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**EXISTING AIR SPARGING MODEL
AND LITERATURE REVIEW FOR THE
DEVELOPMENT OF AN AIR SPARGING
OPTIMIZATION DECISION TOOL**

Prepared by

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MSE Technology Applications, Inc.
P.O. Box 4078
Butte, Montana 59702

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OPTIMIZATION DECISION TOOL**

Prepared For:

**MSE, INC.
BUTTE, MONTANA**

**IN PARTIAL FULFILLMENT OF MSE, INC.'s
REQUEST FOR PROPOSAL NO. A57124, ADMINISTERED
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AUGUST 1995

Prepared By:

**PARSONS ENGINEERING SCIENCE, INC.
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TABLE OF CONTENTS

	<u>Page</u>
EXECUTIVE SUMMARY	
ACKNOWLEDGEMENTS	
SECTION 1.0 INTRODUCTION	1-1
1.1 Purpose of Review Process	1-1
1.2 Scope of Review Process	1-1
SECTION 2.0 LITERATURE REVIEW	2-1
2.1 Findings from Literature Review	2-1
2.1.1 In-Well Aeration and Unterdruck-Verdampfer-Brunned (UVB)	2-2
2.1.2 <i>In Situ</i> Air Sparging	2-5
2.1.2.1 State-of-the-Art for Air Sparging	2-6
2.1.2.1.1 Chemical Contamination Remediated by Air Sparging	2-6
2.1.2.1.2 Soils Applicable for Air Sparging	2-6
2.1.2.1.3 Biological Degradation	2-8
2.1.2.2 State-of-the-Practice for Air Sparging	2-8
2.1.2.2.1 Discussions About Air Flow	2-8
2.1.2.2.2 Groundwater Mounding (Upwelling) and Hydraulics	2-11
2.1.2.2.3 Pulsed or Intermittent Operation	2-12
2.1.2.2.4 Aquifer Clogging	2-12
2.1.2.2.5 Augmentation Technologies	2-13
2.1.2.2.6 "Rules of Thumb" for the Application of Air Sparging	2-13
2.1.2.2.7 Variations on the Application of Air Sparging	2-14
2.2 Current Work in Progress	2-15
2.2.1 International Activities	2-16
2.3 Areas Identified in the Literature for Future Development	2-18
SECTION 3.0 AVAILABLE MODELS	3-1
SECTION 4.0 PARAMETERS RELEVANT TO THE DEVELOPMENT OF THE DECISION TOOL	4-1
4.1 Applicability	4-1
4.1.1 General Properties	4-1
4.1.2 Specific Parameters	4-3
4.1.2.1 Geologic Setting	4-3
4.1.2.2 Type of Impact	4-3
4.1.2.3 Contaminant Type	4-3
4.1.2.4 Geologic Setting (for Conceptual Geologic Model of the Site)	4-4
4.1.2.5 Contaminant Spatial Characteristics	4-4
4.1.2.6 Contaminant Physical Characteristics	4-4
4.1.2.7 Conceptual Design Considerations	4-4
4.1.2.8 Economic/Political Considerations	4-4
4.1.2.9 Pilot Test System Parameters	4-5
4.1.2.10 Monitoring Parameters	4-5
4.2 Optimization	4-5
4.2.1 General Properties	4-5
4.2.2 Optimization Parameters	4-5
SECTION 5.0 QUESTIONS THAT THE DECISION TOOL WILL ATTEMPT TO ANSWER	5-1
5.1 Applicability	5-1
5.2 Optimization	5-2
5.3 Objective Functions	5-2

TABLE OF CONTENTS

(continued)

	<u>Page</u>
SECTION 6.0 SCOPE OF THE DECISION TOOL	6-1
6.1 Conceptual Description of the Decision Tool	6-2
6.1.1 Detailed Discussion of Tier 1: Scenario Approach	6-2
6.1.2 Detailed Discussion of Tier 2: Conceptual Feasibility	6-4
6.1.3 Detailed Discussion of Tier 3: Pilot Studies	6-8
6.1.4 Optimization	6-8
6.1.5 Project Features of the Decision Tool	6-10
SECTION 7.0 KEY SUCCESS FACTORS FOR THE DECISION TOOL	7-1
SECTION 8.0 APPLICATIONS FOR DECISION TOOL USE	8-1
8.1 General Considerations for Use	8-1
8.2 U.S. Department of Energy (DOE) Facilities	8-4
8.3 Other Governmental Facilities	8-5
8.4 General Industrial Sites	8-5
8.5 Technology Transfer	8-6
APPENDIX A - Bibliography	A-1
APPENDIX B - Detailed Overview of Air Sparging Models	B-1
APPENDIX C - Listing of Relevant Parameters for Evaluating Applicability and Optimization	C-1
APPENDIX D - Air Sparging Model Questionnaire	D-1
LIST OF FIGURES	
Figure 1 - Conceptual Representations of In-Well Aeration and Air Sparging	2-3
Figure 2 - Conceptual Representations of UVB Well	2-4
Figure 3 - Sample Template	6-3
Figure 4 - Scale of Projected Air Sparging Effectiveness	6-7
Figure 5 - Preliminary Decision Treet (6 sheets)	6-11
Figure 6 - Potentially Appropriate Opportunities for Decision Tool Use During the Site Remediation Process	8-3
LIST OF TABLES	
Table 1 - Air Sparging Model Review Summary (4 sheets)	3-3
Table 2 - Summary of Decision Tool Scenarios	6-5
Table 3 - Pilot Test Sparging Summary	6-9
Table B-1 - Relationships and Parameters (8 sheets)	B-2
Table B-2 - Modeling Information and Success Ratings (20 sheets)	B-10

EXECUTIVE SUMMARY

The objectives of this Report are two-fold: (1) to provide overviews of the state-of-the-art and state-of-the-practice with respect to air sparging technology, air sparging models and related or augmentation technologies (e.g., soil vapor extraction); and (2) to provide the basis for the development of the conceptual Decision Tool.

To develop the state-of-the-art and state-of-the-practice, the Project Team conducted an exhaustive review of available literature, including conference proceedings, journals, guidance documents, reference books as well as (where accessible) proprietary, confidential and public domain reports. The complete listing of the documents, numbering several hundred and reviewed as a part of this task, is included in Appendix A. Even with the large amount of material written regarding the development and application of air sparging, there still are significant gaps in the technical community's understanding of the remediation technology. The results of the literature review are provided in Section 2.

In Section 3, an overview of seventeen conceptual, theoretical, mathematical and empirical models is presented. Although no evidence of an available or developmental air sparging decision tool was found during the effort, much information valuable for Decision Tool development, was identified. In particular, information from the models reviewed will be useful for developing logical, conceptual and relational aspects of the Decision Tool. Detailed descriptions of each of the models reviewed is provided in Appendix B. Included in Appendix D is a copy of the questionnaire used to compile information about the models.

The remaining sections of the document reflect the analysis and synthesis of the information gleaned during the literature and model reviews. The results of these efforts provide the basis for development of the decision tree and conceptual decision tool for determining applicability and optimization of air sparging. Specifically, a listing of parameters relevant to the development of the Decision Tool, questions that the Decision Tool is being developed to answer and the scope of the Decision Tool are immediate products of the review efforts. The preliminary decision tree and accompanying information provided in Section 6 describe a three-tiered approach for determining air sparging applicability: comparison with established scenarios; calculation of conceptual design parameters; and the conducting of pilot-scale studies to confirm applicability.

The final two sections of this document provide listings of the key success factors which will be used for evaluating the utility of the Decision Tool and descriptions of potential applications for Decision Tool use. The Tool is being developed for wide-spread application by prospective practitioners in U.S. DOE, other governmental, academic and industrial settings. It is anticipated that the Decision Tool will be useful during several stages of remediation planning, design and implementation. The accompanying figure provides examples of opportunities for Tool usage during the various stages of a generic remediation project.

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

ACKNOWLEDGEMENTS

Parsons Engineering Science, Inc. (Parsons ES) would like to express appreciation to the American Petroleum Institute, Envirogen, Inc. and Mike Marley for allowing extensive borrowing from the document titled "*In situ* Air Sparging: Evaluation of Petroleum Industry Sites and Considerations for Applicability, Design and Operation" (Draft 1994).

Parsons ES would also like to extend its gratitude to the many contributors to this document, especially including all those who completed the air sparging model questionnaire (a copy of which is included in Appendix D). Summarized results of the input received have been included in Section 3 and Appendix B of this document.

Finally, and most appropriately, Parsons ES expresses its appreciation to the technical and user community panel reviewers who took time from their already busy schedules to review and to provide comments on the technical accuracy and user-friendliness of this document.

SECTION 1.0

INTRODUCTION

The technical community's understanding of air sparging technology is continuously evolving. Environmental professionals (including researchers, scientists, engineers and field practitioners) are progressively gaining knowledge regarding the underlying scientific principles and processes which control air sparging technology. Advances in this technology are being achieved through research efforts, model development, pilot-scale studies and field-scale implementation funded by government and private interests.

1.1 PURPOSE OF REVIEW PROCESS

The purpose of this review effort is to compile and summarize the available literature and modeling efforts related to the remedial technology of air sparging. There are many individuals and groups who are currently investigating this multi-faceted topic. Some experts are focusing on theoretical multi-phase flow modeling, while others are conducting bench-scale laboratory and large-scale physical demonstrations. This review process is an attempt to provide an insight into the current level of understanding and future directions of air sparging technology. Appendix A provides a list of the literature reviewed for this task.

As part of the review process, the developers of air sparging models were contacted for information with respect to their particular models. They were asked to briefly describe their models, including their models' capabilities. A discussion of the findings from the model review is included in a subsequent section; a table with an overview of each model is included in Appendix B.

This document also serves as a framework to identify the key parameters for determining the applicability and optimization of air sparging at a site. This information will be used to provide a basis for the development of a conceptual Decision Tool to be used in evaluating the applicability and optimization of applying air sparging to individual sites. Also defined is the scope of the Decision Tool, including discussions of what questions the Decision Tool will answer, key success factors for the Decision Tool and potential applications for Decision Tool use.

1.2 SCOPE OF REVIEW PROCESS

The scope of this review process is to review work completed or underway in air sparging (including that reported in literature and demonstrated through modeling) in the United States

and internationally. The review targets include work completed or being undertaken by the U.S. Department of Energy (DOE), other government organizations, private industry, and academia.

As part of this review process, the findings from the model and literature review have been synthesized and are reported. Also as part of the review process, the key parameters for the Decision Tool are established, questions that the Tool will address are developed, key success factors are identified and the scope of the Decision Tool is defined.

SECTION 2.0

LITERATURE REVIEW

The purpose of this review is to present a brief summary of the evolution of air sparging technology, a detailed exposition of the current states-of-the-art and -practice of the technology, and an assessment of where the technology is headed. The following section details the information collected from the review of available literature (including conference proceedings, journals, guidance documents, reference books and proprietary, confidential and public domain reports). A complete listing of the references reviewed for this task is included in Appendix A.

2.1 FINDINGS FROM LITERATURE REVIEW

Due to previous incidences of volatile and semi-volatile contamination, owners and/or operators of Department of Energy (DOE), other governmental agency (i.e., Department of Defense (DoD)) and industrial sites have embarked on programs to remediate impacted soil and groundwater. Technologies such as groundwater extraction, also known as "pump and treat", were (and still are) traditionally used to address hydrocarbon contamination in the saturated zone. However, because most hydrocarbons have relatively low aqueous phase solubilities, large volumes of water must be pumped from the site to solubilize and mobilize these hydrocarbon compounds (Hinchee *et al.* 1987). Consideration of the large quantities of groundwater to be recovered and treated, the costs associated therewith, and the duration of recovery and treatment efforts required to achieve remediation objectives become important factors when implementing groundwater recovery systems.

Recently, environmental professionals have considered enhancements and augmentation to such systems, including injection of (sparging) air into the saturated zone to strip volatile contaminants from the groundwater to improve remediation effectiveness. Air sparging has been reported to enhance the extraction and increase the rate of natural biodegradation of volatile and semi-volatile organic constituents. For this reason, air sparging is growing in popularity as a remedial technology for addressing dissolved volatile contamination in the saturated zone.

Sparging technology involves the injection of air (or other gases) into the saturated zone for the dual purposes of volatilizing organic contaminants and enhancing biodegradation. Currently, there are two distinct remedial techniques utilized for delivering air beneath the water table: in-well aeration (Buermann 1990, Gvirtzman and Gorelick 1992, Pankow *et al.*

1993) and *in situ* air sparging (Gudemann and Hiller 1988, Ardito and Billings 1990, Eddy *et al.* 1991, Loden and Fan 1991, Marley *et al.* 1992, R. Johnson *et al.* 1993, *inter alia*).

In the first type of air injection treatment technology, known as in-well aeration, the air is injected and rises vertically within the casing of the injection well or trench (Figure 1). Treatment by volatilization occurs in the well and oxygenated water flows out of the well into the aquifer. In contrast, the process of *in situ* air sparging involves the injection of air into the saturated zone, typically below the source area of contamination. With *in situ* air sparging, contaminant-free air is forced into the saturated zone facilitating volatilization and biodegradation within the surrounding soil matrix.

2.1.1 In-Well Aeration and Unterdruck-Verdampfer-Brunned (UVB)

Since the principal focus of this review process is *in situ* air sparging, the following cursory discussion of in-well aeration is provided for reader information only, to delineate the two approaches; the balance of subsequent sections focuses on *in situ* air sparging.

The remedial technique utilized for in-well aeration involves forcing air into a specially designed well. The air is injected at the bottom of the well, causing an uplift effect in the well. The injected air induces a convective flow of groundwater into the bottom of the well and laterally out of the top of the well at the water table. As the air rises, it also facilitates the mechanisms of volatilization and biodegradation. The specially designed well is generally screened near the water table surface and at the bottom of the well, with an impermeable seal installed in the sand pack between the two sections of screen. This configuration encourages the formation of a convective flow pattern while eliminating short circuiting. Other processes which are similar to the above technique have been advanced in Germany under the name Unterdruck-Verdampfer-Brunned, abbreviated UVB (and translated as vacuum vaporizer well). The configuration for a UVB is similar to the in-well aeration layout discussed previously. However, there are some notable differences in the way the process is accomplished and the UVB well is constructed (Figure 2). In addition to UVB, more than a dozen patents have been issued by the U.S. patent office for variations of the in-well aeration approach.

The UVB arrangement couples a soil vapor extraction system withdrawing vapor, while air is being injected near the water table surface, with a liquid pump to help induce groundwater flow. The construction of a UVB well actually has a seal on the interior of the well with the discharge of the pump (or the aeration compartment) being the only penetration in the seal.

CONCEPTUAL VIEW OF IN-WELL AERATION

CONCEPTUAL VIEW OF AIR SPARGING WELL

CONCEPTUAL REPRESENTATIONS OF
IN-WELL AERATION AND AIR SPARGING

UPWARD WATER FLOW FOR DNAPLS

DOWNWARD FLOW FOR LNAPLS

CONCEPTUAL REPRESENTATIONS OF UVB WELL

When the UVB arrangement is used to address dense non-aqueous phase liquids (DNAPLs), a vacuum is applied to the unsaturated zone to achieve the dual purpose of capturing any volatilized constituents and to encourage mounding of the groundwater table. Air is injected at the water table surface (also causing mounding) while a pump draws water from a deeper zone within the well, discharging upward into the upper portions of the well. The mounding of the water table, coupled with the pumping, induces flow from the lower portion of the well into the upper portion of the well. This flow promotes a consequent convective flow from the upper portion of the aquifer down into the lower portion of the aquifer. The continuation of the convective flow forces water up the well where it is treated (aerated) and the cycle is continued.

