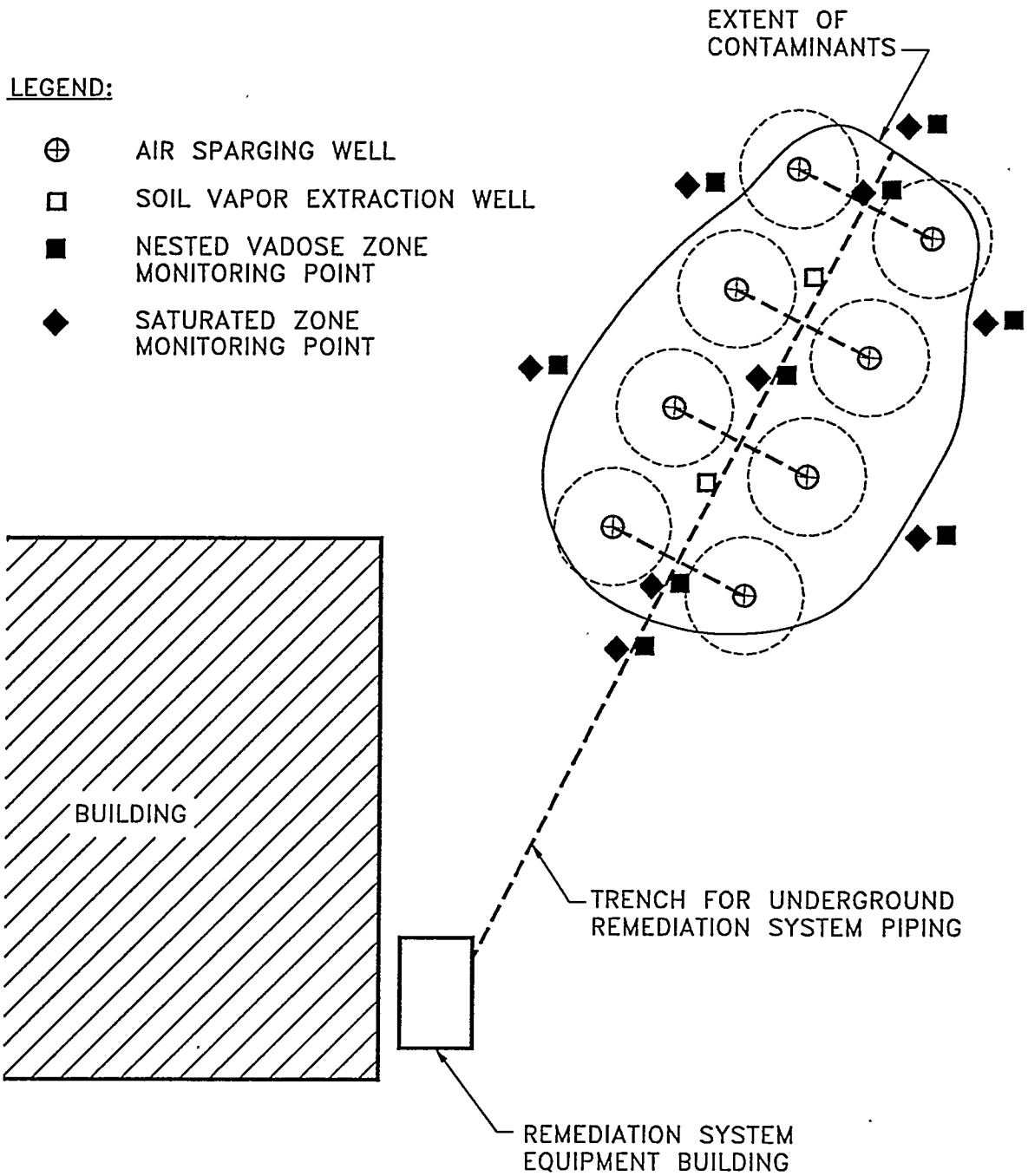
Number of Air Sparging Wells = 8 (from Exhibit - M)

System Flow Rate = 16 ft^3/min (from Exhibit - N)

Duration of Remedail Activities = 7 days (from Exhibit - N)

EXHIBIT - O (Continued)

