# Guidance for Design, Installation and Operation of Soil Venting Systems

PUB-RR-185 June 2002 (Reviewed August 2014)

**Purpose:**
This document is a guide to using soil venting as a remediation technology. Soil venting is atechnology that uses air to extract volatile contaminants from contaminated soils. The technology is also known as soil vapor extraction, in situ volatilization, in situ vapor extraction, in situ air stripping, enhanced volatilization, in situ soil ventilation, and vacuum extraction. The term bioventing has been applied to soil venting projects when biodegradation is a significant part of the remediation process and/or biodegradation is enhanced with nutrient addition.

Soil venting is a multi-disciplinary process. The designer should have a working knowledge of geology and basic engineering to design an optimal system. A basic knowledge of chemistry is also necessary to develop a quality sampling and monitoring plan.

This document is intended as general guidance. Because each site has unique characteristics, it may be necessary for system designers to deviate from the guidance. The DNR acknowledges that systems will deviate from this guidance when site-specific conditions warrant. When deviations occur, designers should document these differences in their work plan to facilitate DNR review. For additional information on the DNR's permitting and regulatory requirements, please refer to Subsection 1.3 in this document.

**Author/Contact:**
This document was originally prepared by George Mickelson who no longer works for DNR. It was reviewed for accuracy by Gary A. Edelstein (608-267-7563) in August 2014.

**Errata:**
This document includes errata and additional information prepared in August 1995. The rule cites and references to other DNR guidance in the document were also reviewed and found to be current, with the exception of publications SW-157, "Guidance for Conducting Environmental Response Actions" and SW-184, "Guidance for Treatment of Groundwater and Other Aqueous Waste Streams", which are no longer current guidance documents.





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Additional information, changes, clarification and errata to the *Guidance for Design, Installation and Operation of Soil Venting Systems* includes the following:

- DNR Rules. This guidance document was completed prior to the effective date of the NR 700 series of rules. There are many additional requirements within NR 724 for submittal contents that are not included in this document. Also, NR 406, 407 and 419 have changed since this document was prepared, refer to the latest DNR guidance on the air rules for more info on this. There may be requirements in other chapters that also affect an individual project.

- In Situ Respiration Tests. In situ respiration tests are only warranted when the site has an oxygen deficiency. If the in situ soil has at least 4 to 5 percent oxygen, oxygen should not be limiting biological activity. When in situ respiration tests are performed at a site that has had an active soil venting system, those tests should be conducted in gas probes, not air extraction wells that have been used to extract air. The soil adjacent to air extraction wells has had much more aggressive treatment than soil that is more distant from the wells, therefore testing on extraction wells is not representative of the site. For more information on in situ respiration tests, see Hinchee and Ong (1992).

- Subsection 1.3.2. Air Emissions. The air rules have changed since publication. Pertinent chapters that have changed include NR 406.04, 407.03 and 419.07. The emission limits for unpermitted soil venting systems have not changed, however many administrative and documentation procedures have changed. The April 5, 1991 guidance memo that was attached as Attachment One is no longer valid, a new memo dated <not finalized as of August 11, 1995 - should be by September 1995> should be used instead.

- Subsection 3.2.2. Pilot Testing and Barometric Pressure. Barometric pressure readings should always be taken during pilot tests at sites where the water table is deeper than approximately 20 feet. A relatively deep soil column can cause a significant lag time for the subsurface soil gas pressure to fully equilibrate with atmospheric pressure. This has resulted in a significant number of pilot tests with zone of influence measurements that fluctuate greatly and do not stabilize on windy days when barometric pressure is changing rapidly. While a direct correlation or correction factor is not practical, using barometric pressure readings over time may help assess which time(s) during the test the barometric pressure was fluctuating the least.

- Subsection 4.1. Model Selection. It is not appropriate to use a 2 dimensional formula from the literature to determine a radius of influence. For the same reason, it is not appropriate to use the computer program Hyperventilate to determine well spacing for full scale design. It is inappropriate because these methods only consider vacuum distribution, they do not take into account contaminant concentrations, volatility, geologic conditions, etc. When these methods are used, proposed well spacing generally is inadequate to cleanup a site. From Johnson and Ettinger (1994): *An interesting feature of the $R_I$-based design practice is that one never tries to quantify expected remedial* *system goals, such as the time to achieve some desired level of contaminant reduction.* Pages 22 through 24 in the guidance discuss the considerations that should be used for well spacing.

- Subsection 4.3.2. Horizontal Air Extraction Trench Design. When designing a horizontal air extraction system in a trench, it may be appropriate to install the air extraction perforated pipe or screen in the middle or upper portion of the gravel instead of the base of the trench. Since the gravel typically is orders of magnitude more permeable than the surrounding native soils, it is likely that the vacuum distribution throughout all of the gravel will be fairly uniform regardless of the perforated pipe or screen location. Therefore, the elevation of the screen or perforated pipe within the trench is somewhat unimportant for air flow distribution. Since an increase in water table elevation due to significant rain fall or vacuum lift may submerge a screen or perforated pipe placed deep within the trench, there is an increased risk of failure when the screen or perforated pipe is placed at or near the base of a trench. A number of systems were flooded and ineffective as a result of the unusually high rainfall and flooding in the summer of 1993, many of these systems would have remained operational if the piping was installed higher.

- Subsections 4.3.3 and 5.4. Gas Probes for System Monitoring. It may also be appropriate to place a gas probe(s) in an area of high soil contamination at a distance away from the nearest air extraction well. Since this is the part of the site that requires the most aggressive cleanup, tracking subsurface soil gas levels over time is an additional tool that can be used to assess when it is time to drill confirmation borings. A water table well with a portion of the screen exposed above the water table can be used instead of a gas probe.

- Subsection 4.4. Manifold Slope. When possible, the manifold should be designed in such a way that the air and condensate water flow the same direction. The guidance discusses sloping the piping towards the air extraction wells to allow the water to drain back into the wells. In this situation, air and water flow in opposite directions. This practice however may result in a significant amount of water that is held at the uphill end of the pipe by the air stream until the blower is shut off. If the manifold must slope towards the wells, there may need to be a timer on the system to allow the blower to shut off for a few minutes periodically to allow any water to drain back. This has only been a problem on systems that use relatively low air velocity within the manifold.

- Subsections 4.9.3 and 4.9.4. Combining Vapor Extraction with Groundwater Extraction. The following general guidelines are appropriate to determine if and when the water table should be lowered through pumping:

  - When there is a mobile/recoverable LNAPL, the water table should not be lowered because that would result in additional smearing of the aquifer.

  - When there is no mobile/recoverable LNAPL, contaminants that are volatile but relatively insoluble (petroleum, some LNAPL solvents, etc.) are best removed in the vapor phase. Wells can be nearly dewatered to increase air flow through the former location of the capillary fringe. Improved contaminant extraction results when the capillary fringe is dewatered and the air stream passes through this zone.

– When there is no mobile/recoverable LNAPL, contaminants that are less volatile, but highly soluble (ethylene glycol, etc.) may be best removed in an aqueous phase. In this case lowering the water table may be counter productive. This category of sites probably represents less than a few percent of the total number of sites.

- Subsection 5.4. Well Abandonment. All wells, including air extraction and injection wells need to be abandoned after the project is complete. This information is included on Page 2 under Wis. Admin. Code NR 141, but was inadvertently left out of Subsection 5.4.

- Section 6.0 References. Additional references that should be added include the following:

Beckett, G.D. and Huntley, D. 1994. Characterization of Flow Parameters Controlling Soil Vapor Extraction. *Groundwater.* Volume 32, Number 2. Pages 239 to 247.

Benson, D.A., Huntley, D. and Johnson, P.C. 1993. Modeling Vapor Extraction and General Transport in the Presence of NAPL Mixtures and Nonideal Conditions. *Groundwater.* Volume 31, Number 3. Pages 437 to 445.

Dupont, R.R. 1991. Assessment of In Situ Bioremediation Potential and the Application of Bioventing at a Fuel-Contaminated Site. *In Situ Bioreclamation. Proceedings of the First International Symposium on In Situ and On-Site Bioreclamation.* Edited by Hinchee, R.E. and Olfenbuttel, R.F. Pages 262 to 282. Butterworth-Heinmann, Boston, MA and elsewhere.

Falta, R.W., Pruess, K, and Chesnut, D.A. 1993. Modeling Advective Contaminant Transport During Soil Vapor Extraction. *Groundwater.* Volume 31, Number 6. Pages 1011 to 1020.

Goltz, M.N. and Oxley, M.E. 1994. An Analytic Solution to Equations Describing Rate-Limited Soil Vapor Extraction of Contaminants in the Vadose Zone. *Water Resources Research.* Volume 30, Number 10. Pages 2691 to 2698.

Hinchee, R.E. and Ong, S.K. 1992. A Rapid In Situ Respiration Test for Measuring Aerobic Biodegradation Rates of Hydrocarbons in Soil. *Journal of the Air and Waste Management Association.* Volume 42, Number 10. Pages 1305 to 1312.

Johnson, P.C. and Ettinger, R.A. 1994. Considerations for the Design of In Situ Vapor Extraction Systems: Radius of Influence vs. Zone of Remediation. *Groundwater Monitoring and Remediation.* Summer 1994. Pages 123 to 128.

Marrin, D.L. 1991. Subsurface Biogenic Gas Ratios Associated with Hydrocarbon Contamination. *In Situ Bioreclamation. Proceedings of the First International Symposium on In Situ and On-Site Bioreclamation.* Edited by Hinchee, R.E. and Olfenbuttel, R.F. Pages 546 to 560. Butterworth-Heinmann, Boston, MA and elsewhere.

Miller, R.N., Vogel, C.C., and Hinchee, R.E. 1991. A Field-Scale Investigation of Petroleum Hydrocarbon Biodegradation in the Vadose Zone Enhanced by Soil Venting at Tyndall AFB, Florida. *In Situ Bioreclamation. Proceedings of the First International Symposium on In Situ and On-Site Bioreclamation.* Edited by Hinchee, R.E. and Olfenbuttel, R.F. Pages 546 to 560. Butterworth-Heinmann, Boston, MA and elsewhere.

Peargin, T.R. and Mohr, D.H. 1994. Field Criteria for SVE Pilot Tests to Evaluate Data Quality and Estimate Remediation Feasibility. *Proceedings of Petroleum Hydrocarbons and Organic Chemicals in Ground Water: Prevention, Detection, and Restoration*. November, 1994. NGWA. Pages ? to ?.

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Figures.



Attachments.



Acknowledgments. In addition to many DNR employees, the following individuals also reviewed and commented on this document:

Kelton Barr, C.P.G. - Geraghty & Miller, Inc.
Chi-Yuan Fan, P.E. - USEPA Risk Reduction Engineering Laboratory.
David Kill, P.E. - Recovery Equipment Supply Inc.
Michael C. Marley - Vapex Environmental Technologies, Inc.
Tom R. Peargin, R.G. - Chevron Research and Technology Company.

This document may not represent the views of all reviewers. The DNR thanks the reviewers for donating their time and input.

Acronyms.

| | |
|---|---|
| CPVC | Chlorinated polyvinyl chloride. Material commonly used for pipe. |
| DNR | Wisconsin Department of Natural Resources. |
| EPA | U.S. Environmental Protection Agency. |
| ERP | Environmental Repair Program of the DNR. |
| ERR | Emergency and Remedial Response Section of the DNR Bureau of Solid and Hazardous Waste Management. |
| FID | Flame Ionization Detector. |
| gpm | Gallons per minute. |
| LUST | Leaking Underground Storage Tank Program of the DNR. |
| PID | Photoionization Detector. |
| PVC | Polyvinyl chloride. Material commonly used for pipe, well casing, and well screens. |
| scfm | Standard cubic feet per minute. |
| TPH | Total petroleum hydrocarbons. As used in this document TPH refers to tests for gasoline range organics and diesel range organics. |
| VOC | Volatile organic compound. |

## 1.0 Introduction.

This guidance document is intended to aid environmental professionals in designing soil venting systems for soil contaminated with volatile organic compounds (VOCs). It provides information to Department of Natural Resources (DNR) staff for efficient and consistent oversight and review.