When the UVB arrangement is used to remediate light non-aqueous phase liquids (LNAPLs), the process is reversed. There is an elevated aeration compartment in the well that has an opening to the deeper portion of the well. A vacuum is applied to withdraw volatilized contaminants and to encourage groundwater flow into the well. Air is injected into the elevated aeration compartment where the water level is kept at a constant head by the pump which draws water from the upper portion the well. The pumping from the upper portion of the well creates an elevated head in the aeration compartment which causes flow into the deeper portion of the well. This process induces a convective current from the lower portion of the aquifer up into the upper portion of the aquifer. The water then flows into the well where it is treated (aerated) and the cycle is continued.

2.1.2 *In Situ* Air Sparging

The following discussions provide a detailed summary of, and illustrate the similarities and differences between, the state-of-the-art and the state-of-the-practice of *in situ* air sparging (hereafter called air sparging). Section 2.1.2.1 describes the state-of-the-art of air sparging and includes the process theory and governing phenomena. It is based on the knowledge and experience gained from peer-reviewed research and demonstration. Section 2.1.2.2 discusses the state-of-the-practice, and endeavors to describe how air sparging is being selected, designed, constructed, and operated/monitored, as well as how some systems have performed. Thus, the section which describes the state-of-the-art discusses what is the current understanding of the science of air sparging while the state-of-the-practice section focuses on what field practitioners are actually doing.

2.1.2.1 State-of-the-Art for Air Sparging

The process of air sparging involves the injection of air into the saturated zone, ideally below the source area of contamination. With air sparging, contaminant-free air is forced into the saturated zone with the intent of facilitating volatilization and biodegradation within the surrounding soil matrix. The injected air is 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. Hydrostatic pressure is equivalent to 1 psig for every 2.3 feet of water column or 0.433 psi/ft. The magnitude of the air-entry pressures can range from less than one inch of water column for gravels to several feet of water column for silty or clayey soils (R. Johnson *et al.* 1993). The use of air sparging also facilitates concurrent enhancement of aerobic biodegradation of contaminants by the addition of oxygen (Hazen 1992). The air pressure gradient imposed by the injection well removes volatile constituents from the saturated zone and mobilizes them into the unsaturated zone. When an air sparging system is activated at a site, the goal is to disturb the equilibrium conditions between the organic phases (as NAPLs, or in soil as vapor or moisture) and enhance vapor partitioning. As VOC removal continues, more volatile constituents in the saturated zone partition into the vapor phase, thereby continuing the cycle. In summary, the air sparging process uses the mechanisms of volatilization, advection, diffusion, dispersion, and biodegradation to reduce the concentrations of dissolved chlorinated, petroleum and other hydrocarbons in the groundwater and the soil of the saturated zone.

2.1.2.1.1 Chemical Contamination Remediated by Air Sparging

As stated, air sparging is thought to be capable of remediating volatile organic and semi-volatile compounds (ie., VOCs and SVOCs) as well as other potentially aerobically biodegradable chemical contaminants (e.g., coal tars and other higher molecular weight constituents). These include chlorinated solvents (e.g., trichlorethene and dichloroethene) and petroleum hydrocarbon constituents (e.g., benzene, toluene, ethylbenzene and xylenes). Air sparging has been attempted to address these contaminants in several general situations: in the aqueous phase; while held immobile at residual saturation within the soil matrix; and combinations of the two situations.

2.1.2.1.2 Soils Applicable for Air Sparging

It has been reported that the dispersion 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 (Marley *et al.*, 1992). Intuitively, this is to be expected. However, due to buoyancy forces, injected air travels primarily in the vertical direction, thus limiting the radius of influence of the air sparging well.

Heterogeneities inherent in the subsurface matrix must be identified and accommodated to promote the successful application of *in situ* remedial technologies, such as sparging. For example, geologic sedimentation generally causes horizontal permeability to be 10 to 1000 times greater than vertical permeability (Freeze and Cherry 1979). As the ratio of horizontal to vertical permeability increases, the radius of influence of the air sparging well also increases; this phenomenon results in lateral movement of the injected air. However, if the vertical air movement is restricted by a confining soil layer (or by a lower horizontal than vertical permeability within a stratum), sparging can result in spreading of the contaminants in a horizontal direction (Martin *et al.* 1992, Nyer and Suthersan 1993, Lundegard 1994). For this reason, air sparging may be inappropriate in situations where soil stratification prohibits the vertical migration of air to the water table surface.

In silty and clayey soils, air sparging may achieve a limited flow rate into the soil matrix. If the air injection pressure significantly exceeds the overburden pressure, then well failure will probably occur due to fluidization. In some cases, soil heaving, fracturing and fluidization have resulted from overpressurized air sparging systems. A breakthrough of this type will result in short-circuiting of the air-flow and may greatly reduce the effectiveness of the system. Therefore, modifications to the operating parameters, design features of an air sparging system or physical characteristics of the matrix may be required for sparging to be suitable for these types of soils.

Since air sparging is highly dependent on contact of the sparging air or dissolved oxygen with the target contaminant, the presence of soil heterogeneities will impact the effectiveness of the technology. In situations where the heterogeneities prevent effective contact with the contaminants, the success of the sparging well may be limited by the mass transport of contaminants from the non-contacted soil matrix to an effective sparging zone. In such cases, sparging would require extensive treatment times, and following system shut-down, a rebound in groundwater concentrations is likely. Instead of volatilization through direct contact of sparging air with target contaminants, several other mechanisms may be in place. These include: the result of groundwater movement associated with system operation; diffusion of the contaminant from the matrix back into the air channel; or both. The diffusion of the contaminant back into the air channel would occur as the result of equilibration of the concentration gradient(s). This process tends to be very slow (in comparison to, say, direct

volatilization). As a result, air sparging systems depending on diffusion (as opposed to direct volatilization) as a primary process will require extended periods for operation (e.g., several years).

2.1.2.1.3 Biological Degradation

Aerobic microbial degradation of petroleum hydrocarbons is much faster (e.g., by an order of magnitude) than anaerobic microbial degradation (except under anaerobic conditions). It is well known that the rate of aerobic biodegradation in aquifers is normally limited by the relatively low levels of oxygen transfer and nutrients naturally occurring in groundwater systems (Domenico and Schwartz 1990, Semprini and McCarty 1991). While indigenous bacteria can recycle existing nutrients, the flux of oxygen into groundwater under natural conditions is very slow. Therefore, a lack of oxygen transfer is often the limiting condition impeding the rate of biodegradation of aqueous phase contaminants.

It is often the primary goal of air sparging systems to remove VOCs via mass transfer mechanisms. However, an additional benefit of air sparging is the accelerated biodegradation of aerobically biodegradable contaminants located in both the saturated and unsaturated zones. This stimulation of biodegradation occurs because of the addition of dissolved oxygen and aquifer mixing.

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

2.1.2.2 State-of-the-Practice of Air Sparging

The following discussion illustrates how field practitioners are currently implementing air sparging. These current practices tend to be based on the general principles outlined in the previous section as well as on empirical results of past remediation experience.

2.1.2.2.1 Discussions About Air Flow

Generally, air sparging is implemented through the use of small diameter wells (i.e., 1 to 4 inches diameter) with the screened portion of the well located 5-15 feet beneath the zone of contamination. Air injection rates vary from 1 to 10 cubic feet per minute (cfm). Monitoring

the air distribution in the subsurface can be a difficult and expensive task, involving the utilization of monitoring points at multiple-depths with small screen lengths. The use of tracer gases (e.g., He, SF₆, etc.) has assisted researches and practitioners in this task.

Channeling

In recent years, groundwater professionals have discussed whether air flow within the saturated zone takes on the form of bubbles or discrete channels. In the air sparging process, the behavior of pressurized air once released into a water-saturated porous media is not entirely understood. A series of flow visualization experiments were conducted in plexiglass tanks using 0.2 to 4 mm diameter spherical glass beads as a porous media to simulate soils (Ji *et al.* 1993). In 4 mm diameter beads, which are intended to correspond to medium to coarse gravels, "bubbly" flow was observed, and air bubbles ranging from 1 to 3 bead diameters in size were observed to move upward with a "stumbling motion". In 0.75 mm beads, which are intended to correspond to coarse sands, air flow was observed to be confined to continuous pore-scale size air channels formed inside the medium. These channels were discrete and stable. When using 2 mm beads, both channelling and bubbly flow were observed. Therefore, it was concluded that 2 mm is the particle diameter where a transition between flow regimes occurs. Increases in air flow rates generally did not result in significant lateral expansion of the radius of influence in the experimental tanks; instead the number of air channels within the radius of influence increased (e.g., the density of the flow pattern increased). No relationship was observed or derived between bead size and the radius of influence. Observations of air flow in mixtures of bead sizes revealed that air channel formation and distribution were distorted by even small media heterogeneities. Lateral migration of air flow did occur in experiments where low permeability soil stratifications were simulated using layers of 0.4 and 0.2 mm beads in a tank filled with 0.75 mm beads. The authors concluded that, in natural soils, small-scale soil heterogeneities will prevent symmetric air distribution patterns.

Wehrle (1990) conducted model-scale experiments to observe the flow of air in saturated soils. These experiments demonstrated that in coarse-grained soils, air could rise solely because of buoyancy forces. When injecting into fine-grained soils, additional external pressure was necessary to overcome pore entry pressures. The dividing line between these two cases occurred within a coarse sand ($d_{50}=0.8$ mm). For sizes greater than coarse sand, the air rose as pulsating bubbles and groups of bubbles. This flow caused displacement of the water above (e.g., mounding) and resulted in considerable mixing of the water.

Due to dependence of air channelling on both micro- and macro-scale heterogeneities, individual channel distribution around a sparge well was observed to be random and unpredictable. In addition, while discrete air channels were observable, at two field research sites (Marley *et al.* 1992, Marley 1994), the stability of the channels was variable. At both sites, the intensity of flow in a number of the channels was observed to fluctuate (likely due to subsurface air pressure fluctuations). A number of the discrete air releases were also observed to exhibit pulsing (i.e., the air release would stop and start at variable frequencies).

During air sparging, it has been speculated that the location of air channels is stable. It is also speculated that temporal changes in air channelling performance could occur due to the local fluctuating subsurface air pressures. It has been suggested that an excessive timeframe would be required for site remediation if there is no change in the air channel distribution at steady state. With no change in the air channel distribution at steady state, mass transfer would be controlled by diffusion of contaminants to the air channels or diffusion of oxygen from the air channels into the matrix to enhance biodegradation. However, as indicated previously, these processes tend to be very slow.

Air Pockets

Further field observations have suggested that, at a number of sites, the air injected into the saturated zone can form large fingers or pockets of air (Marley *et al.* 1992, Marley 1994). The formation of air pockets has been evidenced by the drying of discretely-located monitoring points and by excessively prolonged air releases from the saturated zone following sparging system shut-down. The formation of large air pockets may cause lateral migration of aqueous phase contaminant plumes around or away from the air sparging zone. At sparging sites, where air fingers or pockets are present in the saturated zone, localized groundwater flow may be impeded. The presence of the air pockets seems to act to reduce the effective hydraulic conductivity of the local soils. This phenomenon may be of considerable importance and interest to practitioners considering the use of sparging curtains or trenches to intercept contaminant plumes. Insufficient data are currently available regarding the behavior of the air pockets to assess the impacts of the air pockets on the local groundwater movement associated.

It has been suggested that in cases where large air pockets form, it is likely that the rate of oxygen transfer into the groundwater will be reduced. The rate of oxygen transfer is dependent on the surface area of contact. It would be expected that a single large air pocket would have a significantly reduced surface area of contact with the contaminated groundwater (in comparison with a high density of air channels).

The occurrence of large air pockets during air sparging has some practitioners theorizing that the cone of influence impacted by the air sparging well is transformed into a "pseudo-unsaturated zone". This hypothesis is under investigation in laboratory bench-scale tests, large physical model demonstrations, and field pilot studies.

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

Another current discussion relating to interstitial multiphase flow focuses on the actual flow within what has been called the "radius" or "zone of influence" of the air sparging well. Recent research has shown that the distribution of air flowing through channels in the saturated zone resembles a "flow net" or pattern. The density of the distribution tends to vary inversely with the distance from the air sparging well in homogeneous and isotropic soil matrices. Even in relatively uniform soil matrices, it has been suggested in current research and practice that the effective zone of impact of an air sparging well is within 6 to 12 feet of the well, with a much smaller impact being noted at distances of several times this radius from the well. An effective sparge well design requires placement of wells which will develop overlapping radii of influence. For this reason, the sparging well density required for effective remediation tends to be much higher than originally thought.

2.1.2.2.2 Groundwater Mounding (Upwelling) and Hydraulics

Groundwater mounding or upwelling is a temporary increase in water elevation observed within groundwater monitoring wells. Mounding often results from air sparging and soil vapor extraction activities. It has been observed that, as injected air displaces water from soil pores, mounding of groundwater occurs on top of the sparged region of the groundwater table. Generally, the magnitude and duration of the mounding is a function of the soil permeability and the rate of air injection (Marley *et al.* 1993, Newman *et al.* 1994, Lundegard 1994). As the air permeability of a soil increases, the magnitude and duration of the mounding decreases. When sustained groundwater mounding is observed, it is the probable result of the concurrent operation of soil vapor extraction and air sparging systems or due to excessive air injection pressure (i.e., causing matrix fluidization).

It has also been observed that, following system shutdown, a transient depression of the groundwater table forms around the sparge well. The transient mounding and depression of

the groundwater table, in response to air sparging system start-up and shut-down, demonstrate the development and dissipation of macro-scale groundwater gradients and mixing. In a study by Newman *et al.* (1994), the magnitude and direction of the hydraulic gradients were measured. During the mounding phase, a vertical gradient was observed around the sparge point. When the groundwater mound began to dissipate, the direction of the hydraulic gradient reversed. During air sparging, the mound dissipated over a two-to three-hour period until static water table conditions were achieved and a relatively steady state in the channelling evolved.

Following system shutdown, a similar but reversed trend in the formation and dissipation of hydraulic gradients was observed. For a typical permeable soil in which air sparging is applied, the macro-scale movement (both horizontal and vertical) of the groundwater is expected to be on the order of a few feet or less, due to the induced hydraulic gradients. Therefore, it is speculated that the occurrence of groundwater displacement (due to the formation of hydraulic gradients at system start-up and shut-down) is of lesser concern with respect to contaminant plume migration, than is the potential displacement of water due to large air pocket formation in the aquifer in response to soil stratification or heterogeneities.

2.1.2.2.3 Pulsed or Intermittent Operation

To accelerate mass transfer, it has been suggested by practitioners that air sparging systems be operated in the pulsed mode. The macro-scale groundwater movement associated with system pulsing (periodic system start-up and shut-down) is expected to enhance the mass transfer process. In addition, it has been speculated that pulsed operation of the system, on a site-specific basis, may cause temporal and spatial changes in the distribution of air channels. This effect may be due to changes in the preferred air pathways as a result of fines migration, biomass growth, mineral precipitation and deposition, and relative permeability changes due to air entrapment. It has been suggested that intermittently sparging at a site would also: minimize the formation of air pockets; encourage groundwater circulation; and allow the pulsed air flow to contact different portions of the aquifer. The period of pulsed operation would be site-specific but would be a function of the equalization period of the aquifer.

2.1.2.2.4 Aquifer Clogging

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

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

Typically, the concern for well or air stripper clogging results from the pumping of groundwater with elevated levels of dissolved solids (due to the action of microbes) to a focal point (well or air stripper) where the redox potential is abruptly adjusted, causing rapid biomass or precipitate build up. In air sparging applications, redox changes (e.g., groundwater oxygenation) are generally distributed over a large volume (of the soil matrix), thereby reducing the potential for clogging. In fact, in Water Resource Engineering there is a process (the VYREDOX™ process) where groundwater oxygenation by aeration wells is used to remove iron and manganese from groundwater by precipitation before it reaches a production well. This indicates that aquifer clogging through aeration wells in general is not a major concern (Driscoll, 1986) and has rarely (if ever) been observed in an active air sparging system.