CONCEPTUAL DESIGN LAYOUT



CONCEPTUAL SITE PLAN

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EXHIBIT - P

TABLE 2

AIR SPARGING OPTIMIZATION DECISION TOOL
ESTIMATED INSTALLATION COSTS – WORKSHEET

	Unit Cost	Units
Well Installation		
Geologist	$1,200 /day	8 days
Travel Costs		
Air Travel	$1,500 /unit	1 units
Mileage	$0.30 /mile	0 miles
Rental Vehicle	$80 /day	8 days
Per Diem	$150 /day	8 days
Miscellaneous Costs (computer, telephone, fax, etc.)	$1,000 /unit	3 units
Subcontractor Services –Drilling Costs		
Mobilization and demobilization	$600 /unit	2 units
Per Diem	$150 /day	8 days
Drilling Rates:		
1.) Install 2 " ID PVC well with continuous wrap screen, no spilt–spoon sampling 16 to 30 ft with 5 ft of screen	$120 /ft	300 ft
2.) Install 4 " ID PVC well with continuous wrap screen, no spilt–spoon sampling 16 to 30 ft with 15 ft of screen	$120 /ft	100 ft
Monitoring Point Installation		
Geologist	$1,200 /day	8 days
Travel Costs		
Air Travel	$1,500 /unit	1 units
Mileage	$0.30 /mile	0 miles
Rental Vehicle	$80 /day	8 days
Per Diem	$150 /day	8 days
Miscellaneous Costs (computer, telephone, fax, etc.)	$1,000 /unit	3 units
Subcontractor Services –Drilling Costs		
Mobilization and demobilization	$600 /unit	2 unit
Per Diem	$150 /day	8 /days
Drilling Rates:		
1.) Install 1 " ID PVC well with continuous wrap screen, no split–spoon sampling 0 to 15 ft with 1 ft of screen	$80 /ft	400 ft
2.) Install 2 " ID PVC well with continuous wrap screen, no split–spoon sampling 16 to 30 ft with 10 ft of screen	$120 /ft	300 ft

Total Well Footage 1100 ft

EXHIBIT - P (Continued)

TABLE 2

AIR SPARGING OPTIMIZATION DECISION TOOL
ESTIMATED INSTALLATION COSTS – WORKSHEET

	Unit Cost	Units
System Installation		
Engineer	$1,600 /day	30 days
Technician	$1,000 /day	30 days
Construction Oversight	$1,400 /day	60 days
Travel Costs		
Air Travel	$1,500 /unit	20 units
Mileage	$0.30 /mile	0 miles
Rental Vehicle	$80 /day	80 days
Per Diem	$150 /day	80 days
Miscellaneous Costs (computer, telephone, fax, etc.)	$1,000 /unit	15 units
Contractor Labor, Equipment and Materials:		
Labor: Superintendent / Foreman	$1,200 /day	60 days
Operator(s)	$800 /day	60 days
Pipefitter(s) / Plumber(s)	$800 /day	60 days
Electrician(s)	$800 /day	60 days
Laborer(s)	$600 /day	60 days
Per Diem	$150 /day	300 days
Equip.: Mobilization and demobilization	$2,000 /unit	8 units
Excavator	$1,500 /day	40 days
Multi–purpose Uniloader	$600 /day	60 days
Dump Truck	$400 /day	60 days
Concrete saw rental	$100 /day	30 days
Plate compactor	$100 /day	30 days
Storage/Tool Trailer	$100 /day	60 days
Project Field Trailer	$200 /day	60 days
Materials:		
Pipe / Hose:		
Schedule 40 PVC – 4 " Diameter	$3 /ft	2000 ft
Schedule 40 PVC – 2 " Diameter	$2 /ft	2000 ft
PVC Fittings(elbows, tees, unions,etc.)	$800 /unit	4 units
Schedule 40 Galv. Steel – 1 " Diameter	$5 /ft	2000 ft
Galv. Steel Fittings(elbows, tees, unions,etc.)	$800 /unit	2 units
Other Fittings:		
Ball Valve, Sch. 80 PVC – 4 " Diameter	$25 /fitting	20 fittings
Ball Valve, Sch. 80 PVC – 2 " Diameter	$15 /fitting	20 fittings
Ball Valve, Copper – 1 " Diameter	$5 /fitting	20 fittings
Gate Valve, Steel – 2 " Diameter	$10 /fitting	20 fittings
Check Valve, Copper – 2 " Diameter	$5 /fitting	10 fittings
Solenoid Valve – 1 " Diameter	$20 /fitting	10 fittings