This document should be read with the existing DNR *Guidance for Conducting Environmental Response Actions*, specifically Chapter 7 (Site Investigation) and when available, Chapter 8 (Remedy Selection).

### 1.1 Purpose.

This document is a guide to using soil venting as a remediation technology. Soil venting is a technology that uses air to extract volatile contaminants from contaminated soils. The technology is also known as soil vapor extraction, in situ volatilization, in situ vapor extraction, in situ air stripping, enhanced volatilization, in situ soil ventilation, and vacuum extraction. The term bioventing has been applied to soil venting projects when biodegradation is a significant part of the remediation process and/or biodegradation is enhanced with nutrient addition.

Soil venting is a multi-disciplinary process. The designer should have a working knowledge of geology and basic engineering to design an optimal system. A basic knowledge of chemistry is also necessary to develop a quality sampling and monitoring plan.

This document is intended as general guidance. Because each site has unique characteristics, it may be necessary for system designers to deviate from the guidance. The DNR acknowledges that systems will deviate from this guidance when site-specific conditions warrant. When deviations occur, designers should document these differences in their work plan to facilitate DNR review. For additional information on the DNR's permitting and regulatory requirements, please refer to Subsection 1.3 in this document.

This document discusses the basics of soil venting system design. Refer to the publications listed in Section 6 for more detailed discussions of soil venting systems. A more complete list of articles is included in the reference and the bibliography sections of the U.S. Environmental Protection Agency (EPA) Soil Vapor Extraction Technology, Reference Handbook (1991(a)).

### 1.2 Scope of Soil Venting and Bioventing.

Soil venting generally works well with gasoline and some common solvents such as trichloroethene and tetrachloroethene. Remediating heavier hydrocarbons (jet fuel, kerosene, and diesel oil) with a soil venting system may be possible, but the rate of remediation is very slow compared to more volatile compounds. Enhanced biodegradation takes place through oxygen delivery during soil venting (Hinchee and Miller, 1990, Miller, 1990). Unusual site conditions, such as an inability to excavate, are necessary to make soil venting technology the best alternative for the heavier hydrocarbons. Soil venting is not appropriate for contaminants that do not volatilize or aerobically biodegrade.

Soil venting may be used with other cleanup technologies, such as steam stripping, groundwater extraction, product recovery, air sparging (saturated zone) and heated air injection (unsaturated zone).

Soil venting is an effective technology to prevent vapor accumulation in buildings, and soil is also remediated in the process (Knieper, 1988). Using soil venting to remove vapors from a building can be considered an emergency or interim remedial measure. In such cases, a pilot test is not necessary if the operator has received Bureau of Air Management approval.

## 1.3 Permitting, DNR Regulations and Related Guidance.

Refer to Table 1-1 for more information on permitting and related guidance documents.

### 1.3.1 LUST, ERP, and Superfund Program Requirements.

Submittal Contents. Recommended Leaking Underground Storage Tank (LUST), Environmental Repair Program (ERP) and Superfund program submittal contents are listed in Subsections 3.2.4, 4.10, 5.2, and 5.3.

Wis. Admin. Code NR 141. Air-extraction well designs and gas probes do not need DNR's preapproval under Chapter NR 141. Designers must submit boring logs and well construction diagrams in accordance with NR 141.23 after well installation. Designers must also abandon wells and gas probes in accordance with NR 141.25 after project completion.

Investigative Wastes. Designers should handle drill cuttings in accordance with DNR guidance on investigative wastes.

### 1.3.2 Bureau of Air Management.

Wis. Admin. Code 406, 445, and 419. Soil venting systems must comply with any state emissions standards. Chapter NR 445, Wisconsin Administrative Code, sets hazardous air emission standards for atmospheric pollution sources. Chapter 406 sets requirements for air permits and Chapter NR 419 includes additional requirements. Air emission limits, reporting, methods of monitoring, and a summary of air regulations for petroleum sites are discussed in Attachment 1. See Chapter NR 445 for a complete listing of compound-specific limits for other sites. The total volatile organic compound (VOC) limit in NR 419.07 (4) (b) takes precedence over the hourly limits for individual compounds in Chapter NR 445. Designers may need a permit from the Bureau of Air Management prior to using control or air treatment devices. A pilot test may be necessary to comply with Bureau of Air Management requirements.

Note: If an air permit is necessary, the application for the permit should be submitted early to reduce or prevent project delays. An air permit takes a minimum of two to three months after a COMPLETE application is submitted.

Form 4400-120. Designers must complete Form 4400-120 and receive DNR approval prior to operating a soil venting system at a LUST site. Data from a pilot test may be necessary to complete the form.

### 1.3.3 Bureau of Wastewater.

Water Disposal. Groundwater pumped from air-extraction wells and the accumulated water in a water trap must be disposed of in accordance with state and/or local permits. Local municipalities regulate discharges to

Table 1-1

Guidance Documents Related to Soil Venting

| Topic | Pertinent Rules | Guidance Documents[1] | Agency Contact | Reference Sections |
|---|---|---|---|---|
| Air Emissions | NR 406, NR 419, NR 445 | April 5, 1991 Memo for LUST Sites[2] None for Other Sites | DNR District Air Management Staff | Subsections 1.3.2, 3.2.3, 4.2, 4.7 and 5.3 |
| Drilling, Well Construction, and Abandonment | NR 141 | None Specific to Soil Venting Systems | DNR District ERR Staff | Subsections 1.3.1, 4.3 and 5.4 |
| Vapor Well Labeling and Color Coding | ILHR 10 | None | DILHR | Subsection 1.3.4 |
| Condensate Disposal | Various DNR Rules | Guidance for Treatment of Groundwater and Other Aqueous Waste Streams | DNR District Wastewater Staff or Local POTW | Subsections 1.3.3, 4.5 and 4.10 |
| Investigative Wastes | Various DNR Rules | January 14, 1993 Memo[3] | DNR District ERR Section | Subsections 1.3.1 and 4.3 |
| Electrical Safety | Various DILHR Rules | DILHR UST/AST Program Letter 10, May 25, 1993[4] | DILHR Staff and/or Local Building Inspectors | Subsections 3.2.2, 4.4 and 4.6 |

Notes:

(1) Guidance Documents refers to guidance documents other than this document.

(2) Included as Attachment One.

(3) Guidance titled *General Interim Guidelines for the Management of Investigative Waste.*

(4) Guidance titled *Design Criteria for Process Equipment Buildings Associated with Environmental Remediation of UST/AST Sites*, included as Attachment Two to the *Guidance on Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems.*

sanitary sewers. A Wisconsin Pollutant Discharge Elimination System (WPDES) permit is necessary for storm sewer or surface water discharge. See *Guidance for Treatment Systems for Groundwater and Other Aqueous Waste Streams* for a further discussion of permit requirements.

1.3.4 Department of Industry, Labor and Human Relations.

ILHR 10. ILHR 10.41 covers color coding for flush mount well covers for groundwater monitoring wells and vapor wells.

Electrical Safety. See DILHR's *Design Criteria for Process Equipment Buildings Associated with Environmental Remediation of UST/AST Sites*, which is included as Attachment 2 to *Guidance on Design, Installation and Operation of Groundwater Extraction and Product Recovery Systems*.

## 2.0 Technical Considerations and Site Characterization.

### 2.1 Theory.

This is a brief discussion of the theory and dynamics of soil venting. Anyone using the technology is encouraged to review published literature on soil venting. See Section 6 for a list of selected references.

Soil venting removes VOCs from soils by creating an airstream through the soil that enhances the volatilization of the VOCs and acts as a carrier to extract the VOCs. Soil venting also enhances aerobic biodegradation of contaminants.

The rate of VOC extraction/destruction is controlled by a number of factors, as follows:

- Air-Flow Rate. The rate of air flow controls the advective transport of the VOCs from the subsurface. Soil permeability is a major subsurface physical limitation associated with air-flow rate. Other important factors include the number of air-extraction wells, extraction well placement, size and type of blower, the amount of vacuum applied, and the depth of the water table. Subsection 4.2 discusses air-flow rates to a well. Shan et al. (1992) and Baehr et al. (1989) discuss mathematics of air flow to an air-extraction well. Johnson et al. (1990) also discusses a method to estimate the air-flow rate based on permeability that is useable for initial design estimates.

  Air-flow rates are less critical to the biodegradation process. A soil venting system achieves the most volatilization at high rates of air flow; a bioventing system may operate at a much slower air-flow rate, possibly as much as an order of magnitude less (see biodegradability below).

- Geologic Conditions. The remediation rate in highly permeable soils is primarily controlled by the rate of advection.

  If the unsaturated zone is heterogeneous (i.e. fine-grained soils mixed with coarse-grained soils), the extraction is dependent on the diffusion rate of the contaminants from the fine grained soil matrix into the coarse-grained soil matrix.

  The extraction rate at sites with fractured clay till or fractured consolidated deposits is also dependent on the diffusion rate because the VOCs diffuse out of the soil or rock matrix into the fractures, where advective flow extracts the VOCs.

- Soil Moisture. The air-flow rate through soil may decrease if soil moisture occupies void spaces, making them unavailable to advective air flow. High moisture in the capillary fringe zone reduces the effective porosity to air flow near the water table, and may retard the extraction of the contaminants from the capillary fringe. The highest levels of soil contamination at a site are often near or within the capillary fringe. This occurs because the contaminants often collect at the top of the water table. For these reasons, the zone that is most difficult to remediate (because of air flow patterns) is also the zone that often has the highest contamination. Pumping groundwater to drop the water table may expose more contaminants to the air flow that were formerly submerged. See Subsection 4.9.4 and *Guidance for Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems* for a further discussion of groundwater extraction.

Soil moisture is necessary for maximizing biodegradation. A moderate level of soil moisture is necessary to maintain viable, aerobic bioactivity. Some practitioners propose that soil moisture should be in the range of 40 to 60 percent of field capacity, others propose that moisture should be between 50 to 75 percent of field capacity. If soil moisture drops significantly below this range, the activity and even the microbial population density can drop significantly.

- Upwelling. The vacuum that is applied in the subsurface lifts the water table. The effects of upwelling are greatest near the extraction wells, where the vacuum levels are the highest. If contaminants are submerged (below the water table) by upwelling, the effectiveness of soil venting is reduced.

- Stagnation Zones. Subsurface structures and/or multiple air-extraction wells can result in stagnation zones. These zones are areas that have no or minimal air flow through the soil. The effectiveness of a soil venting system is minimal in these zones. Stagnation zones most often occur at locations in between two or more air-extraction wells that operate at a relatively constant rate, but it can also occur if subsurface structures block the air flow. The reduced air-flow rate through these zones reduces the contaminant extraction rate from these zones. These zones may also be zones of anaerobic conditions (see biodegradability below).

- Vapor Pressure. Vapor pressure is a critical factor in assessing the ability of a soil venting system to volatilize the contaminant in the soil. Generally, the higher the vapor pressure, the more likely a soil venting system will extract the contaminant from the soil. The vapor pressure of the contaminants are highly temperature dependent; higher temperatures increase the vapor pressure and the rate of volatilization. A vapor pressure of 1.0 mm Hg at subsurface conditions is the cutoff for soil venting (Appendix B in the USEPA Reference, 1991(a)).