2.1.2.2.5 Augmentation Technologies

Contaminated vapors that migrate or are sparged from saturated portions of the aquifer to the unsaturated zone may be biodegraded within the unsaturated zone. However, to control the potential migration of hydrocarbon vapors, soil vapor extraction wells have been utilized for vapor control and treatment (P. Johnson *et al.* 1990, Brown and Jasiulewicz 1992, Marley *et al.* 1992), or "relief wells" have been installed to relieve pressure in the subsurface (Somes *et al.* 1994). Other technologies which have been considered for augmentation of air sparging include:

- pneumatic and hydraulic fracturing (ie., to increase or alter the number, size and distribution of channels in low permeability soil matrices);
- thermal processes (e.g., steam injection, RF heating), surfactant flushing and *in situ* soil mixing (i.e., to enhance the mass transfer of contaminants in soil matrices); and,
- bioventing, pump and treat and bioslurping (to remove contaminants mobilized during air sparging).

2.1.2.2.6 "Rules of Thumb" for the Application of Air Sparging

The following "rules of thumb" have been suggested by some practitioners for evaluating the applicability of air sparging to a particular site. However, these ideas are not proven theory, only empirical or supposition.

For VOCs, it has been suggested that a contaminant must have a dimensionless Henry's constant (H) greater than 4.15×10^{-4} (alternate units 10^{-5} atm-m³-mole⁻¹) to be successfully sparged from the aqueous phase (Brown *et al.* 1991). For residual contamination, constituents with vapor pressures greater than 1 mm of mercury at 25°C are considered appropriate for volatilization. It has been suggested in the literature that a minimum soil hydraulic conductivity of 0.001 cm/sec is required to provide adequate air flow for sparging (Loden and Fan 1992, Middleton and Hiller 1990).

It has also been suggested that, in order for air sparging to be effective, air saturation levels should be maintained at 0.1 percent. Doing so will provide an effective zone of influence within a seven-foot radius of the sparging well. As distances from the well increases, the saturation level drops exponentially as follows:

<u>Distance form Well (ft)</u>	<u>Air Saturation (%)</u>
3 -4	1.0
7	0.1
10	0.01

2.1.2.2.7 Variations on the Application of Air Sparging

Air sparging has been proposed to be effective in addressing various aspects of groundwater contamination. Additional scenarios for the containment and remediation of VOC-contaminated groundwater include biosparging and the application of horizontal sparging wells, sparging gate-wells, cutoff trenches or "curtains". These approaches have been suggested in the literature (Kaback *et al.* 1989, Looney *et al.* 1991, Burchfield and Wilson 1993, Pankow *et al.* 1993, Marley *et al.* 1994) and are summarized below:

- The process of enhancing degradation of contaminants in the aqueous phase through air sparging is sometimes termed "biosparging". Biosparging also refers to the treatment of semi-volatile organics (with low volatility levels) and VOCs where the sparging system is designed to maximize the biodegradation processes and to eliminate the requirement for VOC off-gas treatment.
 - Horizontal wells inject air beneath the impacted area of a plume.
 - The sparging gate-well approach utilizes hydraulic barriers to direct contaminated groundwater flow through a treatment zone (sparge gate-well).
 - The sparging cutoff trench is a constructed trench laid perpendicular to the contaminated groundwater flow direction.
 - A sparging curtain resembles a sparging trench in that it is installed perpendicular to the flow of the contaminated groundwater. However, vertical sparging wells are closely spaced at equal intervals along the length of the curtain to emulate the performance of the sparging trench.

Very limited data are available on the design, operation and performance of these alternative sparging techniques. However, as with single well air sparging, when a trench, curtain, or gate-well configuration is utilized, the probability of creating upgradient mounding or lateral spreading of the plume is increased.

Much of the state-of-the-practice of air sparging focuses on empirical results obtained from pilot tests. These pilot studies support the application of sparging, as appropriate. They form the basis of the air sparging system designs. They also are integral to properly characterizing the site and designing an appropriate system for remediating the volatile organic constituents present at the site. However, currently there are no standards or guidance documents available to properly plan and carry out pilot-scale studies. The evaluation and interpretation of the data obtained from pilot tests is also evolving as field practitioners become more sophisticated in defining testing protocol and examining results of pilot testing.

2.2 CURRENT WORK IN PROGRESS

As air sparging is being evaluated and refined as a tool to address volatile contamination at various sites, there is increasing regulatory and research interest in the technology. Various state regulatory agencies have issued very thorough guidance documents for the design, installation, and operation of air sparging system. (The Wisconsin Department of Natural Resources has published an excellent guidance on air sparging for use, especially in the state.) The environmental industry is beginning to expect a more rigorous and critical review of the technology to evaluate the effectiveness and appropriateness of air sparging. The majority of the research being conducted to evaluate the effectiveness of air sparging attempts to quantify how the mechanism of air injection interplays with the transport phenomenon in the saturated zone.

Some researchers (Schima *et al.* 1994 and Lundegard 1994) have utilized cross-borehole electrical resistance tomography (ERT) to map the air flow near an air sparging well under natural conditions. The use of ERT yields a multidimensional image of air distribution on a macro-scale basis. The evaluation compared the results of traditional methods for estimating the areal impact of air sparging (i.e., dissolved oxygen, groundwater mounding, pH, etc.) with those of ERT. A comparison of the region of air flow defined by ERT with conventional monitoring data indicated that the region of air flow may be overestimated in homogeneous systems. It appears that the ERT technique requires considerable instrumentation, data analysis and resources and, therefore, should be viewed primarily as a research tool at this time.

Other research utilizes helium or sulfur hexafluoride (SF₆) as tracer gases to determine the air sparging zone of influence. The tracer test consists of injecting helium or SF₆ in air into the pressurized line going to the sparging well. Tracer gas content is then measured and tracer recovery is attempted from monitoring points surrounding the air sparging well. Monitoring of the tracer gas is typically performed without a soil vapor extraction system in operation since the advective subsurface air movement caused by the soil vapor extraction 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. Current research shows that an advantage of using a tracer such as helium is that it is light and inert, has a relatively low aqueous solubility and is present at relatively low background concentrations. Helium can also be detected at low concentrations with an easily operated, hand-held thermal conductivity detector. Results of tracer recovery monitoring have typically shown that relatively small percentages of the injected gas are recoverable.

Other work utilizes bench-scale testing, large scale physical modeling, and field evaluation to examine the interstitial flow regimes comprising the air/fluid flow process (Ahlfeld *et al.* 1994, Ji *et al.* 1993, P. Johnson *et al.* 1994, R. Johnson *et al.* and 1994, Marley *et al.* 1994). The number of projects evaluating air sparging will continue to increase as more environmental practitioners attempt to optimize the remedial techniques needed to address sites impacted by volatile organic compounds.

2.2.1 International Activities

After initially developing air sparging procedures and completing technology demonstrations and site remediations for a number of applications, especially using the UVB method during the 1980s, developers and practitioners in Europe (principally in Germany) essentially abandoned use of air sparging technology. The primary reasons for doing so were because: (1) contaminant concentrations in groundwater were observed to be increasing (especially in the short-term and in cases where contamination from concentrated source areas was being mobilized; and (2) it was observed that groundwater flow patterns were being disturbed, i.e., flowing around the aerated zone (thus, the technology was not a likely candidate for plume remediation). Due to incomplete understanding of the principles of air sparging throughout the scientific community at the time, responsible regulatory agencies recommended that application of air sparging be discontinued in about 1989 (Hiller, 1995).

More recently (i.e., within the past few years), interest in air sparging in Europe and other international locations has been revived. This renewed interest is primarily thought to be due

to two factors (Hiller, 1995 and Bartholomae, 1995): the reported successes of air sparging elsewhere, principally in the U.S.; and the need to identify more cost-effective technologies for site remediation (especially when compared with traditional approaches which had been widely accepted by the regulatory community, i.e., "dig and dispose", pump and treat, etc.)

Several air sparging demonstration and remediation projects are underway in Europe currently. In the Netherlands, a multi-site demonstration program (known as the NOBIS Project) is commencing in 1995 (Herzien, 1995). A former oil distribution terminal and an electrical power generating station, both located in Nijmegen, are the principal candidate sites under consideration. In addition to the site owners, the primary project participants include Delft Geotechnics, Bodem Milieu Systems (BMS), the Agricultural University of Wageningen, and the Rotterdam Municipal Harbor Authority. The main objectives of the project are:

1. The determination of site data necessary for good design;
2. The evaluation and, following application and, when necessary, further development, of tools (experiments and models) to predict the effectiveness of these techniques (e.g., biosparging and bioventing);
3. The development of a general framework for the design and optimal operation of biosparging and bioventing systems;
4. The determination of an appropriate strategy for monitoring and evaluating the performance of those techniques; and
5. Evaluation of the role and applications of biosparging and bioventing in innovative (extensive) *in situ* remediation strategies.

If the project progresses according to plan, these objectives will be fulfilled by 1997-8.

In another part of the Netherlands, air sparging is being applied as a research project to effect remediation of a small former service station site in Ghenapp. The project, underway for about one year in a layered lithology (with increasing permeability), is successfully being conducted by the Dutch government. Similarly air sparging projects are reported to be underway in Vienna, Austria and Northern Germany (Hiller, 1995 and Bartholomae, 1995).

2.3 AREAS IDENTIFIED IN THE LITERATURE FOR FUTURE DEVELOPMENT

Based on a review of the literature and discussions with several researchers actively pursuing work in further understanding air sparging, several areas have been identified for future development:

- **Full-Scale Operating Data:** Since the technology of air sparging is relatively new, only a small portion of the actual work being done or completed to-date has appeared in peer-reviewed literature regarding site remediation. Much of the work has been conducted at the pilot-scale. Results of full system operations will provide valuable information for developing improved effectiveness of air sparging generally and for use of pilot-scale test results for full-scale design.
- **Vapor and Water Movement in the Saturated Zone:** The movement of both air/vapor and water within the saturated zone at air sparging sites is still not well understood. Factors such as contaminant and oxygen mass transfer and air channel distribution, in response to various conditions of system operation, are not well understood.
- **Air Flow Modeling:** To date, modeling efforts have not been conducted to sufficiently characterize air flow distribution in a manner that could aid in system design.
- **Pilot Study Protocol:** Currently, there are very few published guidance documents or standard protocols for conducting and evaluating pilot studies; there are none available specifically for air sparging. The development of such a guidance would include standards regarding the uniform collection of data during air sparging pilot testing and system operation to quantify and evaluate system performance. The developed guidance document would also include information on the reduction, evaluation and comparison of data.
- **Design Protocol:** The development of a protocol or manual to assist environmental professionals in the design of air sparging systems is needed.
- **Operations Protocol:** In general, the environmental industry lacks the knowledge to properly design, install, and operate air sparging systems. Future development in this area will offer assistance to practitioners who are attempting to utilize the technology but are unsure or unable to determine what steps to follow to design, install and operate an effective and efficient air sparging system.
- **Performance Monitoring:** Identification and development of appropriate parameters, protocols and systems for monitoring air sparging system performance are required to facilitate progress in most of the other areas identified above. Performance monitoring improvements, stated last in this section, is thus the most important aspect of development required.

SECTION 3.0

AVAILABLE MODELS

In an attempt to gather information on current air sparging models, many model developers in U.S. DOE, other governmental agencies, academia and industry were approached for information regarding their work and resulting systems. The primary purpose of the model review was to collect data about the models with sub-purposes of evaluating whether any of the current models are air sparging "decision tools" and determining which information from existing models would be appropriate for inclusion into the Decision Tool.

The use of computer models to solve inherently difficult multi-phase flow equations (such as the equations governing the application of air sparging) is a heuristic approach for generating predictions regarding the response of a site to the use of air sparging. As part of the review effort, many model developers were asked for information regarding their models. A copy of the questionnaire sent to and completed by those who responded is included in Appendix D. Table 1 (included at the end of Section 3) lists the developers who responded and includes a brief description of their model(s); there are presented in alphabetic order by model name.

These models generally assume highly idealized aquifer conditions. While these models provide valuable insights into air sparging behavior, actual field behavior of air sparging is likely to vary. A complete, detailed description of the most current or relevant models is found in Appendix B.

Many of the models utilized numeric adaptations of the information presented in the literature review section. Since the Decision Tool to be developed is a logical tool, the complex numeric relationships presented in most of these models will not be applicable for inclusion in the Tool. Also, the information gleaned from the review process indicated that there is not an air sparging "decision tool" currently available or under development. Nevertheless, there were several, valuable "lessons learned" from this exercise. They include:

- 1) Although no "decision tool" for determining applicability or optimization of air sparging is currently available or under development, several modeling efforts include useful decision-making guidance for incorporation into the Decision Tool. Examples of such guidance may be found in HYPERVENTILATE, UNIVERSAL REMEDIATION TIME MODEL, and BIOPLUME II.

- 2) Similarly, theoretical and mathematical relationships of interest (especially when generalized) to Decision Tool development have been found in several models. These include: SPARG1, SPARCHAN, TRACR3D, HYPERVENTILATE and BIOPLUME II.
- 3) Also useful to Decision Tool development, providing valuable insights into the conceptual design and evaluation process are the CHEVRON RESEARCH CONCEPTUAL MODEL and OGI CONCEPTUAL MODEL.

This listing is not intended to be exhaustive, but to provide examples of information which are being derived from the model review exercise and will likely be contributory to Decision Tool development. In fact, all models reviewed by the Project Team will facilitate the development process in either of two ways:

- A) the models include theories, relationships or concepts which may be incorporated in principle into the decision tree and ultimately the Tool; or,
- B) the models are providing a boundary in the form of the level of detail or complexity which must be incorporated into the Tool. In any case, all of the models reviewed are useful in one way or another.

TABLE 1

Air Sparging Model* Review Summary

Air Sparging Optimization Decision Tool

Name of Model	Developer(s)	Producer	Primary Application/ Target Audience (what application)	Other Model Capabilities/ Information	Model Limitations
3D3PT	Neil R. Thomson	University of Waterloo	Research tool for researchers	--	--
BIOPLUME II	H.S. Rifai, P.B. Bedient, R.C. Bordan, J.F. Haasbeek	Rice University	Consultants and researchers	2-D groundwater flow with retarded advective-dispersive solute transport	Limited model grid size; only 2-D; solution is less accurate as GW velocity increases; can only use a uniform grid; many parameters cannot be varied spatially
BIOTRANS	Environmental Systems & Technologies, Inc.	Environmental Systems & Technologies, Inc.	Evaluated transport and fate of dissolved organic constituents in porous or fractured aquifers under the influence of oxygen limited decay; consultants, regulators, and research scientists.	Simulated dissolved transport of up to 5 species in fractured or porous squifers. Oxygen transport and limited decay can be modeled; time-dependent source rate due to dissolution of NAPL can also be simulated.	Does not explicitly simulate flow conditions
CHEVRON RESEARCH CONCEPTUAL MODEL	Donald H. Mohr	Chevron Reserach and Technology	Concptual model of oxygen mass transport between air channels and groundwater	--	Steady state only, air exists as widely-separated discrete channels, there is no significant mixing or groundwater flow
COMPSIM	Brent Sleep	Brent Sleep, University of Toronto	Modelling various NAPL remediation technologies	--	Computational times are long; equilibrium between phases

* Includes models for related technologies (e.g., soil vapor extraction, pumpand treat, etc.)