EXHIBIT - P (Continued)

TABLE 2

AIR SPARGING OPTIMIZATION DECISION TOOL
ESTIMATED INSTALLATION COSTS – WORKSHEET

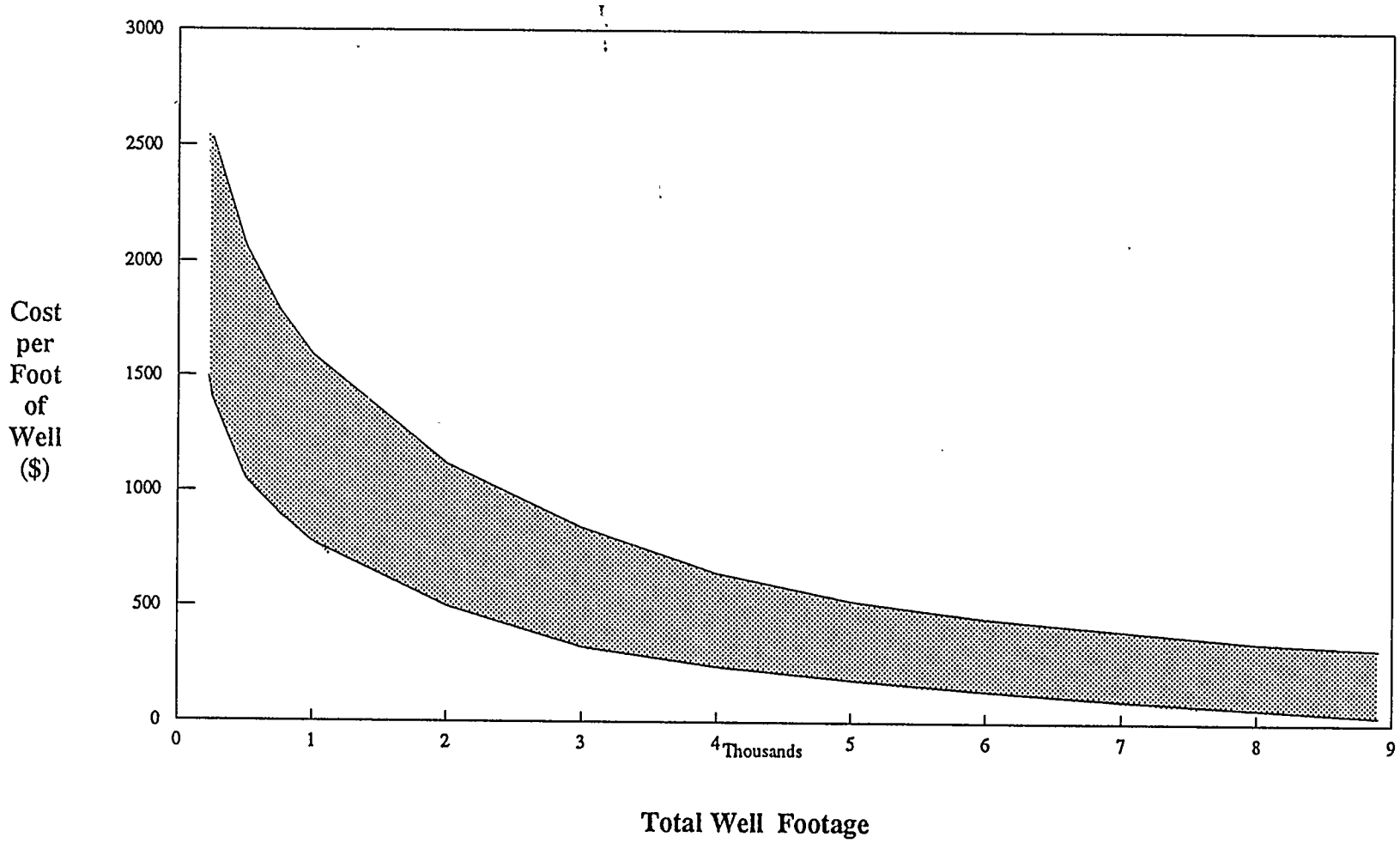
	Unit Cost	Units
Miscellaneous:		
Trench Backfill Material	$15 /yd^3	200 yd^3
Pavement Subbase Material	$10 /yd^3	100 yd^3
Concrete Pav't Replac., 8" thk. with wire mesh	$25 /yd^2	100 yd^2
Asphalt Pave't Replac., 4" base with 2" top	$25 /yd^2	100 yd^2
Equipment Building		/unit 1 units
Electrical Service	$3,000 /unit	1 units
System Controls	$5,000 /unit	1 units
Air Sparging Equipment:		
Compressor / Vacuum Pump		/unit 1 units
Regulator	$200 /unit	6 units
Pressure gauge	$40 /unit	20 units
Pressure relief valve	$100 /unit	1 units
Flow Measurement Device	$300 /unit	6 units
Soil Vapor Extraction Equipment:		
Blower / Vacuum Pump	$8,000 /unit	1 units
Vacuum relief valve	$200 /unit	1 units
Moisture removal tank with level controls	$2,000 /unit	1 units
Transfer pump to evacuate tank	$2,000 /unit	1 units
Lower explosive limit device	$1,000 /unit	1 units
Particulate filter	$800 /unit	2 units
Vacuum Gage	$40 /unit	10 units
Flow Measurement Device	$300 /unit	6 units
Off–gas Treatment	$1,000 /unit	3 units