- Henry's Law Constant and Solubility. The rate that the contaminants are released from the natural soil moisture (pore water) are dependent on the Henry's Law Constant for each compound within the contaminant matrix. The Henry's Law Constant is the ratio of the concentration of a compound in air to the concentration of the compound in water at equilibrium. The Henry's Law Constant for a compound is a measure of the rate that the compound will be released from the moist soil into the soil air. A low Henry's Law Constant indicates that the compound at equilibrium in an air and water mixture is largely held within the water phase. It is, therefore, not readily volatilized into the extracting air stream, resulting in a very slow rate of extraction.

Solubility in water is another factor in the extraction rate for a specific compound. A significant amount of a highly soluble compound (acetone, alcohols, etc.) dissolves in the soil moisture, retarding the rate of volatilization. If the soil venting system has a large enough air-flow rate to dry out the soils, then solubility is a less critical factor.

- Raoult's Law. A mixture of gasoline and heavier hydrocarbon compounds (such as diesel or lubrication oil) can be slow to remediate, because the volatile compounds may be trapped in the heavier, relatively nonvolatile compound matrix. In this case, the effectiveness of a soil venting system depends upon the rate of molecular diffusion of the volatile compounds out of the nonvolatile hydrocarbon matrix. Even a highly volatile substance like gasoline weathers and becomes much less volatile as the highly volatile compounds are removed from the mixture.

  The extraction rate of the less volatile compounds is often the controlling factor in closing out sites with soil venting systems. Some sites are not suitable for soil venting systems because it may not be technically feasible for a system to meet cleanup criteria for some compounds. See Subsection 2.2.1 and the above discussion of vapor pressure and Henry's Law Constant. The vapor pressure and the Henry's Law Constant should be assessed for unusual or unique mixtures of contaminants where soil venting has a limited history. Bench scale tests may also be useful in unusual conditions (EPA, 1991 (b)).

- Adsorption. Adsorption of contaminants on the soil slows the rate of extraction. Soils that have a high surface area (fine-grained soils) or high total organic carbon content have a much greater ability to adsorb contaminants than soils with a small surface area (coarse-grained soils). Therefore, coarse-grained soils release contaminants at a faster rate than fine-grained soils or soils with a high total-organic compound.

- Biodegradation. Petroleum hydrocarbons biodegrade at a higher rate under aerobic conditions than anaerobic conditions. The rate of biodegradation is generally controlled by four factors: oxygen, food (the petroleum product) for the microbes, moisture, and nutrients. The limiting factor under non-venting conditions is usually oxygen. A very slow air-flow rate is usually sufficient to provide enough oxygen to the bacteria. Aerobic biodegradation is not significantly inhibited until oxygen levels drop below 5 percent. When a soil venting system is active, the limiting factors generally will either be a lack of moisture or lack of nutrients.

  It is possible that portions of the soil within a soil venting regime are not frequently replenished by oxygen. If this occurs, these zones will be largely stagnant and only anaerobically active with accumulating fermentation products, such as methane. It is possible that anaerobic conditions could exist in a system, even if there are high oxygen levels in the extracted air. This occurs because some of the extracted air could have passed through "clean" soil.

Generally the halogenated compounds biodegrade at a much slower rate than petroleum fuels under aerobic conditions.

For specific details on biodegradation, as part of a soil venting system, please refer to Subsections 4.9.5 and 5.1.

## 2.2 Site Characterization.

The following is a summary of technology-specific aspects of a site characterization and should be used with Chapter 7 in the *Guidance for Conducting Environmental Response Actions*.

Soil venting as a remediation technology depends on the flow of a fluid (in this case air) through the unsaturated soil. For this reason, environmental professionals need to characterize the geological conditions of the site in sufficient detail so that they can design a soil venting system that is appropriate for the site conditions. An inadequate site characterization may result in a venting system that has large stagnation zones, excessive groundwater extraction during times of high water table, significant short circuiting, or a system that will not work at all.

The following subsections identify the significant site characteristics that should be defined or estimated when considering a soil venting technology.

### 2.2.1 Contaminant Characterization.

Characterize the site for contaminant types in order to prepare a monitoring plan that will comply with criteria set by the Bureau of Air Management. Characterizing the contaminants is also necessary to evaluate the feasibility of successfully remediating the site with a soil venting system. Contaminant volatility should be identified and characterized so designers can estimate the total mass of contaminants to evaluate the size, cost, and life of the project and to determine if there is a need for air emission controls. Air standards are established by the Bureau of Air Management and are found in Subsection 1.3.2 and in Table 1-1.

During the investigation, assess the components of the product lost and its degradation products.

> Example: Halogenated solvents will often degrade to compounds that are more toxic than the original product that was released. Tetrachloroethane will transform to trichloroethane, then to dichloroethane, and finally to vinyl chloride, which is a known carcinogen (Fetter, 1988).

For emission estimates at sites with petroleum contamination, the two parameters that need to be assessed in soil are total benzene and total VOCs (see Attachment 1). If a laboratory test is used to quantify the total VOCs for petroleum products, use an analytical test for TPH that also quantifies compounds that are not identified in a normal VOC scan (propane, butane, pentane, etc.). Do not use a sum of benzene, toluene, ethylbenzene and xylene. The Bureau of Air Management may require an air permit and needs to know what the potential contaminants at the site are and estimated quantities for each.

An assessment of the vapor pressure and Henry's Law Constant for gasoline contamination is not necessary because of the large number of venting systems demonstrating that gasoline is readily removed from the subsurface. Gasoline is a mixture of more than 100 compounds.

Some compounds with less than six carbon atoms in the molecule (C6) have very high vapor pressures and readily volatilize; some heavier hydrocarbons with greater than nine carbon atoms per molecule (C9) volatilize very slowly. Most of the highly volatile compounds are quickly extracted by a soil venting system. Rainwater, et al. (1988) demonstrated in column studies that when greater than 50 percent of the pentane is removed, only 10 percent of the xylene is removed. DiGiulio et al. (1990) estimated that 40 percent of gasoline contamination may still remain when off gas concentrations have fallen to 1 percent of the initial concentration. The lower volatility compounds in gasoline (>C9) that are less readily extracted may prevent a soil venting system from meeting site-specific cleanup standards that are based on TPH.

Soil samples collected from soil borings should be field screened for VOC measurements. Field screening could consist of headspace analysis by PID or FID; headspace analysis by field GC; or headspace analysis by the Lab in a Bag Method (Robbins et al. 1989).

2.2.2 Geological Factors.

This Subsection discusses soil description, horizontal permeability, stratification, vertical permeability, hydrogeology, and other site-specific considerations.

To design an effective soil venting system, it is necessary to sufficiently characterize the site geology to evaluate any preferred zones of air flow. An experienced scientist or engineer should classify the borings in detail.

To describe the soil column, the soil description should include the following:

- Approximate percentages of major and minor grain-size constituents. Note: Terms such as "and," "some," "little," "trace," etc. are acceptable if defined in percentages they represent;
- Color and Munsell color;
- Geologic origin;
- Description of moisture content (dry, moist, wet);
- Any visual presence of secondary permeability;
- Voids or layering;
- Pertinent field observations such as odor;
- Description and notation of any product smearing evidence. Since depth of smearing is evidence of past aquifer water-level variations, note the depths carefully.

- Any other pertinent observations.

2.2.2.1 Horizontal Permeability.

The horizontal permeability of the unsaturated zone is a key factor in designing a soil venting system, and to some degree, in estimating the life of the project. The rate of contaminant extraction by volatilization and advection is proportional to the rate of air flow. At a given operating vacuum, a soil venting system installed in a highly permeable soil will allow a high air-flow rate through the soil, whereas installation in a low-permeable soil will result in a lower achievable air-flow rate.

There are two common ways to estimate what air flow is achievable from a soil venting system: a pilot test, or a permeability estimate of the soil. See Section 3.0 for pilot test information.

2.2.2.2 Stratification and Vertical Permeability.

It is important to evaluate the presence of stratified soils at a site during the site characterization. Stratified soils are soils that have been deposited in layers that are typically horizontal. Stratification can channel the air flow through the relatively coarse-grained horizontal soil layers and restrict vertical flow through the relatively fine-grained horizontal layers. The horizontal component of flow is increased relative to the vertical component, thus the horizontal zone of influence of an air-extraction well is increased. Stratification at a site can easily be identified by an inspection of soil boring logs from the site. Stratification exhibits characteristics similar to a high Kh/Kv ratio on a macro scale.

The Kh/Kv ratio is generally controlled by the natural depositional environment of the soils. Horizontal channeling of the air flow patterns is caused by a high ratio of horizontal permeability (Kh) to vertical permeability (Kv). Eolian silt deposits (loess) may have a Kh/Kv ratio of 100 or more. Glaciofluvial (or outwash) deposits commonly have a Kh/Kv ratio of 3 to 10. Manmade fill typically has a Kh/Kv ratio near 1. On a macro scale, glacial till may have a Kh/Kv ratio that is less than one due to vertical fracturing of the till.

There are two ways to estimate the Kh/Kv ratio: using pilot test data; and identifying the depositional environment and making assumptions for typical characteristics for different depositional environments. The method proposed by Shan et al. (1992) can be used to estimate the Kh/Kv ratio from field pilot tests (Subsection 3.2). The reference also includes figures that portray streamline flow patterns for different Kh/Kv ratios.

System designers can evaluate the effects caused by stratification or the Kh/Kv ratio to adjust well placement to site-specific conditions as discussed in Subsection 4.1.

The volatilization of VOCs from sites with stratified soils is often inhibited by poor air-flow rates through the finer-grained soil layers. The diffusion rate of the VOCs from fine-grained layers into the coarser-grained layers controls the extraction rate, as the coarse grained layers act like short circuiting pathways for the advective air flow, and the air flow passes through the fine grained soils very slowly.

2.2.3 Hydrogeologic Factors.

Certain hydrogeologic factors will affect the design of a soil venting system. The location of the screened portion of the air-extraction wells is determined by the soil geology, surface conditions, and the depth and seasonal fluctuation of the water table. The seasonable-high and the seasonal-low water table should be estimated during the remedial investigation. Since investigations often span periods of only two-to-five months, it is generally necessary to estimate seasonal variations.

## 2.3 Other Site-Specific Factors.

There are many other site-specific factors that affect the design and performance of soil venting systems. A brief discussion of some factors include the following:

- Surface Seal. A surface seal, such as a pavement layer, is often recommended in the literature. A surface seal channels air flow horizontally and restricts vertical air flow from the ground surface near the extraction well(s). Surface seals are difficult to construct properly, see Subsection 4.9.1.

- Artificial Conduits. Backfilled trenches in soils can act as short circuiting paths for the air flow. Trenched sites with relatively impermeable native soils are most affected because the backfill in the trench may be much more permeable than the natural soil. Designers should indicate utility trenches (sewers, water mains, electricity lines, etc.) on maps with soil venting system design plans.

- Air-Flow Obstructions. Building basements are typical air-flow obstructions which may change the subsurface air flow patterns. In these cases, designers should note buildings with basements in the reports, especially if the floor of a basement is near or below the capillary fringe. Underground storage tanks are also obstructions to air flow and designers should also indicate their locations on maps with the soil venting system design.

## 3.0 Treatability or Pilot Testing.

### 3.1 Laboratory Treatability Tests.

Laboratory treatability tests are useful for sites with mixed wastes that have unusual characteristics. Generally, because of past successes with common solvents and highly volatile petroleum products on a national basis, these compounds do not warrant laboratory treatability studies for volatility. See EPA Interim Guidance 1991(b) for guidance on treatability testing.

At sites with aerobic-degradable contaminants and substances that are toxic to microbes, such as leaded gasoline contamination or foundry sand, biodegradation treatability testing may be needed. Other site-specific factors may also warrant biodegradation testing.