TABLE 1 (continued)

Air Sparging Model* Review Summary
Air Sparging Optimization Decision Tool

Name of Model	Developer(s)	Producer	Primary Application/ Target Audience (what application)	Other Model Capabilities/ Information	Model Limitations
HYPER- VENTILATE	Paul C. Johnson	Shell Oil Company	Education and guidance, screening tool for VE applications; consultants, regulators,	--	Not intended to be a "true predictive tool". Intended to give estimates of optimal system performance.
MOTRANS	A.K. Katyal, J.J. Kaluvarachchi, J.C. Parker	Environmental Systems and Technologies, Inc.	Multiphase flow and multicomponent transport in radial or cartesian cross-section	—	Complex Model
OREGON GRADUATE INSTITUTE CONCEPTUAL MODEL	Rick Johnson	Oregon Graduate Institute	Conceptual model of oxygen mass transport between air channels and groundwater	--	Steady state only, air exists as widely-separated discrete channels, there is no significant mixing or groundwater flow
SAVANNAH RIVER <i>IN SITU</i> SIMULATION	Bruce A Robinson, Nina D. Roseberg, George A Zyvoloski, and Hari Viswanathan	Office of Technology Development, Department of Energy	Consultants, industry regulators	Model based in finite element heat and mass model, a three dimensional finite element heat and mass transport code that solves one or two phase (air-water) fluid flow problems. The two phase fluid flow solution is obtained by solving Darcy's law and continuity equations for both phases.	Unknown

TABLE 1 (continued)

Air Sparging Model* Review Summary
Air Sparging Optimization Decision Tool

Name of Model	Developer(s)	Producer	Primary Application/ Target Audience (what application)	Other Model Capabilities/ Information	Model Limitations
SPARCHAN	David J. Wilson, Cesar Gomez--Lahoz, Jose M. Rodriguez--Maroto	David J. Wilson, Vanderbilt University	The mathematical modeling of insitu air sparging for VOC remediation, applications in preliminary screening, pilot test and field scale design, and monitoring cleanup progress; environmental engineers	--	Does not handle NAPL, multiphase flow of air and water in porous medium
SPARG 1	M. Marley, F. Li	Envirogen, Inc.	In house evaluation of governing parameters for air sparging and system design evaluation	--	--
STOMP	Mark D. White & Mart Oostrom, Pacific Northwest Laboratory	Pacific Northwest Laboratory	General purpose tool for simulating subsurface flow and transport, and multidimensional analysis capabilities for modeling subsurface flow and transport ; for scientist and engineers of various diciplines	--	Complex nonlinear problems can require a significant amount of time to execute.
T2VOC	R. Falta, K. Pruess, S. Finsterle, A. Battistelli	Lawrence Berkeley Laboratory	NAPL/VOC remediation by steam injection, SVE, air sparging; scientists and engineers	Extensive; model uses a general and flexible formulation for transient 3--D, phase flow with interphase mass transfer under nonisothermal conditions.	Single component NAPL, in local equilibrium
TETRAD	Dyno Research & UNOCAL	Dyno Research & UNOCAL	Reservior simulation	Predicts air--water--NAPL flow with or without chemical partitioning.	Needs improved graphical user interface and pre-- and post processors

TABLE 1 (continued)**Air Sparging Model* Review Summary**
Air Sparging Optimization Decision Tool

Name of Model	Developer(s)	Producer	Primary Application/ Target Audience (what application)	Other Model Capabilities/ Information	Model Limitations
TRACR3D	Dr. Bryan Travis/ Kay Birdsell	Los Alamos National Laboratory	To simulate two-phase flow and transport in porous media; intended for environmental contamination remediation studies agricultural applications and general hydrology.	Air flow only, or water flow only or fully coupled air and water flow; time dependent transport of N solutes; Henry's law for volatiles; water vapor transport.	Isothermal
UNIVERSAL REMEDICATION TIME MODEL	David H. Bass	Groundwater Technology, Inc.	Design and assessment tool for air sparging and groundwater pumping systems for consulting use.	Gives fast answer to question "how long could this take?". Prevents design of systems which could not possibly work. Allows extrapolation from initial results to desired state and between similar sites.	Calibration requirements
WELLPACK	Francois and Gorlick	Stanford University	Design of in-well vapor stripping systems	It gives design specs. for in-well vapor stripping	None

SECTION 4.0

PARAMETERS RELEVANT TO THE DEVELOPMENT OF THE DECISION TOOL

After a comprehensive search of the literature and available models, it is evident that there are a large number of individual parameters or site features that should be considered when assessing the applicability and optimization of air sparging. The principal determinant for successful application of air sparging as a remediation technology is based on the ability of air (a fluid) to move through porous and/or fractured media. Descriptive parameters of the subsurface (geologic and hydrogeologic setting), which promote or impede fluid flow, must, to some extent, be considered. Also, parameters that assess the physical properties of the contaminant(s) and the nature of its subsurface existence (e.g., size of the residual source, presence of free phase) which may relate to fluid flow, must be considered.

Within the Decision Tool, the parameters must be integrated in a manner that facilitates user decision-making with respect to application of air sparging for a particular site. In assessing any particular site, there may be features which will immediately eliminate this technology from further consideration (i.e., air sparging is not applicable). There are also those sites which are obviously good candidates for air sparging technology. Remaining, indeterminant sites must be assessed either qualitatively or quantitatively as to their continued consideration. More detailed information concerning site parameters, conditions or monitoring data (and/or pilot test data) is then needed to further address consideration for application and, ultimately, for optimization.

4.1 APPLICABILITY

4.1.1 General Properties

From the literature survey, parameters potentially relevant to the applicability of air sparging have been grouped into three general categories:

- Site Geologic Conditions
- Hydrogeologic Characteristics; and
- Contaminant Properties.

As with all fluids, the flow of air in the subsurface will be primarily governed by the framework within which it is placed (e.g., the nature of the subsurface matrix). Site geologic conditions must be clearly identified to assess the potential application of air sparging. This framework is defined by the geologic and hydrologic characteristics of the porous and/or fractured media and can be depicted in a conceptual geologic model specifically prepared for

the site. Specific requirements include the thickness, texture and distribution of existing layers beneath the site. This information can be determined through completion of soil borings and/or monitoring well installations. The details of existing (or anticipated) piezometer and/or monitoring well construction will be needed to identify the existence of unconfined and/or confined conditions beneath the site. Periodic water levels (ideally taken over a period of a year) are critical in establishing the thickness of the vadose zone and the magnitude of its seasonal fluctuation. These data are fundamental to applicability decisions and to the conceptual design of an air sparging system. Groundwater levels are also needed to identify the direction of groundwater flow within important horizons and to identify potential downgradient receptors.

The rate, direction, and extent (horizontal and vertical) of contaminant migration can be defined by this physical framework (as represented in the conceptual geologic model) along with the physical properties of these layers (if present) and of contaminants (see paragraph below): porosity, permeability, moisture content, pressure distribution (including capillary pressures and water levels), and grain size. Guidance on decisions for use of this technology comes from the literature (Loden and Fan, 1992; and Middleton and Hiller, 1990) in suggesting that only those materials exhibiting a hydraulic conductivity of 0.001 centimeters per second or higher will allow an effective rate of air injection. This guidance may be one of the initial factors in a site screening process. Other investigators (Marley and Li, 1994) in modeling the flow of air through the subsurface have incorporated the assumption that air flows according to the fundamental principle of groundwater flow known as "Darcy's Law". In essence, this implies that permeability and hydraulic head distribution beneath a site are critical to describing airflow patterns at any location.

Although Darcy's Law is described by relatively straightforward concepts, the properties of the fluid itself are also necessary to completely describe the flow. Such properties as solubility, Henry's constant, density, vapor pressure, diffusion potential (based on concentration gradients), and the presence and extent of phase-separated fluids describe how the contaminant will partition into the vapor phase. Properties measuring the attenuation of a particular constituent as it migrates (e.g. distribution coefficient, dispersivity, degradation rate) provide an assessment of how the contaminant is adsorbed to soils, how quickly the contaminant plume expands by mechanical dispersion, and how it chemically or biologically degrades. Identification of selected contaminant and attenuation properties can lead to an assessment of the potential applicability of air sparging technology at any location.

The literature suggests that, typically, contaminants must have a dimensionless Henry's constant greater than 4.15×10^{-4} to be successfully sparged from an aqueous phase (Brown et al., 1991). For residual contamination, constituents with vapor pressures greater than 1 mm of mercury at 25°C are considered appropriate for volatilization. It is also suggested that, depending on the main purpose of the sparging technology, sites impacted by VOCs and heavier molecular weight organic compounds which exhibit vapor pressures less than 1 mm Hg (i.e., semivolatile organics), fuel oils, and water soluble organics can be considered where enhancement of aerobic biodegradation is to be considered. In these situations, aeration of the groundwater would be the main objective of the air sparging process. It should be noted that, although cited in the literature, further investigation and experience, via laboratory-scale research, pilot-scale tests and full-scale system implementation are required to validate these guidance levels.

4.1.2 Specific Parameters

Considering all the properties discussed above, there are several generalized categories of information which allow an immediate assessment of whether or not air sparging should be considered as a viable alternate for a candidate site. By using major categories to initially assess the potential applicability of air sparging, the Decision Tool user can minimize time and efforts spent on sites of little promise. Three major categories and their respective sub-categories have been identified and incorporated into the Decision Tool and are summarized below.

4.1.2.1 Geologic Setting

Fractured/Low Permeability

Layered

- increasingly permeable layers with depth
- decreasingly permeable layers with depth
- alternating permeability of layers

Homogeneous

Other (e.g., non-layered, heterogeneous, etc.)

4.1.2.2 Type of Impact

Large (e.g., NAPL)

Small (e.g., dissolved phase, possible residual phase within soil matrix)

4.1.2.3 Contaminant Type

Solvent (typically more dense than water)

Hydrocarbon (typically less dense than water)

Other contaminant types identified but excluded from further consideration in application of the Decision Tool specifically or of air sparging generally include sites with co-contaminants of radionuclides and heavy metals.

Once the site has initially been characterized and categorized by the above general features, more specific site and contaminant parameters can be used to further assess the applicability of air sparging. These more detailed site and contaminant characteristics have been compiled and are listed in Appendix C. A partial listing of the most relevant parameters is indicated below.

4.1.2.4 Geologic Setting (for Conceptual Geologic Model of the Site)

- Soil classification and grain-size distribution
- Hydraulic and pneumatic permeability and variations (horizontal and vertical)
- Depth to groundwater
- Thickness of layers (if applicable)

4.1.2.5 Contaminant Spatial Characteristics

- Presence and extent of NAPL
- Presence and extent of dissolved plume
- Presence and extent of residual NAPL "source area" including "smear zone"

4.1.2.6 Contaminant Physical Characteristics

- Henry's Constant
- Vapor pressure
- Solubility
- Biodegradation potential

The overall objective of considering the site-specific values of these parameters, with respect to determining applicability, is to estimate the degree of overlap of air channel/saturation, as the result of air sparging, with the distribution of contaminants within the matrix. In situations where the probability of air contact with volatile or biodegradable contaminants is high, the effective removal rates will likely be high as well; air sparging will probably be technically feasible and cost-justifiable.

4.1.2.7 Conceptual Design Considerations

- Minimum injection pressure
- Maximum flow rate for likely injection pressures
- Theoretical maximum air distribution radius
- Maximum physical and biological removal rate

4.1.2.8 Economic/Political Considerations

- Area to be treated: Source, Plume, or Edges (containment)
- Time constraints
- Presence and proximity of sensitive receptors
- Remediation alternatives, relative costs

Finally, any detailed monitoring and other performance data obtained from system operations, routine monitoring, or pilot-scale tests at the site will be used to evaluate the potential effectiveness of air sparging activity and to initiate the detailed design (and ultimately optimization) process(es). Parameters of particular interest are described below.

4.1.2.9 Pilot Test System Parameters

- Injection pressure
- Injection flow rate
- Extraction flow rate (if used in conjunction with SVE)
- Concentrations of tracer gasses

4.1.2.10 Monitoring Parameters

- Depth/Relationship of screened interval to target treatment area and water table
- Soil vapor contaminant concentrations
- Contaminant concentrations in groundwater
- Dissolved oxygen concentrations in groundwater

4.2 OPTIMIZATION

4.2.1 General Properties

The optimization process, as provided by the Decision Tool, will consist of the optimization of either an existing system that has been in operation for some period of time or a "conceptual design" of a proposed system with information from a pilot-scale testing program (outlined above). As such, the parameters needed to evaluate the optimization include those given for applicability as well as those that follow.

4.2.2 Optimization Parameters

- Statement of purpose for the system
- Target cleanup levels
- Air sparging system operating requirements
- Well construction information
 - well diameter
 - screen slot size
 - screen length
 - well orientation
 - depth of screen below water level surface)
- Equipment operating parameters
 - flow rate
 - injection pressure)
- System design features
 - number of injection wells
 - size of blower/compressor
 - accompanying soil vapor extraction

- Apparent "radius of influence" of sparging wells
- Relaxation effects following sparging shutdown
- Performance monitoring results
 - VOC data
 - mass recovered
 - water levels

It is anticipated that prospective Decision Tool users will find that the designs of most air sparging systems were based on empirical information and that the systems may have been operating for some period of time. It is expected that monitoring data are also available to determine system effectiveness. Optimization of the program will consist of recommended modifications to the system, additions or deletions to increase the system's effectiveness or changes in the monitoring program. The purpose of the program or operating requirements will be preserved so that the system will continue to comply with the requirements initially established for the site.

The optimization process will be iterative, with the user making changes to an operating system, observing the resulting effects, analyzing the effects, and making additional changes to achieve optimum performance for a site. It is probable that identification of inappropriate uses of air sparging may result from Decision Tool application. It is also expected that alterations in the system flowrate, injection pressure, number and location of air sparging points, or operational mode (pulsed versus continuous) will be suggested. Since the optimization process attempts to manipulate the air distribution in the subsurface, monitoring after one or more modifications is necessary. One potential outcome of the optimization evaluation may be the realization that an air sparging system may not be capable of meeting the intended objectives for the particular site.

SECTION 5.0

QUESTIONS THAT THE DECISION TOOL WILL ATTEMPT TO ANSWER

After an extensive review of the literature and existing air sparging models, the following list of questions has been compiled. The final goal of the Decision Tool currently being developed is to accurately answer these defining questions. In essence, these questions are structured to confirm understanding of the purpose and to help define the scope of the Decision Tool. These questions will be utilized throughout the process to maintain the direction of the conceptualization and production of the Decision Tool. The questions will also be used at the end of the subsequent work units to determine compliance with the scope and objectives of the project.

The ability of the Decision Tool to answer the following questions assumes that the site has been investigated to a sufficient degree and that appropriate data is available for utilization of the Tool. Although the results of the Decision Tool development will be based on appropriate theoretical, conceptual operating and performance principles, the Decision Tool is not being developed for the detailed design of air sparging systems.

5.1 APPLICABILITY

The following questions will be answered with respect to the applicability of air sparging to a given site.

- a. Compared to idealized conceptual scenarios, is the technology of air sparging applicable for use at this specific site?
- b. How is applicability defined? [For example, applicability will be determined with respect to time-based or risk-based remediation goals (e.g., air sparging at the site would be effective in removing 90% of the contamination within a one-year period if optimally installed and operated in a theoretically optimal manner), applicability will be evaluated in terms of cost-effectiveness, conceptual calculations will also be used to evaluate applicability, etc.]
- c. What are the major site-specific factors which contribute to the applicability of air sparging for this site? [i.e., contaminant characterization (or type), contaminant distribution, presence and number of sensitive receptors, ability to inject and distribute air into the saturated soil effectively, soil heterogeneities, etc.]
- d. What does the evaluation process tell the user about the applicability of air sparging to a site? (i.e., measurement criteria will include rating and comparing the site with sites where air sparging is expected, or has already been demonstrated, to be effective.)

- e. Are all the required data available to determine item a.? [The Tool will be able to identify data gaps and suggest how to fill them (in the field) or to provide default data from look-up tables within the Tool.]
- f. When the Tool is used to evaluate the applicability of air sparging to a site, are there special conditions which might affect the decision of whether air sparging is applicable? Are there any parameters in the Decision Tool which have a high degree of sensitivity? (i.e., proximity of basements, utility lines, or other sensitive receptors, extensive heterogeneities in the subsurface, political issues, etc.)