Estimated Installation Cost $935,000

Assumptions / Clarifications:

- Well installation should be supervised by a qualified geologist.
- System installation should be supervised by a qualified representative/firm.
- Other Installation and Non–installation Costs (not included on table)
  - Final design and/or preparation of Bid Documents (plans and specifications).
  - Bonds, Permits, Licenses, etc.
  - Barricades, Shoring and Dewatering of Excavations.
  - Appropriate disposal of impacted or non–impacted soil and water generated by installation activities., excavated from trenching or drill cuttings.
  - Reporting Requirements
  - Project Management
  - System Startup and Ongoing Operation, Maintenance and Monitoring.
  - Appropriate disposal of Soil Vapor Extraction, Off–gas Treatment Media, if used.

FIGURE 11
Cost Guidance - System Installation



Note: Cost curve based on typical large-scale government projects. Smaller industrial projects may be significantly discounted. Based on General Accounting Office study, a factor of about 3.0 may be used.

EXHIBIT - Q

EXHIBIT - R

TABLE 3
AIR SPARGING OPTIMIZATION DECISION TOOL
PILOT TEST SPARGING SUMMARY

What You Expect to Learn	Activities	Required Equipment	Duration
Feasibility of injecting air into subsurface	Inject air, pressure monitoring, and observations of impact.	1 injection well and 1 monitoring well if available.	1-2 days
First determination of air sparging performance	Monitor increased recovery in a SVE system (compared with pre-established baseline).	Turn on soil vapor extraction or assume previous soil vapor extraction operational performance history.	2-3 days
Qualitative determination of air sparging performace	Monitor for changes in vadose zone concentrations (CO_2,O_2, VOCs, etc.).	Add vadose zone monitoring points.	1-2 days
Better understanding of horizontal and vertical distribution of air flow	Monitor for changes in DO in the saturated zone and for changes in vadose concentrations (CO_2,O_2, VOCs, etc.).	1 injection well, 1 monitoring well, and 2 multi-depth piezometers.	1-2 days
Changes in dissolved oxygen level distribution and potential for biodegradation	Longer term monitoring for changes in vadose zone and saturated zone concentrations.	1 injection well, multiple monitoring wells, and 2 multi-depth piezometers	3-5 days
Three dimensional conceptual model of air flow and saturation	Monitor tracers and percentage of sparge air (tracer) recovered with soil vapor extraction. Measure appearance of tracer in vadose zone. Determine air flow patterns from tracer test.	1 injection well, multiple monitoring wells, 2 multi-depth piezometers, and add tracers (He, SF_6)	1-5 days

APPENDIX D

BIBLIOGRAPHY

The bibliography which follows originates from Appendix A of the report entitled "Existing Air Sparging Model and Literature Review for the Development of An Air Sparging Optimization Decision Tool", dated August 1995. The bibliography has been revised to include additional literature discovered and used during the development of the "Conceptual Air Sparging Decision Tool" document. Complete citations for the stated references in this document are included in the bibliography as well as additional citations that may provide further reference for review by the end-user.

APPENDIX D

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