### 3.2 Pilot Tests.

A pilot test is preferred over a laboratory grain-size test to estimate the possible air-flow rate from a proposed soil venting system. A pilot test is the only method that directly measures all pertinent site characteristics and geologic heterogeneities as an inherent part of the test procedure.

A pilot test is a short-term test that typically is smaller in scale than a full-scale remediation system. Generally, a pilot test at a LUST site or small ERP site is conducted for no longer than one day. Some practitioners and the EPA may recommend long-term testing for certain situations, such as CERCLA treatability studies (EPA, 1991(b)). NR 419.07 (3) exempts pilot tests of negative pressure venting systems from emission limits if the rate of air extraction does not exceed 100 scfm, and the test does not exceed eight hours at a site. The pilot test is not exempt from notification and emission limits if it is conducted longer than eight hours or exceeds 100 scfm.

#### 3.2.1 Purpose of a Pilot Test.

The purpose of a soil venting system pilot study is to determine design parameters prior to and for construction of a full-scale soil venting system. For these purposes, a short-term pilot test with a small blower is usually sufficient.

Key parameters include the following:

- The air-flow rate that is achievable from a soil venting system extraction well configuration under a given vacuum rate.
- The measurable vacuum at a distance from the air-extraction well (zone of vacuum influence).
- A quantitative estimate of the VOC emissions that initially occurs with a soil venting system.

#### 3.2.2 Conducting a Pilot Test.

A pilot test should be conducted under conditions that are typical at the site. For example, misleading pilot test results could occur if a pilot test is conducted during or shortly after a rain storm. The temporary wetting front in the soil column created by infiltrated or pooled water may create a temporary surface seal to air flow. In this example, a temporary seal would suggest that the zone of influence is much greater than it really is. Misleading results could also occur if there is a significant ambient barometric pressure change during the test; specifically, if vacuum readings in distant gas probes are taken for designing well placement.

The following equipment is needed to conduct a pilot test:

- Air-Extraction Wells. Designers should install one to three air-extraction wells at the site for the pilot test. Construct these wells according to the criteria for permanent full-scale soil venting system use. See Subsection 4.3 for construction details.

  A water-table well may be used if there are no air-extraction wells constructed at the site for testing. However, the existing water-table wells should have a filter pack and screen-slot size that is appropriate for soil venting. If the slot size and filter pack are too fine, the vacuum measured in the extraction well will be too high and will not reflect a realistic vacuum for a given air-extraction rate.

  It is important to choose a well with known construction details if a water-table well is used, because water-table wells typically have less than 5 feet of screen exposed to the unsaturated zone. It is also important to operate the pilot test in a manner that does not significantly lift the water table during the test. Lifting the water table by the vacuum more than half way up 5 feet of unsaturated screen greatly limits the use of the data for estimating achievable air flow per foot of well screen. It is highly recommended that the consultant use a small-diameter pump to lower the groundwater to assure accurate pilot test data. See Subsection 4.9.3 for a discussion of matching drawdown to the applied vacuum.

- Portable Blower (or Vacuum Extractor). A small blower should be used to pull air from the air-extraction well(s) during the pilot test. The blower can be almost any size. Since pilot tests are exempt from the air emission limits — provided the test is conducted at less than 100 scfm — a large blower may not be useful in high-permeable soils. Blowers should be equipped with a discharge stack. A muffler (or silencer) on the exhaust and a dilution (or bleed) valve on the blower inlet are also recommended. Designers should use blowers with an explosion-proof motor and switch. In most cases, regenerative blowers are used for pilot tests, however, a high vacuum blower may be necessary at sites with low-permeable soils.

- Extraction Well Sample Port and Instrumentation. The basic instrumentation needed on a pilot test is an air-flow meter, vacuum gauge, and thermometer. See Subsection 4.4 for a further discussion of instrumentation. A sample port is also needed to collect air samples. It may be most convenient to install all instrumentation and the sample port on a single temporarily-installed pipe between the blower and the extraction well. A section of 2-inch diameter or smaller pipe is recommended for this purpose if an averaging pitot tube or regular pitot tube is used. See Subsection 4.4 for a discussion of sizing a pipe to a pitot tube.

Note: The temperature of the air stream at the wellhead may be a qualitative indication of the residence time of the air in the subsurface. If a pilot test is conducted in mid-summer and the extracted air is significantly warmer than the natural groundwater temperature, the air has a low residence time in the soil. The converse is also true -- unusually cold wellhead temperatures in winter also indicates a low residence time.

- Sample Collection Equipment or Instruments. See Attachment 1 for a discussion of typical sampling equipment. Attachment 1 is designed for petroleum sites. However, field instruments, portable gas chromatographs, and carbon tubes (or other adsorptive media) are useable at other sites. The equipment used must be appropriate for the site contaminants. See Subsection 3.2.3 for a further discussion of equipment parameters.

  A combustible gas meter may be needed at sites with ignitable contaminants to ensure that the off gas measured at the stack is below the lower explosive limit.

- Zone of Influence Instrumentation. The vacuum in the soil at a distance from the air-extraction well can be measured at existing water-table wells, other air-extraction wells, or with temporary gas probes that are normally used for soil gas surveys. Some designers also install permanent gas probes as discussed in Subsection 4.3.3. Since water-table monitoring wells generally have less than 5 feet of exposed screen above the water table, measuring the vacuum in water-table wells provides a vacuum reading that is essentially measured at the water table, provided that the well casing couplings are air tight. Air-extraction wells generally have longer screens and measure an average vacuum over the entire screened interval. Because there are significant vertical pressure gradients under active venting, it is IMPORTANT to use vacuum monitoring points that are equal in depth (or as close as possible), unless a three-dimensional model is used that corrects vertical gradient.

  To measure the vacuum in a well, fit an air-tight cap with a hose barb to the well and use an inclined manometer, vertical manometer, or magnehelic gauge. Vacuum measurements should be to two digits of accuracy (e.g., 0.01 to 0.99, 1.0 to 9.9, and 10 to 99). If the vacuum is very low, use an inclined manometer or other device that can accurately measure to 0.01 inch of water column. Vacuum measurements should be taken after the vacuum in the subsurface has stabilized. A minimum of two measurements, at different times, at each data point should be taken to assure that the vacuum has stabilized. Generally, in coarse-grained soils the vacuum measurements are reasonably stable after a half hour. Subsection 4.1 describes how to use this data to evaluate well placement. Note: If designers use manometers instead of magnehelic gauges, they are available with oil instead of water. This may be an advantage in freezing weather. Oil manometers are calibrated to the density of the oil and cannot be used with water. Some air-flow modeling methods require barometric pressure monitoring during the pilot test to correct for atmospheric pressure changes.

Some sites are sufficiently simple so three-dimensional vacuum measurements are not needed, but sites with complex stratified soil may need three-dimensional vacuum measurements to fully understand the air flow patterns. Probes that are normally used for soil-gas surveys can be used instead of wells to measure the vacuum at specific discreet depth intervals.

If multiple air-extraction wells are available for testing, test each well by extracting air from it during the pilot test. Test wells that are most likely to be used in a full-scale system. If the vacuum stabilizes at a distance from the well in a reasonable period of time, multiple air-extraction well tests can be used for zone of influence measurements. If it takes more than two hours for an air-extraction well to stabilize, only a few wells can be tested during the eight hour air emission exemption period.

If the air-extraction well is screened into the water table, measure the depth to the water table -- both before and IMMEDIATELY after the pilot test. Even if the well is not screened into the water table, inspect the well IMMEDIATELY after the pilot test for water accumulation in the bottom plug of the well. This data is used to assess the screen length available to air flow during the test.

Some consultants operate the pilot test at two or more air-flow rates during the pilot test to gather information for air modeling. The method proposed by Clarke et al. (1993) and Wilson et al. (1992) — to scale up from a pilot test to a full-scale system — requires flow and vacuum measurements at three or more different flow rates. Note: If the method proposed by Clarke et al. (1993) and Wilson et al. (1992) is used, the DNR recommends flow and vacuum measurements at four or more different flow rates.

3.2.3 Analytical Monitoring Methods for Pilot Tests.

Use the same analytical methods during the pilot test as would be used in a full-scale remediation. Frequency of sampling is not specified for a pilot test, but a minimum of two gas samples should be collected for analysis. If a field portable instrument is used, take samples every half hour or every hour.

Do not take the first sample until after approximately 100 to 300 cubic feet of air has been evacuated from the soils adjacent to the well air-extraction well. This initial purge of air is needed to thoroughly evacuate the air that has been in and near the air-extraction well and filter pack. If 100 cubic feet was not produced within 30 minutes because of low permeable soils, sampling after 30 minutes is acceptable.

3.2.3.1 Sites With Petroleum Product Contamination.

During the pilot test, assess both total VOCs and benzene (see Attachment 1).

3.2.3.2 Sites With Non-Petroleum Contamination.

Assess the known and suspected contaminants and any biodegradation products of the contaminants during the pilot test. Any other non-natural gases or vapors that may be in the subsurface from on-site and possible off-site sources should also be assessed.

> Example: There is a tetrachloroethene loss at a manufacturing facility, and there is an UST containing gasoline 200 feet from the tetrachloroethene spill site. Even though there is no known gasoline loss, the pilot test at the tetrachloroethene spill site should also test for benzene and/or petroleum hydrocarbons in this case because vapor phase migration may occur over significant distances ( Mendoza and McAlary, 1990). Besides gasoline constituents and tetrachloroethene, samples should be analyzed for trichloroethene, 1,2-dichloroethene, and vinyl chloride because these compounds are degradation products of tetrachloroethene and are expected to be present.

3.2.4 Reporting Results From Pilot Tests.

The results of a pilot test can be included in the site investigation report, the design report or as a separate report. The report from a pilot test should include the following:

Discussion.

- A description of the test and final conclusions. The text should include dates, weather (ambient temperature, wind, etc.), and any other pertinent field observations from the pilot test. The barometric pressure and whether climbing or falling may also be listed.

Figures.

- A site map drawn to scale (horizontal accuracy to +/- one foot). The map should indicate:
  - Locations of air-extraction wells and vacuum measuring points;
  - Suspected and/or known source location(s) (if differing contaminants types are present at a site, the locations should identify the contaminant types);
  - zone of soil contamination (if three-dimensional data is available; multiple maps may be used);
  - Paved areas, buildings, and structures that may act as a surface seal or an infiltration barrier;
  - Buried utility trenches that may act as zones of higher permeability;
  - Scale, north arrow, title block, site name, key or legend, and date(s) of pilot test;
  - Any other pertinent site information that may affect a

permanent soil venting system on the site, such as overhead power lines (they may conflict with future drilling activities).

- A graph representing subsurface vacuum at a distance from the extraction well is recommended if there are three or more data points in addition to the air-extraction well. The distance scale should be on the horizontal axis and the vacuum should be plotted on the vertical axis. The graph may be plotted on normal graph paper or on semilog paper with the vacuum on the log scale. Note: The DNR recommends semilog graphs for this purpose. The graph should identify which data points were used. A line or curve predicting the vacuum at a distance from the air-extraction well should be drawn on the graph. The line or curve may or may not intersect the air-extraction well due to partial penetration effects and possible extraction well inefficiency. Note: If the screened intervals between different monitoring points vary significantly, the graph may not provide a smooth curve because there are significant vertical pressure gradients under active extraction.

- A water-table map of the site for the day of the pilot test.

- A cross section showing screened intervals, geological units, contour lines of vacuum readings, and vacuum measuring points.

- If sufficient data points are available, a map of measured vacuums and contours of the vacuum in the soil during the pilot test may be included. This map is only recommended if the full-scale remediation system will use a single air-extraction well.

Tables.

- Tabulated flow rates, vacuum distribution, soil gas temperatures, times of readings, ambient barometric pressure (if taken), and the ambient temperature.

- Water levels in all wells.