5.2 OPTIMIZATION

The following questions will be answered with respect to the optimization of an air sparging system at a given site.

- a. What aspects of a currently operating air sparging system can be practically altered to optimize the system? (This identifies the physical limitations of the system.)
- b. How is optimization defined? (i.e., an increase in removal efficiency or operating effectiveness, etc.)
- c. What does the data obtained from the current monitoring program illustrate about the system and the site (i.e., how close to optimal design is the current system)?
- d. What additional data are needed for optimization?
- e. Are the operational parameters indicating optimal performance?
- f. What are the constraints or conditions that limit optimization, and how do they limit it? (e.g., there is no active SVE system, there are basements within 25 feet of the impacted area, etc.)
- g. What is the most cost-effective (or least cost) operation of the installed air sparging system?
- h. How much time should the practitioner expect for the optimal system to remove contaminants to target levels?

5.3 OBJECTIVE FUNCTIONS

In addition to the questions listed above, the field practitioner may use the Decision Tool to solve objective functions for applicability and, ultimately, for optimization at each site. In both cases, the objection function can be related as a conceptual relationship. In order for sparging to be considered applicable for a particular site, there must be a reasonable degree of overlap of sparged air distribution with that of the contaminant(s) targeted for removal. As boundary conditions, an ideally mixed, homogeneous matrix provides for the opportunity for the highest degree of overlap (say, arbitrarily, 10% efficiency of air contact); on the other extreme, a low permeability matrix, depending entirely on diffusion, provides the lowest level

(arbitrarily, almost 0% efficiency). Thus, the objective function with respect to applicability is a function of the projected degree of contact of sparging air with the contaminant.

With respect to air sparging system optimization, the objective function incorporates the conceptual relationship defined for applicability plus several additional factors:

- contaminant removal efficiency;
- cost-effectiveness (as compared with other viable technologies); and
- time efficiency (as compared with the amount of time available to complete the desired levels of contaminant removal).

In maximizing the objective function for air sparging optimization, the field practitioner (supported by pilot-scale testing results) can modify several system design features: flow rate, injection pressure, number and location of sparging wells, and type of operating mode (pulsed versus continuous). In doing so, the practitioner will attempt to find the optimal overlap of sparging pattern (with respect to contaminant distribution), concurrently resulting in the highest removal efficiency, the least expensive remediation overall, and the longest (acceptable) period of time.

SECTION 6.0

SCOPE OF THE DECISION TOOL

The Decision Tool will identify the essential information needed for assessing and determining (and quantifying, if needed, from available data or by using the limited data to check a default list) the degree of applicability or optimization of air sparging at a particular site. The underlying logic of the Decision Tool will be based on sound scientific theory. In the absence of proven scientific theory, accepted, demonstrated engineering practice and operating principles will be incorporated. However, the Decision Tool is not being developed as a predictive model or an air sparging system design guide.

As part of the scope of the Decision Tool, the essential information for determining the applicability of air sparging at a particular site will be established. The level of detail and the certainty of results will be proportional to the level, detail, accuracy and availability of input and comparison data relating characterization of site contamination and geology to established scenarios. The Decision Tool will also determine which essential information varies (or follows a hierarchical layering, i.e., contaminant type, then soil characteristics, etc.) between sites.

After establishing the parameters which are essential for determining the applicability or optimization of air sparging, the Decision Tool will evaluate which site data can be estimated (or obtained from literature or default values) versus that which must be determined through employment of pilot scale testing.

The Decision Tool will predict the applicability of air sparging to a particular site. The Tool also will provide guidance for optimizing an air sparging system by first determining the theoretical optimal remedial rate (based on mass removal or air exchange) of a conceptualized design.

The Tool will be developed to assist field practitioners and environmental managers assess the applicability or assist in optimizing air sparging systems. The Tool will be user friendly and applicable to a wide variety of contamination scenarios and geologic settings.

6.1 CONCEPTUAL DESCRIPTION OF THE DECISION TOOL

A three-tiered approach is being considered for the development of the Decision Tool. The purposes of using a three-tiered approach are to educate the user and to evaluate the applicability of 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. The three tiers to be developed are:

Tier 1 - Scenario Approach A number of general geologic/contaminant scenarios are being developed (realizing that not all possible scenarios will be included) which could be used to quickly determine if sparging definitely is or is not applicable to a particular site and to aid the user in classifying his/her site.

Tier 2 - Conceptual Feasibility Limited site-specific information (geologic and contaminant) is then used to calculate several conceptual design parameters and to conduct a semi-quantitative evaluation of the applicability and feasibility of sparging at a site.

Tier 3 - Pilot Studies In this step, the practitioner determines the infeasibility of sparging at a site and optimizes the design (of existing or proposed systems). Results provide the basis for conceptual, rather than detailed, design of an air sparging system.

6.1.1 Detailed Discussion of Tier 1: Scenario Approach

The focus of Tier 1 is to educate the end-user with respect to the general applications of air sparging. The purpose is to expeditiously reject sites where sparging is wholly inappropriate. This will be accomplished through the use of approximately 16 templates, (or when computerized, screens). Each template will include a site conceptual model (generalized cross-section with contaminant distribution displayed), a verbal description of the site, air sparging related experience at similar sites, possible alternative treatment technologies, concerns experienced with similar sites, and a "Consumer's Report" scale in which the likely applicability of sparging is indicated. The user will compare his/her site to the templates to determine if one provides a match.

Each template title would include the scale (large impact (i.e., major source area with probable coincident occurrence of groundwater contamination and NAPL phase) or small impact (i.e., minor levels of dissolved contamination, no NAPL, no smear zone and/or the significant portion of contamination is in the unsaturated zone)), contamination type (hydrocarbons or solvents), geology (layered, homogeneous or fractured/tight) and remediation goal/target (source, plume or containment). A sample template has been included as Figure 3.

LARGE (SEPARATE PHASE) - HYDROCARBON - HOMOGENEOUS FORMATION

DESCRIPTION OF CONCEPTUAL SCENARIOS

The subsurface materials at the site are isotropic and homogeneous and are composed of silts, sands or gravels. The hydraulic conductivity of the materials is nearly uniform in all directions. The contaminant of concern is hydrocarbon based. The contaminant has advanced from the vadose zone into the saturated zone. There is a residual separate phase of hydrocarbons on the water table surface (LNAPL) which has produced a smear zone at the interface of the vadose and saturated zones. In addition, hydrocarbons are in dissolved phase and are migrating in the direction of groundwater flow.

EXPERIENCE - SPARGING APPLICATIONS

Air sparging has the potential to be an applicable remedial technology in a homogeneous lithologic setting with hydrocarbons being the target contaminant. The potential for "uniform" air distribution patterns in a homogeneous material coupled with the hydrocarbon remaining on the water table surface (because of density differences) causes air sparging to be a plausible candidate to address the contaminant scenario at the site. By injecting air below the contaminated smear zone (or LNAPL), radial (uniform) flow of the sparged air will impact (by volatilizing and enhancing biodegradation) the residual contamination. A soil vapor extraction system may have to be employed to capture volatilized VOCs.

Source

In this particular application, the source is not necessarily a separate phase, but more accurately the residual components trapped in the smear zone. Air sparging would both be technically and physically possible and would provide a good or unique target for sparging in this particular conceptual scenario.

Plume

In this particular application, the plume is generally dissolved hydrocarbons. Air sparging would both be technically and physically possible and might provide a good or unique target for sparging in this particular conceptual scenario, depending on the of groundwater velocity.

Containment

In this particular application, containment would address plume migration. Air sparging would both be technically and physically possible and might provide a good or unique target for sparging in this particular conceptual scenario depending on lateral spread of the source or smear zone.

ALTERNATIVES

Other remedial alternatives for addressing this conceptual scenario include: pump and treat, dewatering and bioventing/soil vapor extraction, bioslurping, and/or natural attenuation.

CONCERNS

Issues of potential concern at this site include: depth to water, groundwater velocity, saturated thickness, and presence, number and proximity of sensitive receptors.

Seventeen different scenarios are being developed (see Table 2 for a summary of the identified scenarios). The layered scenarios are being delineated into three sub-scenarios, based on changing permeability with depth: decreasing permeability with depth, increasing permeability with depth, and alternating permeability with depth.

The "Consumer's Report" applicability scale is based on two discrete questions: is air sparging physically/technically possible? and is this scenario a good/unique target for sparging? (or are there other, perhaps more appropriate alternatives?). If a scenario is determined to be a good physical/technical possibility and a good/unique target for sparging, it is given a "++". If a scenario is determined to be a good physical/technical possibility and a justifiable (but not unique) target for sparging the scenario is given a "+". If the scenario is determined to be an unknown physical/technical possibility, it is given a "-". Finally, if the scenario is determined to be not physically/technically possible, it is given a "--". The "Consumer's Reports" scale has been applied to the seventeen scenarios as shown in Table 2.

6.1.2 Detailed Discussion of Tier 2: Conceptual Feasibility

The focus of Tier 2 is to further evaluate the applicability of sparging at a given site. The objective of Tier 2 is to evaluate a site without requiring excessive or prohibitive amounts of data, time and expense. Tier 2 is broken down into four major parts.

The first part of Tier 2 involves the estimation of air sparging parameters which are functions of the geology, contaminant type and contaminant distribution. The calculations proposed are simple (i.e., algebraic), allowing a potential user to do the calculations by hand, if necessary, without being burdened with numerous, complex manipulations and iterations (i.e., as typically found in groundwater flow models). Parameters which are proposed include:

- 1) Minimum Injection Pressure;
- 2) Maximum Flow Rate for a Given Injection Pressure;
- 3) Maximum Theoretical Removal Rate for Given Air Flow (Volatilization and Biodegradation);
- 4) Theoretical Air Distribution (Radius of Influence for a Homogeneous Site);
- 5) Time Required to Remediate NAPL;
- 6) Minimum/Maximum Removal Effectiveness for a System (Diffusion Limit = Minimum; Well-Mixed Flow = Maximum); and
- 7) Bioremediation Rates

TABLE 2
AIR SPARGING OPTIMIZATION DECISION TOOL
SUMMARY OF DECISION TOOL SCENARIOS

Description of Scenarios	Code	Objectives		
		Source Remediation	Plume Remediation	Containment
Large (Phase-Separated)-Solvent-Layered Formation (Decreasing Permeability with Depth)	LSL1	-	+	+
Large (Phase-Separated)-Solvent-Layered Formation (Increasing Permeability with Depth)	LSL2	--	-	-
Large (Phase-Separated)-Solvent-Layered Formation (Alternating Permeability with Depth)	LSL3	--	-	-
Large (Phase-Separated)-Hydrocarbon-Layered Formation (Decreasing Permeability with Depth)	LHL1	++	+	+
Large (Phase-Separated)-Hydrocarbon-Layered Formation (Increasing Permeability with Depth)	LHL2	-	-	-
Large (Phase-Separated)-Hydrocarbon-Layered Formation (Alternating Permeability with Depth)	LHL3	-	-	-
Small-Solvent-Layered Formation	SSL	-	-	-
Small-Hydrocarbon-Layered Formation	SHL	+	-	-
Large (Phase-Separated)-Solvent-Fractured/Tight Formation	LSF	--	--	-
Large (Phase-Separated)-Hydrocarbon-Fractured/Tight Formation	LHF	--	--	-
Small-Solvent-Fractured/Tight Formation	SSF	--	--	-
Small-Hydrocarbon-Fractured/Tight Formation	SHF	--	--	-
Large (Phase-Separated)-Solvent-Homogeneous Formation	LSH	-	+	+
Large (Phase-Separated)-Hydrocarbon-Homogeneous Formation	LHH	++	+	+
Small-Solvent-Homogeneous Formation	SSH	+	+	+
Small-Hydrocarbon-Homogeneous Formation	SHH	+	+	+
Other	OTH	?	?	?

Information required prior to conducting the above calculations would probably include:

- a) Conceptual Cross-Section. A conceptual cross-section indicating subsurface geology/hydrogeology and contaminant type and distribution (horizontal and vertical).
- b) Characterization Elements. The following elements may be included: grain size analysis, hydraulic conductivity, visual classification of borings, analytical results, natural dissolved oxygen in groundwater, and velocity of groundwater.

The second part of Tier 2 provides using a sliding scale for projecting effectiveness of air sparging at a given site (see Figure 4) and, consequently, projecting well spacing and the number of wells required to address the contaminated matrix. The actual maximum degree of effectiveness will depend on the factors determined previously (i.e., grain size, etc.) as well as the projections of the degree of mixing likely to occur.

By looking at the probable zone of sparging impact (for scenario type), the user can weigh well spacing with air saturation level to determine approximate well spacing. For isotropic heterogeneous or homogeneous situations, the air saturation level is assumed to decay exponentially with the radius of influence. The further away from the sparge well, the lower the saturation level in the groundwater. Using the information acquired during Tier 2, the field practitioner would select the approximate well spacing by comparing the projected remediation time with the well spacing, assuming that effectiveness was proportional to air saturation level.

The third part of Tier 2 estimates costs based on the above-computed criteria and approximate spacing and, hence, the approximate number of sparging wells. As opposed to being compared to detailed cost tables, this evaluation could be an "order of magnitude" comparison. Air sparging will be compared against one or more applicable technology(ies), as appropriate. As part of Tier 2, a conceptual cost worksheet would be offered to assist the practitioner. This worksheet would serve as a common sense "checklist" to ensure that simple items needed to design/operate a system would not be overlooked in the cost estimating and comparison process.

The fourth part of Tier 2 determines whether sparging meets the user's non-quantifiable needs. Factors to be considered include time, risk (potential receptors, type and proximity), remediation goals and politics. The user must relate his/her specific scenario to the scenarios developed in Tier 1 to determine maximum/minimum expectations.

FIGURE 4

SCALE OF PROJECTED AIR SPARGING EFFECTIVENESS
(E.G., DEGREE/LEVEL OF CONTRACT WITHIN MATRIX)

- 0 - DIFFUSION LIMITED MATRIX - MINIMUM
- 100 - WELL MIXED HOMOGENEOUS MATRIX - MAXIMUM

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6.1.3 Detailed Discussion of Tier 3: Pilot Studies

The principle focus of Tier 3 (Pilot Studies) is to determine if a site which appears to be a good candidate under Tier II analysis has unexpected fatal flaws. Using expected remediation effectiveness rates projected in Tier 2, pilot testing of varying degrees of complexity and duration can be undertaken to verify technology effectiveness. Results should confirm, with reasonable levels of confidence, the applicability of sparging. Results will later be used to develop the conceptual design of a sparging system and to "tweak" either existing or new systems toward optimization (see Optimization Subsection below).

Red flags (i.e., demonstrating infeasibility) during a pilot-scale test could include, for example, extreme lateral movement, excessive injection pressure, vapor migration into unwanted places, and poor or low recovery efficiency.

Table 3 provides a description of what you can expect to learn during various pilot testing scenarios. The table illustrates what can (and by process of elimination, cannot) feasibly be learned about a site during a pilot-scale study.

6.1.4. Optimization

Optimization is focused on two distinct aspects: optimizing an existing/operating system and optimizing the "conceptual design" of a proposed system with information obtained during a pilot study (Tier 3) in comparison with the predicted values from the calculations (Tier 2).

Optimization of an existing sparging system, as presented in the Decision Tool will be an iterative process (i.e., the user changes a parameter, monitors for specific impacts and repeats - then changes a different parameter, etc.). The principal means of optimization will include such parameters as: changing the flowrate; altering the injection pressure; adding or altering sparging points; and changing operational modes (pulsed versus constant flow), etc.

Optimizing a proposed system will consist of comparing data obtained during field tests to the predicted values from Tier 2. Utilizing the pilot-scale test information, the applicability of air sparging can be more readily ascertained and "optimization" of the proposed system can be performed.

A preliminary decision tree outlining the logical decision structure of the Decision Tool is presented as Figure 5.