Appendices.

- A complete description of the field equipment and field procedures that were used.

- Sampling methods and procedures.

- Analytical methods, analytical results, and lab reports. The analytical results should be quantified in mass per volume units, such as pounds per cubic foot or milligrams per cubic meter of contaminants in air.

- Boring logs and well-construction diagrams for air-extraction wells. If groundwater monitoring wells are used for measuring vacuum, the screened interval of the monitoring wells should be listed in a table and/or the well construction diagrams should be included in an appendix. Any vacuum measuring points that are in fill should be identified as such.

- Engineering calculations. Clearly state all assumptions. Legible, hand written calculations are acceptable. Include the initials or name of the author and the person who performed a quality-control check of the calculations. List references for any formulas that were used.

- Any other pertinent field data.

Some pilot test reports also include a conceptual or detailed design of a full-scale soil venting system. If a pilot test report includes a detailed design, see Subsection 4.10 for recommended submittal contents.

## 3.3 Alternative to a Pilot Test.

Another way to estimate the air flow available from a soil venting system is by estimating the permeability of the soil based on a grain-size analysis. This method should only be used if all of the following conditions exist:

- The unsaturated zone of the site is a single relatively homogenous geologic unit.

- The volume of contaminated soil is very small.

- The total mass of contamination is relatively small.

- The Bureau of Air Management approves of the soil remediation without conducting a pilot test.

The best reason for using this method is the low cost of a grain-size analysis relative to a pilot test. The following are disadvantages of using this method:

- The effects of geologic heterogeneities are exaggerated by using only a small sample(s) to characterize a site. Sampling location selection can inadvertently bias the results.

- Layered geologic conditions cannot be evaluated by using a grain-size analysis to estimate intrinsic permeability because of the variations in permeability.

- Air emissions cannot be estimated.

- The calculated permeability assumes dry soil. If there is significant soil moisture, the permeability to air flow could be less than estimated.

To calculate the air flow available by the grain-size analysis method, first estimate the hydraulic conductivity by using a mathematical analysis of the grain size (Shepherd, (1989), Masch and Denny, 1966 or by the Hazen method in Freeze and Cherry, (1979) and Fetter (1988)). Note: The Hazen Method is only valid when $0.1 < D_{10} < 3.0$ mm. Then calculate the intrinsic permeability of the soil from the hydraulic conductivity. Note: At 15 degrees celsius, the conversion factor is approximately 1 darcy = 8.5 E-4 cm/sec based on data from Fetter (1988), page 84. Finally, estimate the air-extraction rate (Johnson et al., 1990, see figures 4 and 5) per unit length of extraction-well screen.

## 4.0 Design and Installation of a Soil Venting System.

The soil venting system components are described in this beginning with a discussion of well placement. The discussion of design parameters then follows the same route as the flow of air: from well design, to manifold, to water trap, and the blower (or vacuum extractor). Subsections 4.7 through 4.9 discuss other equipment that may or may not be used at a site. This Section concludes with a discussion of the information that should be submitted to the DNR.

### 4.1 Well Placement and Air-Flow Modeling.

The key design variables with soil venting are the number of air-extraction wells and the flow rate from each well. There is no equation to determine these parameters. In the literature, well spacing generally ranges from 20 to 50 feet.

A capture zone for a well can be mathematically determined for groundwater plume capture (given the gradient, extent of contamination, pumping rate and aquifer transmisivity). Soil venting systems do not have a single mathematical solution to use for determining well placement. Some mathematical models exist that are excellent tools for estimating well spacing, however, the users of these models should be sufficiently skilled to know if and when model assumptions are valid.

Some system designers use a model that estimates the number of pore volumes that are needed to clean up a site. An air-flow rate that is based on pore volumes is then selected. If a method based on pore volumes is proposed, the volume of air that enters the well(s) through the ground surface near the well should be assessed using a method that evaluates three-dimensional air flow, such as the method described by Shan et al. (1992) or by a similar method. Other models are complex two- or three-dimensional models of air flow patterns. Some models use pilot test data to determine site-specific parameters, such as Kh/Kv ratio, intrinsic permeability, etc. Some of the mathematical models (both analytical and computer) used for modeling air flow through soil are based on horizontal flow only and do not take into account vertical recharge through the ground surface. Models that use limited assumptions, such as horizontal and not vertical air flow, are good tools for rough estimates, but are not useful for determining an exact distance for well spacing. Designers should assess the key assumptions in an air-flow model prior to its use. Professional judgement is necessary in interpreting model results.

The DNR does not endorse any models and does not require air modeling for the system design. If a model is used, include the key assumptions and results of the model in an appendix to the design report.

The zone of influence is the area from which an extraction well can effectively draw air. Figure 4-1 is based on the mathematical formulas in Shan et al. (1992); it simulates the vacuum that would be measured in water-table wells at different distances from a single air-extraction well. There are four different graphs simulating Kh/Kv ratios of 0.67, 1, 3, and 10. As demonstrated in Figure 4-1 there is no clear cut "radius" of influence; the effectiveness gradually decreases with distance. In theory the vacuum extends significant distances beyond the point where it can be measured by field measuring devices. Even though in theory there is a vacuum at these great distances, in reality, the vacuum is so low that there is essentially no induced air movement through the soil. The

## Figure 4-1
## Vacuum at a distance from a single extraction well

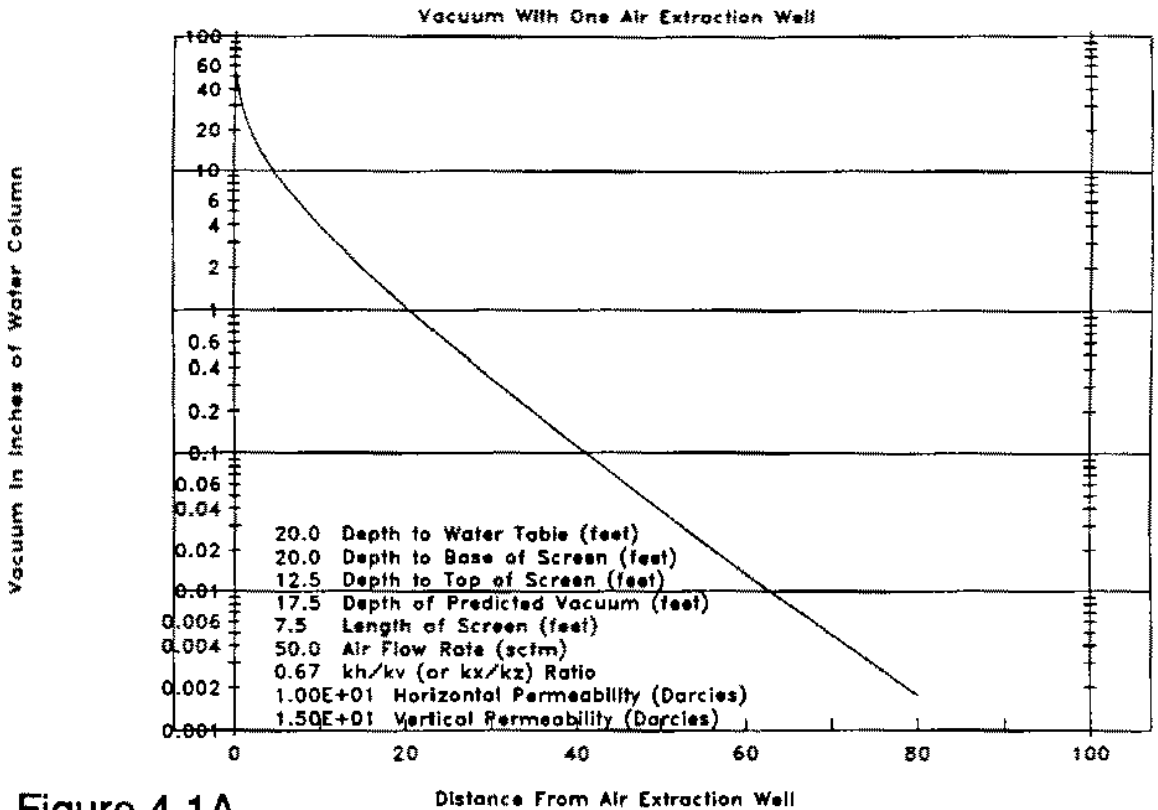



Figure 4-1A

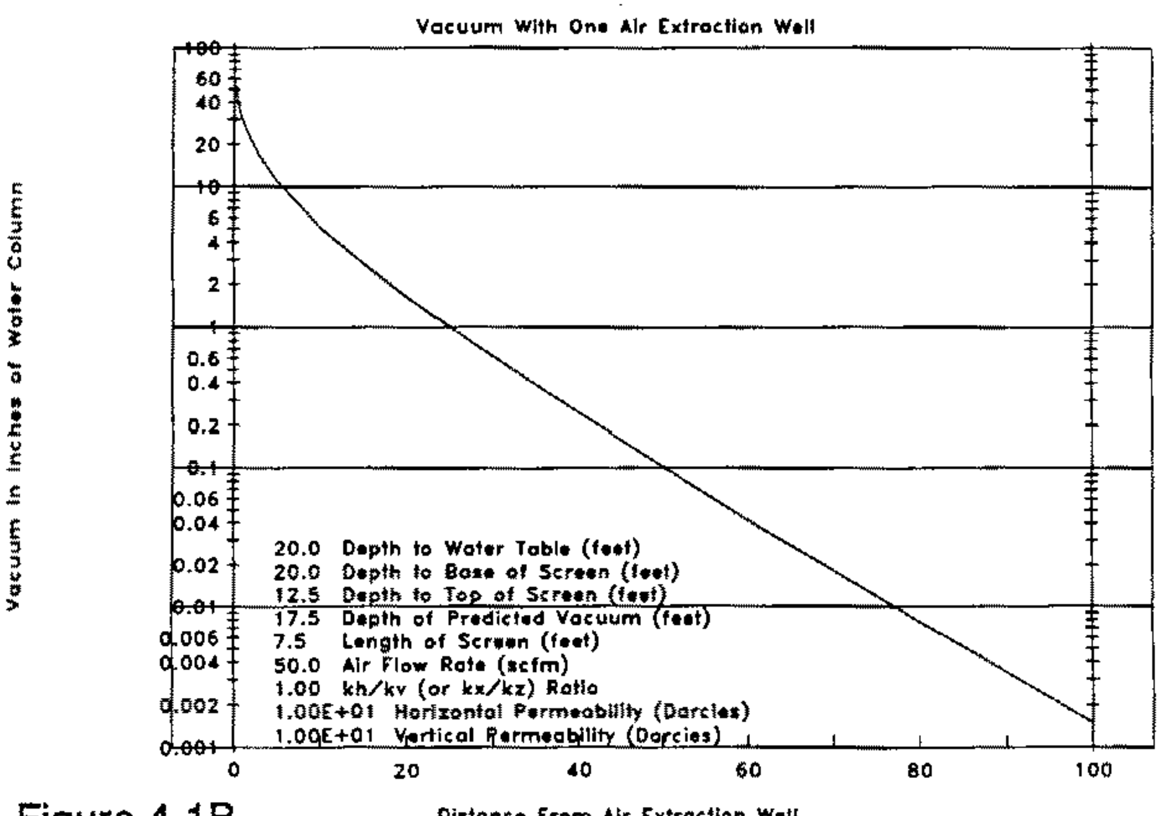



Figure 4-1B

# Figure 4-1 continued

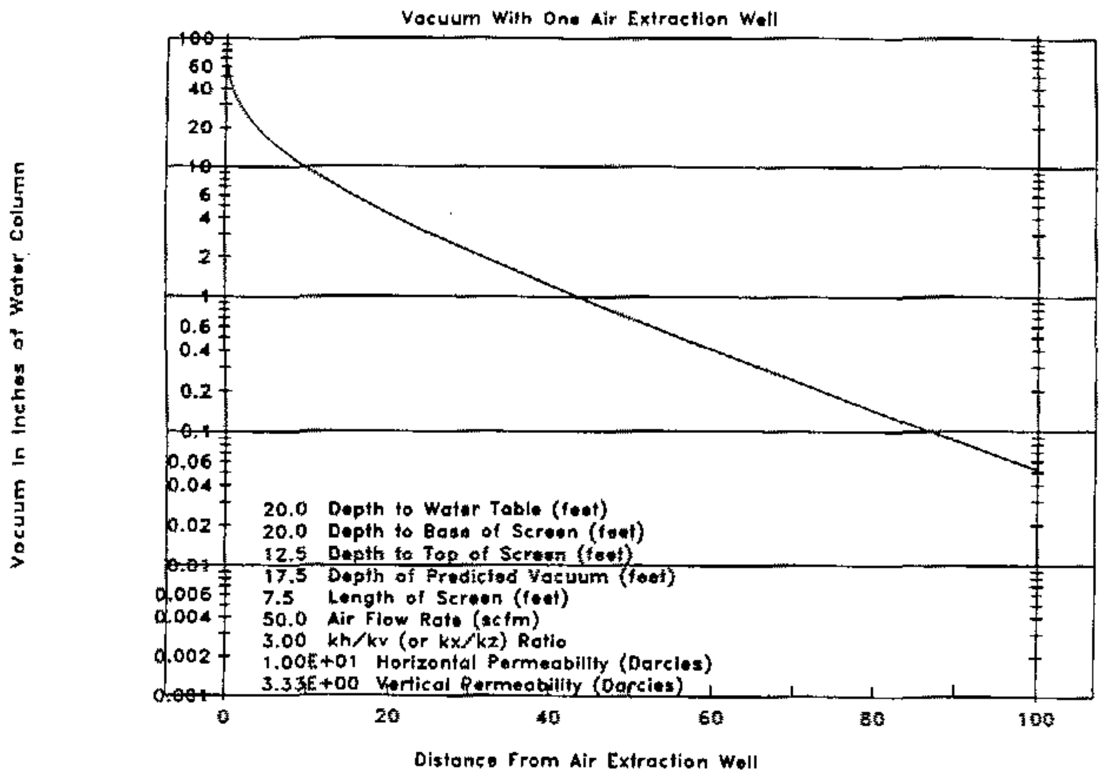



Figure 4-1C

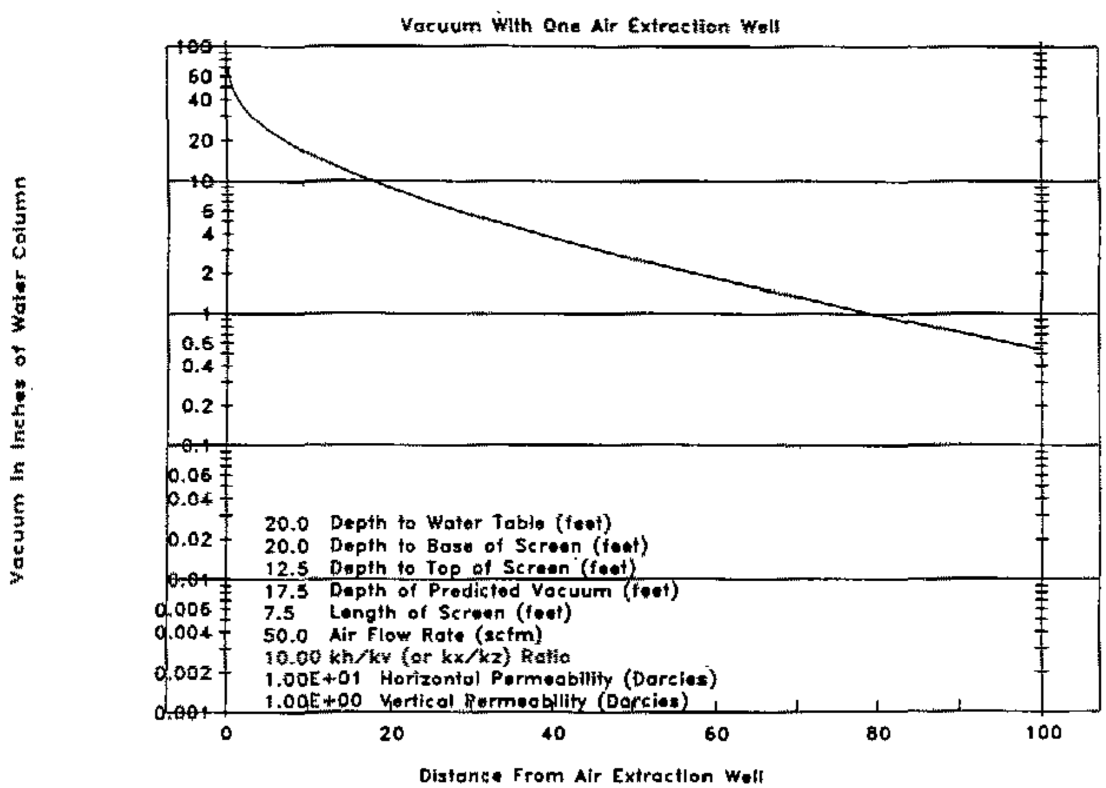



Figure 4-1D

numerical example below is based on the graph in Figure 4-1B where the Kh/Kv ratio is one.

Example: The stabilized (steady state) vacuum and the distances from the vacuum measuring points to a single air-extraction well in a uniform sand are as follows:

| Measuring Point | Vacuum (Inches of Water Column) | Distance (feet) |
|---|---|---|
| VW-1 | 54 | NA |
| MW-2 | 5.2 | 10 |
| MW-1 | 1.6 | 20 |
| MW-5 | 0.25 | 40 |
| MW-4 | 0.10 | 50 |

In this case, the vacuum decreases by 3.6 inches of water column from 10 feet to 20 feet, and it decreases by 0.15 inches of water column from 40 to 50 feet. Assuming that the rate of horizontal air flow is directly proportional to the horizontal difference in pressure head, the air velocity through the soil at 40 to 50 feet from the air-extraction well is only 4.2 percent of the velocity at 10 to 20 feet (*0.15 / 3.6 = 0.042 or 4.2 percent*).

As the air velocity through soil decreases at greater distances from the well, the system's ability to volatilize and remove VOCs by advection is reduced at a distance. In this example, the effectiveness of the system is only marginal at distances beyond 50 feet even though there is measurable vacuum to 75 feet and unmeasurable vacuum beyond.

Since there is a significant vertical pressure gradient, it is VERY IMPORTANT that all vacuum measuring points are equivalent in depth when using vacuum versus distance data to evaluate well spacing, unless a three-dimensional model is used that corrects for vertical gradient.

Use professional judgement to estimate the well spacing that is needed in each specific situation. Take the following items into account when assessing optimal well placement:

- Some areas of a site usually have much higher levels of soil contamination than others. It may be appropriate to use a closer well spacing in these areas to increase the rate of remediation.

- Generally, there is a tradeoff between time, efficiency, and cost. Closer well spacing speeds the cleanup, but increases costs for wells, analytical testing and blower capacity. If the total cost of wells is significant, a longer cleanup time with fewer wells, spaced farther apart may be more appropriate.

- Relatively close well spacing is needed in low permeable soil because the rate of air flow from each well is very low, and therefore the rate of contaminant extraction on a pounds-per-time basis is also very slow per well. In high permeable soil, wells can be placed farther apart because higher air flow per well can result in a greater rate of contaminant extraction per well.

- If the Kh/Kv ratio is very high due to the depositional environment of the soil, or if there is a high quality surface seal, the air-flow pattern will have a preferred horizontal orientation. In this case, wells can be placed farther apart because there is less vertical recharge near the air-extraction wells.

- In a heterogenous, mixed lithology site, the zone of influence in the more permeable layers is augmented by overlying layers of silts and clays, which allows increased well spacing. The silts and clays, however, take longer to clean up because extracting contaminants from these soils is limited by the rate of diffusion.

- At sites with a very shallow water table, a significant proportion of the air that enters the air-extraction well(s) is from the ground surface near the well. In these cases, relatively close well spacing may be necessary.

- To remediate contaminants that have a low vapor pressure through volatilization, relatively rapid air-flow rates through the soil are necessary. In this case, relatively close well spacing may be appropriate. Enhancing biodegradation, however, does not usually require a high air-flow rate.

- At sites where geologic conditions at depth are sufficiently uniform, a single set of wells at the same depth may be sufficient. Sites that are significantly stratified or that have other geologic heterogeneities in the site soils may have a very high rate of contaminant removal initially, but the removal rate will decline rapidly after the coarse-grained layers are remediated. Late in a project the rate of extraction is controlled by the rate of VOC diffusion out of the fine-grained soils. At a site with these conditions, tailor the design for the natural geologic conditions.

    Example: A site has two distinct, fairly thick geologic units, a sand and gravel unit and a silty sand unit. Remediation of the silty sand unit is expected to be much slower than the sand and gravel unit. In this case, fewer extraction wells screened in the sand and gravel, and more extraction wells screened in the silty sand may maximize the remediation rate of the silty sand. Air-injection wells (Subsection 4.8) may also be needed in complex geological conditions.

The spacing of air-extraction wells in a full-scale soil venting system is determined by the desired air-flow rate through the impacted soil and the desired rate of cleanup. Use professional judgement to weigh the costs against the cleanup time when determining well placement. A higher air-flow rate is needed for an increased rate of volatilization and advection. The air-flow rate is less important if diffusion and biodegradation are controlling factors in the remediation rate.

Buscheck and Peargin (1991) suggest that the design radius of vacuum influence at a gasoline contaminated site be at the distance where the vacuum in the soil is 1 to 0.1 percent of the measured extraction well vacuum. According to the Buscheck and Peargin method applied to the numerical example above, the well spacing (which is twice the design radius of vacuum influence) should range from 20 to 65 feet.

Generally, the well spacing should range from 20 to 50 feet. If proposed well spacing is closer than 20 feet or farther than 50 feet, and the Buscheck and Peargin (1991) method is not used, the spacing selected should be justified in the workplan submitted for the site.

4.2 Air Permeability, Achievable Air-Flow Rates, and Air-Emission Limits.

Use the vacuum and air-flow rate measured from the air-extraction well during the pilot test to estimate the vacuum and air-flow rate that are achievable in a full-scale soil venting system design.

If pilot test results from multiple geologic strata are evaluated, it may be appropriate to evaluate the achievable air-flow rate per foot of screen and/or the intrinsic permeability of each geologic unit. If all the wells in a final system design have equal screen lengths in the same lithologic materials, the flow rate per well can be used instead of calculating the flow per foot of screen.

In most cases, if the vacuum is less than about 40 inches of water column (one-tenth of an atmosphere), designers can assume that the rate of air flow to vacuum is linear. Note: This assumption is invalid because air is compressible, but the method is useful for estimating air flow under low vacuum conditions.

Example: If the pilot test indicates that 72 scfm is achievable from a well under 9 inches of water column vacuum, the system is designed to have 14 inches of water column at the well head. The flow rate would be:

$$72 \text{ scfm} * \frac{14}{9} = \text{approximately } 112 \text{ scfm}$$

Where the vacuum is greater than about 40 inches of water column, the rate of air flow to vacuum is not directly proportional because air is a compressible fluid. In this case, adjust the required vacuum to account for the compressibility of air. A multiplier that approximates the compressibility of air is appropriate.