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 performance	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 vadose zone 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

6.1.5 Projected Features of the Decision Tool

Based on the foregoing discussion, the Decision Tool is expected to include the following features:

- PC-based system, suitable for lap-top use in field offices;
- a three-tiered, logical decision tree approach, rapidly focusing on applicability;
- approximately 16 templates, depicting "standard" conceptual scenarios;
- contamination assessment information such as presence of non-aqueous phase liquids (NAPLs), extent of contamination (e.g., source area, groundwater plume) and zones affected (e.g., vadose, saturated, smear);
- contaminant characterization factors;
- geologic and hydrogeologic factors such as depth to groundwater, definition of confining layers, presence of channels, presence of other intrusions, direction and rate of groundwater flow;
- soil characterization factors;
- physical, chemical, and biological processes;
- libraries or tables to provide default values (as appropriate) for hydrogeologic properties;
- look-up (reference) tables for physical, chemical, and biological properties of contaminants;
- conceptual feasibility and design calculations;
- equations for calculating contaminant removal efficiency;
- cost-effectiveness considerations;
- pilot-scale study guidances; and
- calculation of requirements for optimization (pressure, rate, etc.).

PRELIMINARY DECISION TREE

FIGURE 5a

FIGURE 5b

FIGURE 5c

FIGURE 5d

STOP I
AIR SPARGING IS
THE TECHNOLOGY
OF CHOICE FOR
THIS SITE.

OPTIMIZATION OF EXISTING SYSTEMS

SECTION 7.0

KEY SUCCESS FACTORS FOR THE DECISION TOOL

To evaluate the success of the Decision Tool, the Tool will be assessed for its technical completeness, user relevance and applicability, and scientific accuracy. The Tool will be validated and "fine tuned" with data from sites where the applicability "quotient" is known. Data from these sites will be input into the Decision Tool and the output will be compared with known information from the site. The same process will be utilized when evaluating the success of the optimization feature of the Decision Tool.

To evaluate the relevance of the Decision Tool for use by the various user communities, the Tool will be distributed for testing by several different user groups. These include U.S. DOE, other governmental agencies, consulting and industrial personnel. The Tool will also be offered for testing by users within these groups with different levels of skill and experience. They will evaluate the Tool based upon their ability to follow its logic and steps and the ease with which they can apply the Tool. As part of the evaluation process, a standardized list of objective questions will be prepared and employed. These questions will be utilized by the test users to assess the Tool's utility.

The evaluation of the technical completeness, user relevance and applicability, and scientific accuracy of the Tool will be based on the review teams' responses to the following questions:

- How practical is this tool?
- How user friendly is the Tool? For novice users? For experienced modelers?
- What is the likelihood of providing an inappropriate response (i.e., one that later is proven through full-scale application to be wrong)?
- Does the Tool provide a logical progression (i.e., a decision path or tree) for assessing the applicability or optimization of air sparging?
- Does it address all target contaminants through a general range of sites?
- Does it address the general range of sites potentially targeted for application of air sparging technology and identified as of specific interest to DOE?
- Does it convincingly and confidently provide a "go-no go" decision for use of air sparging at a site?

After completion of the Decision Tool evaluation process, a complete listing and discussion of all comments will be included in the review report for the Decision Tool.

SECTION 8.0

APPLICATIONS FOR DECISION TOOL USE

8.1 GENERAL CONSIDERATIONS FOR USE

In general, application of the Decision Tool will be limited to those situations and specific sites for which air sparging is a realistic candidate for remedial technology selection. By the nature of the processes which dominate air sparging, the application of the Decision Tool itself will probably be constrained. On the other hand, use of the Decision Tool may confirm the appropriateness (or lack thereof) of air sparging for remediation of selected, "marginally attractive" sites.

The Decision Tool is being developed for application by field practitioners or program managers responsible for managing many site remediation projects. The primary objective of Decision Tool use is expedited and accurate decision-making with respect to remedial technology selection, especially considering the potential benefits of using air sparging at particular sites under consideration. Use of the Tool is not intended for detailed design applications or for fate and transport modelling of specific sites. In fact, the Tool is not intended to model physical systems; instead it is a "model" of the decision-making process, focussing on remedial technology (i.e., specifically air sparging) selection and optimization of that selection.

The Decision Tool is intended to be used by the field practitioner during several stages in the decision-making and remediation strategizing processes. These stages may include:

1. During confirmatory site characterization, being undertaken to determine the probable likelihood that air sparging (or one or 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 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);
6. During installation and 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 Decision Tool accuracy).

The above-listed potential applications of the Decision 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 Decision Tool which were anticipated and taken into account during development. Refer to Figure 6 for a schematic depiction of potential appropriate opportunities for Decision Tool use during the site remediation process.

With respect to the type of situation or specific site in which the Decision Tool may be most frequently applied, it is anticipated that the nature of the site or situation will likely dictate. Unless prospective field practitioners are contemplating use of air sparging in their remediation strategies, it is not likely that the Decision Tool will be considered for usage. Thus, 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 the practitioner's consideration of the use of air sparging for site remediation and, hence, the potential use application of the Decision Tool, are (in no particular order):

- 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;

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

- presence of bedding (horizontal) or layering;
- presence of a source area or focussed groundwater plume;
- desired remediation end-point, e.g., target level;
- length of time available for remediation;
- resources available for remediation; and
- accessibility (e.g., infrastructure) of the site, among others.

This listing of factors is not intended to be exhaustive, but rather to provide an illustration of the issues to which a prospective field practitioner may refer when considering application of the Decision Tool.

8.2 U.S. DEPARTMENT OF ENERGY (DOE) FACILITIES

It is probable that field practitioners and program managers within U.S. DOE facilities (e.g., national laboratories) and supporting organizations (e.g., Plumes Focus Area) may be interested in and could potentially benefit from application of the Decision Tool at a number of the project stages described above. The range of potential applications within the DOE Complex extends from national laboratories and supporting facilities, organizations and contractors to private and academic research facilities whose efforts have supported the Complex. Field practitioners responsible for remediation of the following facilities and sites (within facilities) could potentially benefit from applying the Decision Tool for determining applicability of and for optimizing air sparging systems:

- DOE (e.g., GOCO) national laboratories;
- Energy and weapons production facilities;
- Systems and parts manufacturing facilities;
- Solvent storage and cleaning facilities; and
- Fuel storage and handling facilities.

Other groups of facilities or types of sites may also be appropriate for considering application of the Decision Tool in developing remediation strategies for the facilities or sites.

It has been proposed to and accepted by representatives of the DOE Plumes Focus Area that the Decision Tool is not intended to be used in conjunction with remedial technology decision-making for sites contaminated by mixed or radioactive wastes or heavy metals.

Complex remedial efforts involving these wastes are beyond the intended scope of the Decision Tool.

8.3 OTHER GOVERNMENTAL FACILITIES

Application of the Decision Tool for use in the decision-making process for remediation of other governmental facilities may be similarly appropriate. For instance, U.S. Department of Defense (DoD) operations historically have been large users of chlorinated, petroleum and other hydrocarbon products. As a result, many DoD facilities and sites may face substantial remediation requirements. The Decision Tool could be useful for application by program managers and field practitioners (e.g., in AFCEE, AMC, Navy, or Corps of Engineers environmental restoration programs) who are responsible for screening appropriate technologies for large numbers of sites and facilities. The Decision Tool could help facilitate the screening process by determining the applicability of air sparging in a timely fashion, perhaps at an earlier stage in the overall remedial strategy planning process. Later in the process, during design, installation and operations of the site remediation systems, the Tool could be applied for optimizing air sparging systems.

Similarly, there are large numbers of sites owned or operated by State, regional or local governmental bodies with similar remedial technology selection opportunities. The owners or operators of these sites could also potentially benefit from application of the Decision Tool to their situations.

8.4 GENERAL INDUSTRIAL SITES

There are large numbers of facilities and sites owned or operated by many different industrial corporations which could potentially benefit from application of the Decision Tool. These include, but are by no means limited to:

- Petroleum production, refining, transportation and marketing;
- Chemical and petrochemical processing, transportation and marketing;
- Mechanical and electrical systems and parts manufacturing;
- Semiconductor and electronic parts manufacturing;
- Natural and manufactured gas plants and storage;
- Dry cleaning and other solvent cleaning operations;
- Other manufacturing, industrial and commercial sectors.

8.5 TECHNOLOGY TRANSFER

Technology transfer within the DOE Complex will be promoted by existing networks of technology users and providers. Examples include the Plumes Focus Area and other similarly focused groups.

Technology transfer within industrial and commercial sectors is theoretically more difficult than with their counterpart sectors of the DOE Complex. Although trade organizations are quite prolific, distribution of information potentially useful in the remedial technology selection process is cumbersome and uneven.

The adoption and application of the Decision Tool will depend on several factors:

- appropriateness;
- accessibility;
- awareness;
- usability; and
- authority (or lack thereof) to control the decision-making process.

Nonetheless, through "chance" encounters at government-sponsored and industry trade association-sponsored conferences, trade shows, symposia and seminars, as well as through direct marketing, prospective users often become aware of decision-making aids, such as the Decision Tool.

APPENDIX A
BIBLIOGRAPHY

APPENDIX A

BIBLIOGRAPHY

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APPENDIX B
DETAILED OVERVIEW OF AIR SPARGING MODELS

APPENDIX B

DETAILED OVERVIEW OF AIR SPARGING MODELS

The following Tables are the detailed listing of information received from developers with respect to the models they have developed. This information was solicited by means of a standardized questionnaire (see Appendix D) which was sent to various developers for their input and assistance in the completion of this compendium. The Tables are a condensation of information gathered on various air sparging and/or related augmentation technologies.

Table B-1 consists of a more detailed presentation of the information listed in Table 1 (see Section 3). Relationships and parameters such as inputs and outputs, air permeability relationship parameters, are presented in Table B-1. Table B-2 displays the information relevant to the modeling effort and the success factors of the models. In Tables B-1 and B-2, the models are presented in alphabetic order by model name.

Appendix B

TABLE B-1
Relationships and Parameters
Air Sparging Optimization Decision Tool

Name of Model	Developer(s)	Producer	Basis of Model (empirical/theoretical)	Model Parameter Summary
3D3PT	Neil R Thomson	University of Waterloo	Mathematical model	Responder: Too many to list here
BIOPLUME II	HS Rifai, PB Bedient, RC Bordan, JF Haasbeek	Rice University	--	--
BIOTRANS	Environmental Systems & Technologies, Inc.	Environmental Systems and Technologies, Inc.	Mathematical model	--
CHEVRON RESEARCH CONCEPTUAL MODEL	Donald H. Mohr	Chevron Reserach and Technology	Theroetical	number and length of air channels, diameter of air channels, concentrations in the gas and aqueous phases.
COMPSIM	Brent Sleep	Brent Sleep, University of Toronto	Mathematical model	Multiphase, multicomponent flow and transport,

Appendix B

TABLE B-1
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Name of Model	Developer(s)	Producer	Basis of Model (empirical/theoretical)	Model Parameter Summary
HYPER-- VENTILATE	Paul C. Johnson	Shell Oil Company	--	Mass balances, chemical equilibria laws, Darcy's Law
MOTRANS	AK Katyal, JJ Kaluarachchi, JC Parker	Environmental Systems and Technologies, Inc.	Mathematical model	Unsaturated hydraulic properties, NAPL physical properties, component solubility, and vapor concentration
OREGON GRADUATE INSTITUTE CONCEPTUAL MODEL	Rick Johnson	Oregon Graduate Institute	Physical/chemical processes, especially diffusion	number and length of air channels, diameter of air channels, concentrations in the gas and aqueous phases.
SAVANNAH RIVER IN SITU SIMULATION	Bruce A Robinson, Nina D. Roseberg, George A Zyvoloski, and Hari Viswanathan	Office of Technology Development, Department of Energy	Conceptual model based on observation of pilot test results, modeling based on FEHM flow and transport code.	dual phase transport, relative permeability, advection, molecular diffusion, dual porosity heterogeneties, initial contaminant distribution, equilibrium sorption, permeability,

Appendix B

TABLE B-1
Relationships and Parameters
Air Sparging Optimization Decision Tool

Name of Model	Developer(s)	Producer	Basis of Model (empirical/theoretical)	Model Parameter Summary
SPARCHAN	David J. Wilson, Cesar Gomez-Lahoz, Jose M. Rodriguez-Maroto	David J. Wilson Vanderbilt University	Dispersive mass transport principles, Henry's Law, and observation of air transport in persistent channels in aquifer; mathematical model	Too complex to discuss here;
SPARG 1	M. Marley, F. Li	Envirogen, Inc.	Mathematical model – Deterministic	Fluid flow in accordance w/ Darcy's Law; relative K based on Corey-Brook & Van Gentry relationships
STOMP	Mark D. White & Mart Oostrom, Pacific Northwest Laboratory	Pacific Northwest Laboratory	numerical solver of partial differential equations that govern flow and transport through variably saturated geologic media	Designed to solve a wide variety of nonlinear, multiphase, flow and transport problems for variably saturated geologic media. Partial differential conservation equations for component mass, energy and solute mass comprise the fundamental equations for the simulator.
T2VOC	R. Falta, K. Pruess, S. Finsterle, A. Battistelli	Lawrence Berkeley Laboratory	Mathematical model based on physical/thermodynamic principals	Solves the coupled non-linear mass and energy balance equations for air, water, chemical, heat in a multiphase flow system.

Appendix B

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Air Sparging Optimization Decision Tool

Name of Model	Developer(s)	Producer	Basis of Model (empirical/theoretical)	Model Parameter Summary
TETRAD	Dyno Research & UNOCAL	Dyno Research & UNOCAL	numerical finite difference	multiphase, multicomponent, three-dimensional flow model
TRACR3D	Dr. Bryan Travis/ Kay Birdsell	Los Alamos National Laboratory	Mathematical model	Based on conservation of mass, Darcy's Law plus relative permeability and matric potential are functions of saturation.
UNIVERSAL REMEDIATION TIME MODEL	David H. Bass	Groundwater Technology, Inc.	Empirical	Model assumes partitioning within a treatment volume between various phases. Partition varies from equilibrium by contact efficiency factors which decrease as extent of remediation proceeds.
WELLPACK	Francois and Gorlick	Stanford University	Experimental and Theoretical fluid mechanics	For a desired water pumping rate the model tells you how much air to inject into the well

Appendix B

TABLE B-1
Relationships and Parameters
Air Sparging Optimization Decision Tool

Name of Model	Processes included	Inputs	Outputs	Air Permeability Relationship	Assumptions/ Capabilities
3D3PT	Advection, hydrodynamic dispersion, sorption, volatilization, mass transfer between phases	Geologic K, fluid properties, K_w (sw)	Single time data, or time series data for multiple outputs at multiple points	Parker et.al.(1985), Brookes and Corey	Fluid moves according to Darcy's Law
BIOPLUME II	Advection, dispersion, sorption, biodegradation of dissolved contaminants	Hydraulic conductivity, effective porosity, longitudinal dispersion, bulk density distribution, anaerobic decay, hydrocarbon/oxygen ratio	Hydraulic head, predicted solute and oxygen concentrations; can be output as x,y,value, text files	Question deleted	Darcys law is valid and head gradient are only flow mechanism; porosity and hydraulic conductivity do not change with time; porosity is uniform—OTHERS
BIOTRANS	Advection, hydrodynamic dispersion, sorption, NAPL Desorption, Fracture/Matrix Mass Structure, volatilization	Porosity, Bulk Density, Dispersivity (L&T) Mass Transfer (Initial, O/W, & fracture, Solubility, Adsorption, Oxygen Mixing, stachrometric, vapor transfer	Concentrations of five species including oxygen; can be plotted using graphs or contours, exported as .dxf	Does not specifically simulate airflow.	Oxygen—limited decay is instantaneous; steady state
CHEVRON RESEARCH CONCEPTUAL MODEL	volatilization, diffusion	aqueous and gas phase concentrations, the diameter of the air channels, the number of air channels, the thickness of the zone of contamination.	mass of oxygen transferred from the sparge air to the groundwater or mass of contaminant in the groundwater volatilized to the sparge air.	not an issue where air channeling considered	steady state only, air exists as widely-separated discrete channels, there is no significant mixing or groundwater flow
COMPSIM	Advection, hydrodynamic dispersion, sorption, volatilization, transport,	Pressures, saturations, concentrations of phases and components	Pressures, saturations, concentrations of phases and components	van Genuchten, Brooks—Corey, Rossi—Nimmo, or tabular	Full three—phase, three—dimensional

Appendix B

TABLE B-1
Relationships and Parameters
Air Sparging Optimization Decision Tool

Name of Model	Processes included	Inputs	Outputs	Air Permeability Relationship	Assumptions/ Capabilities
HYPER-VENTILATE	Partitioning between residual NAPL and vapor; air flow	Permeability, chemical properties, composition, well geometry, process conditions	Tabulated values such as flowrate, removal effectiveness vs volume of air, and number of wells	Question deleted	Model assumes well-mixed systems, chemical equilibria, and residual NAPL present
MOTRANS	All	Porosity, Spatially variable soils, relative K varies in time, Hydraulic conductivity, van Genuchten, parameters, transient flow	Phase saturations, air and water phase concentrations, ASCII and graphs	van Genuchten	Darcy flow for all phases; equilibrium or first order phase transfer kinetics
OREGON GRADUATE INSTITUTE CONCEPTUAL MODEL	volatilization, diffusion	aqueous and gas phase concentrations, the diameter of the air channels, the number of air channels, the thickness of the zone of contamination.	mass of oxygen transferred from the sparge air to the groundwater or mass of contaminant in the groundwater volatilized to the sparge air.	--	steady state only, air exists as widely-separated discrete channels, there is no significant mixing or groundwater flow
SAVANNAH RIVER IN SITU SIMULATION	pressure distribution diffusion, sorption, Voc partitioning to air and water,	--	--	van Genuchten	Fluid phase transport for air and water is isothermal, equilibrium sorption assumed with a linear sorption isotherm.