Example: A pilot test indicates that 40 scfm are achievable under 3 inches of Hg. Note: 1 inch of Hg = 13.55 inches of water column. The full-scale system is intended to provide 100 scfm from each air-extraction well.

$$3 \text{ inches Hg} * \frac{100 \text{ scfm}}{40 \text{ scfm}} = 7.5 \text{ inches Hg uncorrected for compression}$$

Assume that atmospheric pressure is 29.92 inches Hg.

$$7.5 \text{ inches Hg} * \frac{29.92 - 3 \text{ inches Hg}}{29.92 - 7.5 \text{ inches Hg}} = 9.0 \text{ inches Hg}$$

In this example, 9 inches of mercury vacuum is necessary to achieve 100 scfm per well. This empirically-derived approximation is not very accurate at vacuums above 10 inches of Hg, but it is generally usable in the vacuum range of most soil venting systems. A better, more complicated correction factor that compensates for the laminar to turbulent flow transition is described in Clarke et al. (1993) and in Wilson et al. (1992). If the system is very large and/or will run at high vacuums, use the correction method described by Wilson instead of the simplistic method described in the example above.

The above correction factors assume that there is no water-table upwelling. If there is significant upwelling, the screen length in the unsaturated zone changes, and the estimate is not correct.

If the pilot test uses a 2-inch well and the full-scale system uses a 4-inch well, approximately 15 percent more air flow will be extracted at the same vacuum because of the larger well (Johnson et al., 1990).

The above means of estimating the achievable air-flow rate in a full-scale soil venting system assumes that the soil intrinsic permeability and the exposed length of screen remains the same over time. There are a number of reasons that the air-flow rates in soil venting systems change with time, including the following:

- Seasonal water-table fluctuations and vacuum induced water-table fluctuations change the amount of well screen available for air flow.

- Clay and silt soil types may dry out and crack during while operating a soil venting system, increasing air flow through secondary permeability.

- The effective porosity (to air flow) of the soil and thus air permeability can increase as moisture is reduced in the soil by the drying effects of the air flow.

- The air permeability of the unsaturated zone changes with infiltration events because of fluctuating effective porosity to air, changing the air flow to the well(s). A paved ground surface can minimize this effect.

Pilot test data should be used because it is the best data available for designing a soil venting system, even though it may not provide 100 percent accurate results.

Determine a total desired air-flow rate for the site using the total available well-screen length from all wells and the rate of air flow per linear foot of screen. If all wells in a final system design have equal screen lengths in the same lithologic materials, the flow rate per well can be used instead of calculating the flow per foot of screen. In general, the total flow rate will be between 50 and 500 scfm for most petroleum sites. Sites that have a larger area than typical petroleum sites may have higher total flow rates. Some sites that have contamination in a very limited area (diameter of 50 feet or less) may only require one air-extraction well and less than 50 scfm.

To evaluate whether or not the vacuum will be too high, which may create an unacceptable amount of upwelling, designers should determine the design vacuum and air-flow rates. It is possible that the vacuum will lift the water table above the zone with the highest level of contamination. In this case, the high vacuum is counterproductive because the contamination is submerged below the cleansing effects of the air flow. A lower vacuum and corresponding lower air-flow rate is more productive over time, unless the groundwater table is lowered by pumping. Pumping groundwater is discussed in Subsection 4.9.4.

The rate of contaminant extraction will decline with time during a full-scale site remediation. The anticipated contaminant removal rate at start-up is similar to the pilot test results. If the air-extraction wells are not installed in the highest soil contamination zone, the contamination extraction rates may actually climb for the first few days after full-scale start-up as contaminants are drawn towards the well(s). Otherwise, the pilot test results may provide the highest achieved contamination extraction rates. For engineering design purposes, apply a safety factor of 1.5 to the highest levels of contaminants in the air during the pilot test to predict the highest levels of contaminants from a full-scale system.

Compare the maximum air emissions at start-up to the total desired air-flow rate using the emission limits and the achievable air-flow rate calculated from the pilot test data (with safety factor). It is possible that air emission control will be needed; no emission control is necessary or; the initial flow rate from the system needs to be limited using a timer or a dilution valve. Air emission control devices are discussed in greater detail in Subsection 4.7.

The air emission limits in Wisconsin are based on the total mass of contaminants emitted during a period of time. If no emission control is anticipated, the contaminant extraction limits are the limiting factor during start-up. The limits for petroleum sites are discussed in Attachment 1. System designers can estimate the maximum air-flow rate at start-up by dividing the total emission limit by the concentration measured during the pilot test.

Example: A LUST site pilot test indicates that total VOCs are 1.0 E-3 pounds per cubic foot and benzene is 1.0 E-6 pounds per cubic foot. Assume that the total VOCs are limited to 5.7 pounds per hour and benzene is limited to 300 pounds per year. The maximum air-flow rate for total VOCs is then estimated to be:

$$\frac{5.7 \text{ pounds per hr}}{1 \text{ E-3 pounds per foot}^3} = 5{,}700 \text{ standard cubic feet per hour}$$

$$\frac{5{,}700 \text{ standard feet}^3 \text{ per hr}}{60 \text{ minutes per hr}} = 95 \text{ scfm}$$

Applying a safety factor of 1.5, the maximum becomes:

$$\frac{95 \text{ scfm}}{1.5} = 63 \text{ scfm}$$

A similar calculation for benzene is:

$$\frac{300 \text{ pounds per yr}}{1.0 \text{ E-6 pounds per foot}^3} = 300{,}000{,}000 \text{ standard cubic feet per year}$$

$$\frac{300{,}000{,}000 \text{ standard feet}^3 \text{ per yr}}{525{,}600 \text{ minutes per year}} = 570 \text{ scfm}$$

Applying a safety factor of 1.5, the maximum becomes:

$$\frac{570 \text{ scfm}}{1.5} = 380 \text{ scfm}$$

In this example the limiting factor is total VOCs. The designer (based on past experience) anticipates that the system will have a contaminant extraction rate at about one-third of the maximum after two months. Therefore, the designer selects a blower much bigger than 63 scfm. The flow rate at start-up is limited to approximately 63 scfm by using a dilution valve (Subsection 4.4). If approximately two or three months of sampling indicates that a higher air-flow rate can be used while complying with the air rules, the system operator increases the flow rate by adjusting the dilution valve to increase the contaminant extraction rate.

Note: Upon start-up, a dilution valve may be used to control total VOC emissions, but not to control benzene emissions.

## 4.3 Well or Trench Design.

Vertical air-extraction wells at most sites are used to extract air from the soil. In rare cases, a horizontal air-extraction system is warranted over vertical wells. Conceptually, a trenched system is preferred if the groundwater table is very shallow (less than about 10 feet) or if the soil contamination is very shallow. Figure 4-2 shows a typical well design.

### 4.3.1 Vertical Extraction Wells.

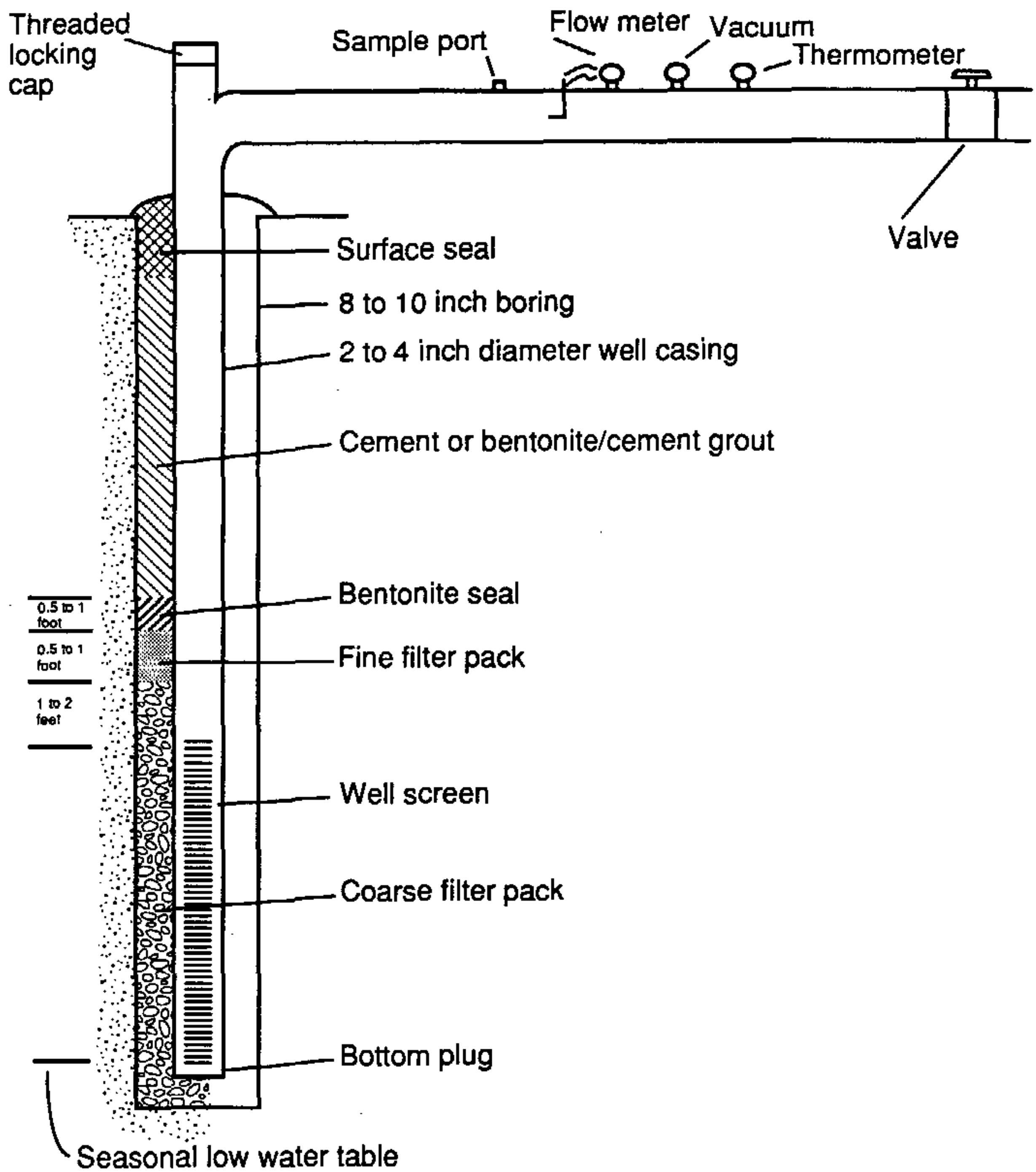
The extraction wells should be constructed using 4.25-inch or larger inside-diameter, hollow-stem augers. Any drilling methods (other than hollow-stem auger), such as mud or clear-water direct rotary, should not be used if the method creates an excessive filter cake buildup on the bore-hole wall. Refer to Subsection 1.3.1 for a discussion of regulatory requirements on well construction.

The pipe and screen should be flush threaded schedule 40 PVC or CPVC. Steel or other materials may also be used. The recommended diameter of the screen and casing is 4 inches. Two-inch, 2.5-inch, and 3-inch diameter screen and casing are also used on some systems.

The advantages of 4-inch diameter over 2-inch are:

- The flow rate at a given vacuum is higher with a larger well (Johnson et al., 1990). Doubling the well diameter increases the air-flow rate by 15 percent. Two-inch diameter wells are more restrictive to air flow.

Figure 4-2
**Typical air extraction well design with above grade manifold**



- Little water is lifted up the well, if the up-hole air velocity flow is limited to 1,000 feet per minute or less. This reduces water production and accumulation. In many cases, a water trap (Subsection 4.5) is not needed on a soil venting system if the up-hole velocity is minimized. A 2-inch diameter, schedule 40 well casing will only deliver 23 scfm if the up-hole velocity (at atmospheric pressure) is 1,000 feet per minute. A 4-inch diameter, schedule 40 well will produce 88 scfm at 1,000 feet-per-minute of up-hole velocity.