Appendix B

TABLE B-1
Relationships and Parameters
Air Sparging Optimization Decision Tool

Name of Model	Processes included	Inputs	Outputs	Air Permeability Relationship	Assumptions/ Capabilities
SPARCHAN	Advection, hydrodynamic dispersion, sorption, volatilization.	P. 2397 of attached paper;	listing of residual contaminant mass vs time, hard copy plot of residual contaminant vs time, report listing all parameters used.	not an issue when air channeling considered; air distribution into channels is proportional to local mean air flux rate and constant characteristic of porous aquifer	Air is compressible and moves along channels, handles only dissolved VOCs wells are line or point sources, steady state only, airflow induced water circulation considered
SPARG 1	Advection	Porosity, relative air K are distance variant	Air distribution in saturated zone	Corey-Brockes relationship	Steady-state only
STOMP	diffusion, dispersion, organic component sorption, Nonhysteretic and hysteretic k-s-p functions, nonwetting fluid entrapment, NAPLs, numerous heat transfer properties, evaporation and condensation of water and organic components, advective and diffusive-dispersive transport, phase partitioning, sorption and retardation, radioactive decay.	too numerous to list	too numerous to list	gas phase relative K computed by: Constnat, Mualem, Burdine, Fatt and Klikoff, Corey, Dual Porosity, and Tabular, with both Linear Interpolation and Cubic spline interpolation.	Dependent on specific operational mode.
T2VOC	Advection (multiphase), diffusion, evaporation of NAPL, volatilization, sorption, interphase mass transfer, boiling, condensation....	Porosity, K, relative K, capillary pressures, thermal/chemical properties	Predicted phase saturations, concentrations, pressure, temperature, mass and energy fluxes, contaminant mass in system	Write in	Multiphase Darcy's Law, local chemical and thermodynamic equilibrium, single chemical (VOC) component

Appendix B

TABLE B-1
Relationships and Parameters
Air Sparging Optimization Decision Tool

Name of Model	Processes included	Inputs	Outputs	Air Permeability Relationship	Assumptions/ Capabilities
TETRAD	advection hydrodynamic dispersion, sorption, volatilization	std. rock and fluid properties, eg porosity, K, K _{ri} , viscosity, density, compressibility	pressures, saturations, mole fractions	user defined relative K functions or tables	air moves according to Darcy
TRACR3D	Advection, diffusion dispersion, volatility, decay chains, sorption.	Porosity, permeability compressibility, dispesivities, sorption coefficients; properties can vary spatially.	Pressure, saturation, concentrations, at specified times; formatted line printer listings, filed for graphics post processing packages.	User-specified tables or Brooks-Corey or van Genuchten	Darcy or Forcheimer flow for two-phase flow
UNIVERSAL REMEDIATION TIME MODEL	dissolution; also biodegradation and abiotic degradation	Contaminant vapor pressure/K _h , K _{oc} , MW, biodegradation rate constants, abiotic degradation rate constant. Matrix Foe, porosity. System groundwater recovery rate and sprage air flow rate per unit volume contaminanted soil.	Remediation time for various pathways (degradation, pumping, sparging, various combinations)	NA	Deviation from mixed-tank equilibrium increases linerly with extent of remediation, reflecting preferential cleanup of preferential pathways.
WELLPACK	it is a model for in-well processes-- multiphase flow of air and water in a well	Well diameter, air line diameter, depth of sparger, desired water flow rate	required air injection rates, stripping factor, water air production	Not used	Turbulent mutiphase flow in a well containing an expandable isothermal gas and and incompressible liquid. Kinetically mediated (non-equilibrium) mass transfer of VOCs

Appendix B

TABLE B-2

**Modeling Information and Success Ratings
Air Sparging Optimization Decision Tool**

Name of Model	Version Reviewed	Production Date of Version	Developer(s)	Legal Restrictions	Producer
3D3PT	revisions ongoing	Current version	Neil R Thomson	No	University of Waterloo
BIOPLUME II	1.1	Not known	HS Rifai, PB Bedient, RC Bordan, JF Haasbeek	No	Rice University
BIOTRANS	1.12	1995 April	Environmental Systems & Technologies, Inc.	Yes	Environmental Systems and Technologies, Inc.
CHEVRON RESEARCH CONCEPTUAL MODEL	--	1995 April	Donald H. Mohr	--	Chevron Reserach and Technology

Appendix B

TABLE B-2

**Modeling Information and Success Ratings
Air Sparging Optimization Decision Tool**

Name of Model	Version Reviewed	Production Date of Version	Developer(s)	Legal Restrictions	Producer
COMPSIM	none	1995 May	Brent Sleep	Proprietary	Brent Sleep, University of Toronto
HYPER- VENTILATE	1.01 (MacIntosh) 2.0 (Windows)	1991	Paul C. Johnson	No	Shell Oil Company
MOTRANS	1.1	--	AK Katyal, JJ Kaluarachchi, JC Parker	Yes	Environmental Systems and Technologies, Inc.
OREGON GRADUATE INSTITUTE CONCEPTUAL MODEL	--	--	Rick Johnson	No	Oregon Graduate Institute

Appendix B

TABLE B-2

**Modeling Information and Success Ratings
Air Sparging Optimization Decision Tool**

Name of Model	Version Reviewed	Production Date of Version	Developer(s)	Legal Restrictions	Producer
SAVANNAH RIVER IN SITU SIMULATION	--	June 1994	Bruce A Robinson, Nina D. Roseberg, George A Zyvoloski, and Hari Viswanathan	unknown	Office of Technology Development, Department of Energy
SPARCHAN	1.0	March, 1994	David J. Wilson, Cesar Gomez-Lahoz, Jose M.rodriquez-Maroto	NO	David J. Wilson Vanderbilt University
SPARG 1	1.0	1994 January	M. Marley, F. Li	Proprietary	Envirogen, Inc.

Appendix B

TABLE B-2

Modeling Information and Success Ratings
Air Sparging Optimization Decision Tool

Name of Model	Version Reviewed	Production Date of Version	Developer(s)	Legal Restrictions	Producer
STOMP	Beta version—limited release	1995 October	Mark D. White & Mart Oostrom, Pacific Northwest Laboratory	Available for test and evaluation only, under DOE or Federal contracts only	Pacific Northwest Laboratory
T2VOC	T2VOC	1995 April	R. Falta, K. Pruess, S. Finsterle, A. Battistelli	No	Lawrence Berkeley Laboratory
TETRAD	11.0	March 1995	Dyno Research & UNOCAL	YES	Dyno Research & UNOCAL

Appendix B

TABLE B-2

**Modeling Information and Success Ratings
Air Sparging Optimization Decision Tool**

Name of Model	Version Reviewed	Production Date of Version	Developer(s)	Legal Restrictions	Producer
TRACR3D	2.1	1995 March	Dr. Bryan Travis/ Kay Birdsell	Copyrighted	Los Alamos National Laboratory
UNIVERSAL REMEDIATION TIME MODEL	Version 1.0	1993	David H. Bass	Proprietary	Groundwater Technology, Inc.
WELLPACK	4.95	1995 April	Francois and Gorlick	Yes	Standford University

Appendix B

TABLE B-2

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Air Sparging Optimization Decision Tool**

Name of Model	Groundwater Mounding Addressed?	Initial Conditions	Boundary Conditions	Type of Model (predictive/analytic)	Numeric Basis of Model (finite difference/finite element/method of characteristics)
3D3PT	No	Flexible	Dirichlet, Neuman, Cauchy	Mathematical/Theoretical	Control volume
BIOPLUME II	Question deleted	Starting heads and concentrations (dissolved)	Dirichlet, Neuman,	Mathematical/Theoretical	Finite solution for GW flow; MOC for transport
BIOTRANS	Derived from flow solution	Hydrocarbons volume, GW velocity, Concentrations	Dirichlet (specified volume)	Mathematical/Theoretical	Finite element
CHEVRON RESEARCH CONCEPTUAL MODEL	no	--	--	mathematical and conceptual	Analytical

Appendix B

TABLE B-2

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COMPSIM	Yes	Saturations, pressures, concentrations	Dirichlet, Neuman, Cauchy	Mathematical/Theoretical	Finite difference
HYPER- VENTILATE	Question deleted	Concentrations and composition	Dirichlet, Neuman,	Mathematical/Theoretical	Semi-analytical (finite difference)
MOTRANS	Yes	Uniform or arbitrary	Specified head concentration specified flux; or zero gradient	Mathematical/Theoretical	Finite element
OREGON GRADUATE INSTITUTE CONCEPTUAL MODEL	--	--	--	mathematical and conceptual	Analytical

Appendix B

TABLE B-2

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Air Sparging Optimization Decision Tool**

Name of Model	Groundwater Mounding Addressed?	Initial Conditions	Boundary Conditions	Type of Model (predictive/analytic)	Numeric Basis of Model (finite difference/finite element/method of characteristics)
SAVANNAH RIVER IN SITU SIMULATION		injection well 48M from surface, extraction well 22 meters from surface	pilot study area 60 meters by 500 meters	Numerically based and observations	see model capabilities
SPARCHAN	NO	contaminant concentrations in aquifer	Neuman	Mathematical/ & Emprical	Solution of partial differential equations by finite difference technique
SPARG 1	No	Hydraulic head, flow, pressure;		Mathematical/ Theoretical	Finite element

Appendix B

TABLE B-2

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Air Sparging Optimization Decision Tool**

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STOMP	Yes	Can include all intrinsic properties; restriction: specified initial conditions do not over specify the thermodynamic or hydrological state of the system.	Dirichlet and Neumann; additional flow boundary conditions include saturated, unit gradient, hydraulic and free gradient; additional transport boundary conditions are outflow and inflow.	mathematical, theoretical and empirical	Model discretizes the governing partial differential equations using an integrated volume finite-difference technique with fully implicit temporal discretization
T2VOC	yes	Pressure distributions, phase saturations, temperature	Dirichlet, Neuman, Cauchy	Mathematical/Theoretical	Integral finite difference, fully implicit in time
TETRAD	Yes	pressures, saturations mole fraction	several choices	mathematical	empirical, theoretical; finite difference

Appendix B

TABLE B-2

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Name of Model	Groundwater Mounding Addressed?	Initial Conditions	Boundary Conditions	Type of Model (predictive/analytic)	Numeric Basis of Model (finite difference/finite element/method of characteristics)
TRACR3D	Yes	Spatial distribution of pressure, saturation, and concentrations	Dirichlet, Neuman, Cauchy	Mathematical/Theoretical & Empirical	Integrated finite difference; implicit in time; numerical dispersion cancellation option for transport
UNIVERSAL REMEDIATION TIME MODEL	no	NA	NA	Mathematical	Empirical/ Analytical
WELLPACK	yes	initial head (water table elevation)	constant pressure top and bottom	Mathematical/ empirical / theoretical	semi-analytical and analytical

Appendix B

TABLE B-2

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Air Sparging Optimization Decision Tool**

Name of Model	Dimensionality	Hardware/ Software Requirements	Model Limitations	Error Checks	Result Check Verification Process	Learning Curve Experience
3D3PT	Three dimensions	486	None	No	Sample problem compared to analytic solution	Need modelling experience
BIOPLUME II	Two dimensions	PC w/ 600K free ram	Unless recompiled, 20X30 grid; solution unstable at high GW velocities; user cannot vary most transport parameters spatially	Yes for MOC; model computes mass balances as check	Relied on documented verification and use of code (in literature)	Experienced—based; few days to few weeks
BIOTRANS	Two dimensions	8 MB RAM, Math coprocessor	Node Limitation—10000	Yes, data checks	Based on analytical solution; results compared with recognized numerical solutions: BIOPLUME and SUTRA	1–3 days
CHEVRON RESEARCH CONCEPTUAL MODEL		No hardware requirements	steady state only, air exists as widely-separated discrete channels, there is no significant mixing or groundwater flow	no	--	--

Appendix B

TABLE B-2

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Name of Model	Dimensionality	Hardware/ Software Requirements	Model Limitations	Error Checks	Result Check Verification Process	Learning Curve Experience
COMPSIM	Three dimensions	IBM RS/6000; 486 with math coprocessor	Finite difference; rectangular domain	Mass balance and convergence checks	Analytical comparisons and lab data	Need understanding of multiphase flow in porous media, math background
HYPER-VENTILATE	One and two dimensional	IBM- Windows, Minimum 4MB RAM; Mac needs hypercard	Lumped parameter approach; cannot simulate heterogeneities; multi-dimensional effects	Yes	Results compared to hand calculation	1-2 hours
MOTRANS	Two-dimension, cross section	586 preferred; pre and post-processor	Node Limitation- 1500	No	Other solutions, lab data	High
OREGON GRADUATE INSTITUTE CONCEPTUAL MODEL	--	No hardware requirements	steady state only, air exists as widely-separated discrete channels, there is no significant mixing or groundwater flow	no	--	--

Appendix B

TABLE B-2

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Name of Model	Dimensionality	Hardware/ Software Requirements	Model Limitations	Error Checks	Result Check Verification Process	Learning Curve Experience
SAVANNAH RIVER IN SITU SIMULATION	three dimensional	--	--	history match		site specific
SPARCHAN	Two-dimensional assumes axial symmetry	386 DX MS-DOS computer, 33MHz, math coprocessor	allows modification of finite-difference grid	NO	checked by examining the dependence of results on all model parameters	Environmental engineer with a little exp. & acquaintance with sparging - one hour
SPARG 1	Three dimensions	486, with math processor only			Compared to analytical solution for simplified case	2-3 days for uses with moderate experience

Appendix B

TABLE B-2
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Name of Model	Dimensionality	Hardware/ Software Requirements	Model Limitations	Error Checks	Result Check Verification Process	Learning Curve Experience
STOMP	One, two or three dimensions in Cartesian, tilted Cartesian, and cylindrical coordinate systems.	written in ANSI FORTRAN 77, and requires appropriate compiler; otherwise is memory & size dependent on complexity of solved problem.	limited only by machine's operating speed and memory capacity.	Yes	Model has been verified against numerous analytical, numerical solutions, and experimental results, documentation available.	built for scientists and engineers, learning curve based on problem to be solved and applied operational mode.
T2VOC	Three dimensions	486, with math processor or better	Code slow for large 3-D simulations	Yes; all mass balances must be $<10^{-5}$ relative accuracy	Compared to experimental results; references available	One month with high level experience
TETRAD	One, two or three dimensions, radially symmetric	multiplatform PC's, supercomputers	All can be varied and the code re-compiled; runs w/ 1000 nodes and 100 time steps are routine	YES	field test with geophysical ground	Requires substantial user expertise

Appendix B

TABLE B-2

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Name of Model	Dimensionality	Hardware/ Software Requirements	Model Limitations	Error Checks	Result Check Verification Process	Learning Curve Experience
TRACR3D	One, two or three dimensions	Runs on anything from 486 PC's to Crays	Uses dynamic memory allocation. Only limits in time and space depend on speed and capacity of computer	Mass balance monitored;	Compared to variety of analytic solutions, other code results, and experimental data	With some familiarity, a few weeks.
UNIVERSAL REMEDIATION TIME MODEL	stirred tank	Runs on 286 or higher, coprocessor not necessary	Requires extensive calibration from similar sites.	No	Laugh test only	A little common sense and 30 minutes
WELLPACK	one dimensional	Macintosh or PC, Excel; is programmed in excell	None	Yes	Compared to other air lift solutions and to a full scale air lift pumping lab set up	A hydrogeologist familiar with air lift pumping and VOC stripping can learn it in 2 hours

Appendix B

TABLE B-2

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Name of Model	Disadvantages or Needs of the Model	Sensitivity Analysis (most sensitive)	Success Factor (% Probability of Success)	Scientific Users Acceptance (Scale 1-10)	Other Pertinent Data
3D3PT	--	--	100%	9 - 10	Rough user's guide available
BIOPLUME II	Limited model grid size; only 2-D; solution is less accurate as GW velocity increases; can only use a uniform grid; many parameters cannot be varied spatially	Transmissivity; decay coefficients	Success depends on available data	7-8	OTHER MODELS Bioplume III is under development; Biotrans
BIOTRANS	Does not explicitly simulate flow conditions	Source, oxygen concentration (stoichiometry) dispersivity	Utilized at numerous sites across country	8	User's guide available
CHEVRON RESEARCH CONCEPTUAL MODEL	limitations are no mixing other than diffusion, fixed channel geometry	--	--	see Don Mohr at Chevron RTC	A description of the model is published in the proceedings of the 1993 On Site and In Situ Biore Restoration Conference.

Appendix B

TABLE B-2

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Name of Model	Disadvantages or Needs of the Model	Sensitivity Analysis (most sensitive)	Success Factor (% Probability of Success)	Scientific Users Acceptance (Scale 1-10)	Other Pertinent Data
COMPSIM	Computational times are long; equilibrium between phases	Permeability, capillary pressure, saturation	Limited experimental verification	8-10; Jim Mercer, Geotrans	Supporting Documentation and User Guide
HYPER-VENTILATE	Not intended to be a "true predictive tool". Intended to give estimates of optimal system performance.	Permeability	100%	5	see EPA/600/R-93/028
MOTRANS	Complex Model	Depends on problem	Utilized at numerous sites across country	8; Joe Williams EPA/Ada; Michael Daly P.E. Bio Tech Remediation, (505) 632-3365	User's guide available; OTHER MODELS-AIRCAD 2-D
OREGON GRADUATE INSTITUTE CONCEPTUAL MODEL	limitations are no mixing other than diffusion, fixed channel geometry	--	--	see Don Mohr at Chevron RTC	A description of the model is published in the proceedings of the 1993 On Site and In Situ Bioremediation Conference.

Appendix B

TABLE B-2

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Name of Model	Disadvantages or Needs of the Model	Sensitivity Analysis (most sensitive)	Success Factor (% Probability of Success)	Scientific Users Acceptance (Scale 1-10)	Other Pertinent Data
SAVANNAH RIVER IN SITU SIMULATION	unknown	--	unknown 255-2288.	unknown	
SPARCHAN	Does not handle NAPL, multiphase flow of air and water in porous medium	Dispersivity of VOC, mean distance between air channels	Too new to determine; Dr. Ann Clarke, Eckenfelder, Inc. 227 french Landing Drive, Nashville, TN, 615	unknown; Ann. Clarke, Eckenfelder	Documentation available
SPARG 1		Air permeability	Good	5, as evaluation tool; 6-10, as design tool	

Appendix B

TABLE B-2

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Name of Model	Disadvantages or Needs of the Model	Sensitivity Analysis (most sensitive)	Success Factor (% Probability of Success)	Scientific Users Acceptance (Scale 1-10)	Other Pertinent Data
STOMP	Complex nonlinear problems can require a significant amount of time to execute.	Sensitivity analyses are strongly problem dependent.	Proven to be an invaluable tool"; for technical information, Mark D. White, Pacific Northwest Laboratory, PO Box 999, Richland WA 99352	9;	User guide release to be October 1995
T2VOC	Single component NAPL, in local equilibrium	Permeability distribution and anisotropy, capillary and vapor pressure, Henry's constant	% relative to knowledge of system parameters	9; references available	User's guide available
TETRAD	Needs improved graphical user interface and pre- and post processors	injection pressure, permeability structures	90; Author, Seruipetrol LTD. 736 6th Ave SW Calgary, Canada, T2P3T7	7; Mike Shoole, JNEL	

Appendix B

TABLE B-2

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Air Sparging Optimization Decision Tool

Name of Model	Disadvantages or Needs of the Model	Sensitivity Analysis (most sensitive)	Success Factor (% Probability of Success)	Scientific Users Acceptance (Scale 1-10)	Other Pertinent Data
TRACR3D	Isothermal	Sensitivities vary with the problem	100% if used properly; Bryan Travis, MS-F665, LANL, Los Alamos, NM 87545	--; Dr. Bridget Scanlon, University of Texas, Bureau of Economic Geology, Austin TX	A version of code with pre and post processors packaged in MS Windown on PC platform will be commercially available soon.
UNIVERSAL REMEDIATION TIME MODEL	Calibration requirements	equilibrium approach factors, Flow, flow of sparge air per unit volume of contaminated soil.	Model prevents design of systems which could not possibly work and provides only a rough estimate of remediation time based on past experience. Given it limited objectives, its success rate is high (>80%).	I'd give it a 2 charitably. Academia genrally doesn't think too highly of stirred-tank representations of a non-stirred system, even when you throw in a fudge factor to make up the difference.	supporting documentation available if needed.
WELLPACK	None	Depth of air sparger, well diameter	unknown-- validated against full scale lab test	8, EG and G Environmental Inc.	WELLPACK is not an aquifer flow model, nut a design model for in-well air injection requirements;

APPENDIX C

**LISTING OF RELEVANT PARAMETERS FOR EVALUATING
APPLICABILITY AND OPTIMIZATION**

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LISTING OF RELEVANT PARAMETERS FOR EVALUATING APPLICABILITY AND OPTIMIZATION

APPLICABILITY PARAMETERS

General Properties

Parameters potentially relevant to the applicability of air sparging have been grouped into three general categories:

- Geologic Setting;
- Source Size; and
- Source Characteristics.

These are further defined below:

Geologic Setting

Fractured/Low Permeability

Layered

- increasingly permeable layers with depth
- decreasingly permeable layers with depth
- alternating permeability of layers

Homogeneous

Other (e.g., non-layered, heterogeneous, etc.)

Type of Impact

Large (e.g., NAPL)

Small (e.g., dissolved phase, possible residual phase within soil matrix)

Contaminant Type

Solvent (typically more dense than water)

Hydrocarbon (typically less dense than water)

Other contaminant types identified but excluded from further consideration in application of the Decision Tool specifically or of air sparging generally include sites with co-contaminants of radionuclides and heavy metals.

Detailed List of Properties

Geologic Setting (for Conceptual Geologic Model of the Site):

- Grain size distribution
- Geologic classification
- Porosity
- Hydraulic and pneumatic permeability (vadose and phreatic zones)
- Permeability variations (horizontal and vertical)
- Hydraulic conductivity
- Depth to groundwater
- Aquifer thickness
- Groundwater flow direction and rate
- Seasonal/culturally influenced groundwater level and flow variations
- Characteristics of layers (if applicable)
 - thickness,
 - lateral continuity,
 - intersection with cultural features.
 - physical properties described above (grain size, etc)

Contaminant Spatial Characteristics

- Presence and extent of NAPL
- density (DNAPL or LNAPL)
- extent of NAPL plume (lateral and vertical)
- Presence and extent of dissolved plume
- Presence and extent of residual NAPL "source area" including "smear zone"

Contaminant Physical Characteristics

- Henry's Constant
- Concentrations
- Density
- Vapor pressure
- Solubility
- Biodegradation potential
- Baseline DO in proposed treatment zone

Conceptual Design Considerations

- Minimum injection pressure
- Maximum flow rate for likely injection pressures
- Theoretical maximum air distribution radius
- Maximum physical and biological removal rate
- Sparging effectiveness factor

Finally, any detailed monitoring and other performance data obtained from system operations, routine monitoring, or pilot-scale tests at the site will be used to evaluate the potential effectiveness of air sparging activity and to initiate the detailed design (and ultimately optimization) process(es). Parameters of particular interest are described below.

Economic/Political Considerations

- Area to be treated: Source, Plume, or Edges (containment).
- Remediation targets
- Time constraints
- Financial/Other resource constraints
- Sensitive receptors
- Groundwater plume receptors
- Vapor plume receptors (if sparging utilized)
- Location and relative vulnerability (qualitative)
- Remediation alternatives, relative costs

Pilot Test System Parameters

- Injection well design
 - well diameter
 - screen length
 - depth of screened interval and relationship to target treatment area and water table
- Injection pressure
- Injection flow rate
- Extraction flow rate (if used in conjunction with SVE)
- Concentrations of tracer gasses

Monitoring Parameters

- Monitoring point design
 - casing and screen diameter
 - screen length
 - depth of screened interval and relationship to target treatment area and water table
 - point emplacement techniques
- Soil vapor pressures
- Soil vapor contaminant concentrations (VOCs and SVOCs)
- Other soil vapor concentrations (carbon dioxide, oxygen)
- Contaminant concentrations in groundwater
- Dissolved oxygen concentrations in groundwater

OPTIMIZATION PARAMETERS

General Properties

The optimization process, as provided by the Decision Tool, will consist of the optimization of either an existing system that has been in operation for some period of time or a "conceptual design" of a proposed system with information from a pilot-scale testing program (described above). As such, the parameters needed to evaluate the optimization include all of those given for applicability as well as the following:

- Statement of purpose for the system
- Target cleanup levels
- Air sparging system operating requirements

DETAILED OPTIMIZATION PARAMETERS

- Well construction information
 - well diameter
 - screen slot size
 - screen length
 - well orientation
 - depth of screen below water level surface)
- Equipment operating parameters
 - flow rate
 - injection pressure)
- System design features
 - number of injection wells
 - size of blower/compressor
 - accompanying soil vapor extraction
- Apparent "radius of influence" of sparging wells
- Relaxation effects following sparging shutdown
- Performance monitoring results
 - VOC data
 - mass recovered
 - water levels

APPENDIX D
AIR SPARGING MODEL QUESTIONNAIRE

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AIR SPARGING MODEL QUESTIONNAIRE

This questionnaire is provided to solicit input from various model developers to ensure that a complete and accurate representation of their model(s) is presented as part of a review package currently being developed by Parsons Engineering Science for the U.S. Department of Energy. As part of the supporting documentation for the review package, a complete listing of models (and how to obtain them) will be included. This package may result in the development of a Decision Tool which will attempt to integrate applicable information or underlying principles from the models as permissible and appropriate. Your prompt completion of this request will ensure that your model(s) will be included in that list.

Information to be provided by the Model Developer for reference by and inclusion in the DOE Air Sparging Review Package. If you only have time to answer a few questions please answer the following:

1. What is the name of the model?
2. What is the most current version (name or number) available for use?
3. What is the production date of the version reviewed?
4. Who were the developers and/or technical contributors to the model?
5. Is the model patented, copyrighted, or proprietary?
6. Who was the producer of the model? (What university, company, etc. produced the model?)
7. What is the intended primary application of the model? Who is the target audience/user group for which this model has been developed?
8. What is the basis of the model (e.g., scientific, experiential, experimental, mathematical, logical, etc.)?
9. Please provide a brief summary of the model's parameters and their interrelationships (including key equations, scientific principles, accepted rules of thumb, etc.).
10. What is the success factor of the model? (What is the probability (%) of the model correctly and successfully achieving its goal?) Who can I (or report to readers) call for further technical information - Name, location, phone, fax, e-mail address?

11. Can you send a copy of (any or all of the following):
 - a. The Model
 - b. Supporting Documentation
 - c. The User's Guide
12. Are you aware of other models that we may wish to consider that have been developed or are under development?

If you have more time, both the DOE and Parsons ES would appreciate for you to answer the following:

13. Is the model logical or mathematical?

If the model is mathematical, please answer the following questions as applicable or appropriate.

- (a) Is the basis of the model empirical, theoretical, or stochastic?
- (b) What is the numerical technique used in the model? (Is the solution technique finite difference, finite element, method of characteristics, semi-analytical, analytical, etc.?)
- (c) What is the dimensionality of the model (e.g., one, two, or three dimensions, or radially symmetric)?
- (d) What processes does the model include (e.g., advection, hydrodynamic dispersion, sorption, volatilization)?
- (e) What are the inputs (e.g., porosity, hydraulic conductivity, relative air permeability)? Can the inputs accommodate variability (permeability varying with time/distance, etc.)?
- (f) What are the outputs (e.g., predicted concentrations of oxygen, formatted line printer listings of concentrations, graphical, DXF)?
- (g) What are the initial conditions (e.g., concentrations in porous media, hydraulic head)?
- (h) What are the boundary conditions (e.g., Dirichlet, Neuman, Cauchy)?

- (i) What are the major assumptions or conceptualization features (e.g., air moves according to darcy, no phase separated hydrocarbons, wells are line sources, steady-state only, sources/sinks)?
- (j) What are the hardware/software requirements (e.g., 386, 486, math processor, pre-processor, post-processor, etc.)?
- (k) What are the limitations of the model (e.g., domain, number of nodes, time steps, run time)?
- (l) Are there error checks built into the model (e.g., input data checks, numerical dispersion checks)?
- (m) What was your code verification process or how did you check your results (e.g., sample problem compared to analytic solution)?
- (n) What is the expected relative time required to learn use of the model or experience required of the operator (e.g., hydrogeological expertise, duration of the learning curve)?
- (o) What are the disadvantages and/or recognized needs for the model (e.g., calculations close to air source are not as accurate, or are accurate within some percent)?
- (p) When performing a sensitivity analysis on the model, what parameters were most sensitive?
- (q) What is the relationship for relative air permeability?
- (r) Does the model account for mounding?

14. What are the capabilities of the model?

15. On a scale of 1 to 10, what is the acceptance rating that would be given by the scientific user community?
Do you have any references of who I may call to verify the utility.

16. Is there any other information that has not been specifically asked for that would clarify what the model does or is?

Parsons ES will compile the information provided in response to the questions listed above into a compendium of available models for U.S. DOE. Prior to finalization, a copy of your information will be sent to you for verification to ensure that the resulting tables and supporting text accurately describe your model(s), capabilities, accessibility, etc.

Please forward your response to Mr. David Schaad at Parsons Engineering Science, Inc., 19101 Villaview Road, Cleveland, Ohio 44119 or via facsimile to (216) 486-6119 at your earliest convenience. Parsons ES and U.S. DOE appreciate your assistance in this matter.