- Packers may be used to seal off portions of a screen that intersect relatively clean soils. There are packers and similar devices available off the shelf for insertion in a 4-inch diameter pipe.

- If there is a sufficient water accumulation to block off a significant portion of the screen, it may be necessary to pump groundwater from the well. A greater variety of pumping equipment is available that can be used inside 4-inch wells rather than 2-inch wells.

If the diameter is less than 2 inches or greater than 4 inches, the diameter should be justified in the work plan submitted for the site.

The screen length is a function of the water-table depth and the contamination zone. In isotropic soil conditions, set the base of the screen at the seasonal-low water table. Set the top of the screen at a depth that will channel most or all of the air flow through the contaminated soil and limit short circuiting of relatively clean air from the ground surface. At some sites with unusual or complex geological conditions, it may be appropriate to nest wells. In this case, set the well-screen depth for each well for the specific purpose of that well (such as nesting screens in differing geologic strata to reduce short circuiting effects).

At petroleum sites, the soil near the capillary fringe may have the highest levels of soil contamination because contaminants often collect at the top of the water table. The air-flow rate through the soil is reduced near the capillary fringe because of reduced effective porosity for air flow. By screening the wells near the water table, the rate of contaminant extraction in these cases is maximized. This channels more air flow past the high contamination zone. This may be an appropriate action at this type of site to reduce the air flow through the upper, relatively clean soils.

It is permissible to install additional screen length below the water table to place a groundwater extraction pump. With a pump that has sufficient capacity, this form of pump placement allows the system operator to dewater the entire screen, if necessary. See Subsection 4.9.3 and 4.9.4 for a discussion of groundwater extraction and free-product recovery. Designers should place a plug at the base of the well screen in accordance with NR 141.

The filter pack should be sized for the formation. Since air-extraction wells are not developed, a filter pack that is coarser than a typical well used for groundwater extraction, is usually acceptable. Size the screen-slot size for the filter pack. Generally, a slotted pipe provides sufficient open area per linear foot of screen. The filter pack and well screen-slot size at and below the seasonal-high water table should be determined based on groundwater extraction criteria. Please refer to the *Guidance for Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems* for groundwater extraction well design.

The top of the filter pack should be a short distance above the top of the screen; generally 1 to 2 feet is appropriate. If a coarse-gravel pack is used, a fine-filter pack that is 6 to 12 inches in height can be placed above the coarse-gravel pack to limit the potential for grout or bentonite entering the well screen.

A bentonite seal is often used to prevent grout from entering the screened interval. In air-extraction wells, limit the bentonite seal to a short thickness of 6 to 12 inches because bentonite can dry out in the unsaturated zone. This may allow air to short circuit through the annular space.

Cement grout or bentonite/cement grout in the annular space above the bentonite seal should be used. The grout seals the annular space up to the ground surface or to the manifold, if a buried manifold is used. If the grout is poured instead of tremied into place, use care to avoid displacing or damaging the bentonite seal and upper-most portion of the filter pack.

A tee fitting and not an elbow to connect the air-extraction well to the manifold should be used. Using a tee fitting allows for the attachment of a threaded cap to the top. The threaded cap provides access to the interior of the well to take water-level measurements or to install pumps or packers.

If the manifold is buried, the surface seal should be constructed in a manner similar to that described in Chapter NR 141. An air and water-proof manhole cover should also be used. Other fittings (valves, etc.) discussed in Subsection 4.4 can also be installed under the manhole cover(s).

4.3.2 Horizontally Screened System Design.

Horizontally-screened systems are sometimes used at sites where groundwater tables are shallow or where contamination is limited to shallow portions of the soil column. A significant amount of care is necessary when designing and installing an efficient horizontally-screened soil venting system.

Short circuiting of air flow through the backfill above the screen or perforated pipe is a common problem. Mixing a small amount of bentonite into the spoils prior to back filling may reduce the permeability and short circuiting problems.

A thorough hydrogeologic knowledge of the site is essential to design a trench for an air-extraction system. Because vacuum induced water-table upwelling and/or seasonal variations in the water table can flood the air inlets in the perforated pipe or screen, the screen or perforated pipe needs to be installed high enough to prevent flooding.

Generally, a horizontal system is installed with a backhoe. Dig the trench and install a PVC perforated pipe or screen in a pea gravel backfill. Place the spoils that were removed during trenching over the gravel. Placing plastic sheeting above the gravel and below the backfilled spoils reduces vertical short circuiting of air through the trench backfill.

Compact the spoils as much as possible to reduce the vertical permeability. If the trench is not safe to enter, compact the spoils by tamping the soil with the backhoe bucket in very thin lifts.

If pavement is placed over the trench, plastic sheeting should be installed under any gravel subgrade that is placed below the pavement. This will limit vertical recharge from the subgrade to the backfill.

Installing a trench that is very long may increase the occurrence of short circuiting. Since the construction of a trench may cause a short circuiting route for air flow, the longer the trench, the greater the probability of inadvertently constructing a short circuit route in the trench.

Handle excess spoils that are not placed back in the excavation in accordance with the DNR guidance on investigative wastes or solid and hazardous waste regulations dependant on the volume of contaminated soil.

4.3.3 Gas Probes.

Permanent gas probes are vapor wells that are installed to assess vacuum/pressure and subsurface vapor concentrations of VOCs and/or biodegradation products. Temporary gas probes, such as those used for soil gas surveys are also acceptable. The construction details, materials, diameters, etc. are not specified in Chapter NR 141. However, gas probes should have an annular seal and a surface seal constructed to Chapter NR 141 standards to prevent the gas probe from acting as a conduit for contaminants and/or a short circuit route for air flow. If a gas probe is installed at or below the seasonal-high water table, then the probe is a water-table well. In this case, construct the gas probe to Chapter NR 141 criteria for wells.

Purging a minimum of 3 to 5 volumes (of air) is appropriate when taking samples for field instruments or laboratory analysis.

See Subsection 5.1 for a discussion of placing gas probes in predicted stagnation zones.

4.4 Manifold and Instrumentation.

The manifold in soil venting systems is either installed above grade or it is buried. When the area is used for activities that will not allow the use of above-ground manifolds (parking lots, driveways, dispenser islands, etc.), the manifold should be buried. Above-ground manifolds are suitable when uninhibited access does not have to be maintained at a site.

If contaminant migration is minimal AND if the DNR project manager approves, some systems may operate only during the warmer portions of the year. In cases where the project must operate all year, the manifold should be winterized (or capable of being winterized) at a later date. Generally, an above-ground manifold can be winterized with self regulating heat tape and/or pipe insulation at any time. Above-ground systems, therefore, are not usually winterized until it is necessary. Buried manifolds are not easily winterized, so these systems are usually insulated or installed near or below the frost level. If the manifold is winterized at a later date with heat tape, use CPVC pipe instead of PVC pipe to provide higher strength in high temperatures.

Generally, manifolds should be constructed with 4-inch pipe. Systems have been installed with manifolds as large as 24 inches in diameter, but these large systems have centrifugal blowers that require a low manifold vacuum. The designer should evaluate pipe friction in the system to ascertain that the manifold will conduct the desired air-flow rate under either of the following conditions:

- If a 2-inch manifold pipe is used, the air-flow rate is over 50 scfm and any piping run is longer than 50 feet.
- If a 4-inch manifold pipe is used, the air-flow rate is over 300 scfm and any piping run is longer than 50 feet.

The manifold may accumulate condensation if the air velocity is lower than a few thousand feet per minute. One method to avoid a condensation buildup is to slope the manifold towards the air-extraction wells where it can drain. Another satisfactory method with buried manifolds is to use a relatively small-diameter vertical pipe where the direction changes from horizontal to vertical, allowing the airstream to carry condensation up towards a water trap. This method is satisfactory if the air flow in this smaller pipe has an up-hole air velocity of 3,000 feet per minute or more. A less satisfactory method is to maintain a high air velocity on the entire manifold by using a small-diameter pipe. This alternative is less satisfactory because pipe friction may be excessive, resulting in added requirements for blower capacity and excessive electrical costs.

Designers should configure the manifold and place valves in such a way to allow control and sample collection at each well. Above-ground systems may have the sample ports and instrumentation for each well near the well itself. The sample ports and instrumentation on buried manifold systems may be located near the blower system where the manifold pipe exits the ground. Figure 4-3 shows two different options for instrumentation locations on a buried manifold. The option that places the instrumentation nearest the well generally provides the best vacuum and temperature information for the well, but is more likely to freeze up in winter on low flow systems and systems with a shallow water table.

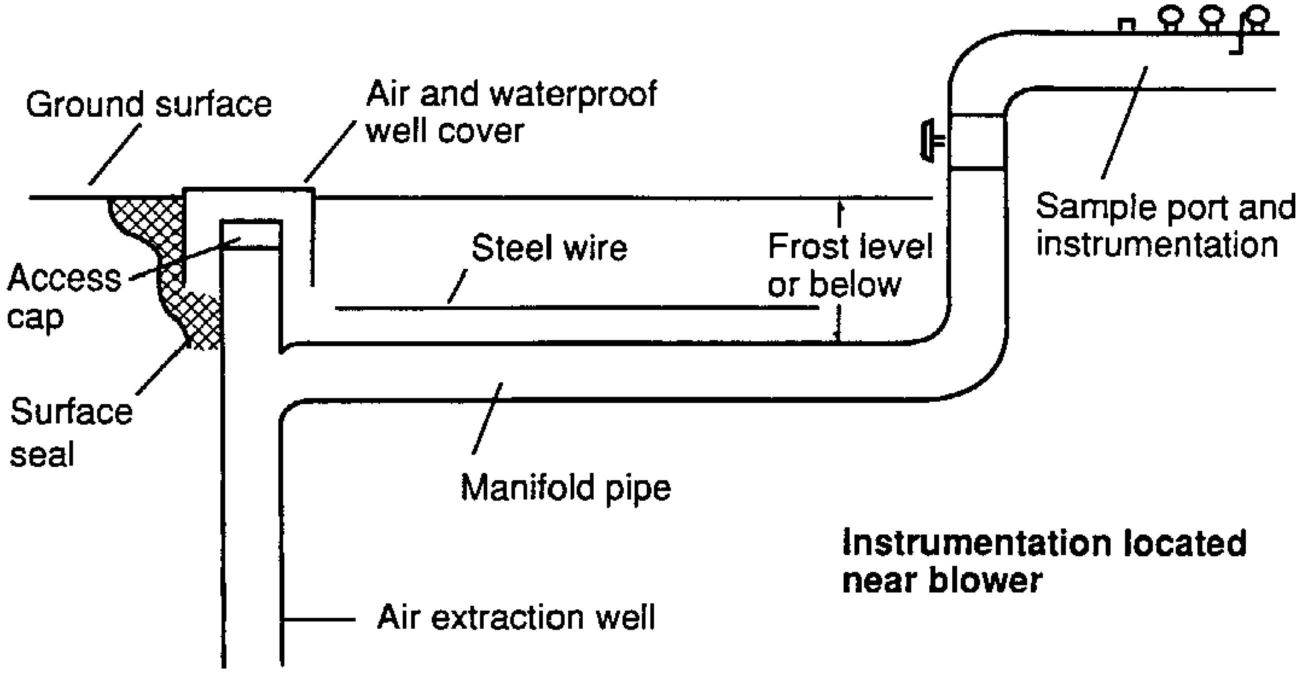
Construct the manifold with glued fittings, since slip fit joints may fail with time. It is recommended that a steel wire or similar material is installed in the trench with buried manifolds that have plastic pipe to find the trench later with a metal detector. Note: This is unnecessary at sites with reinforced concrete pavement, since the metal detector will only "see" the rebar.

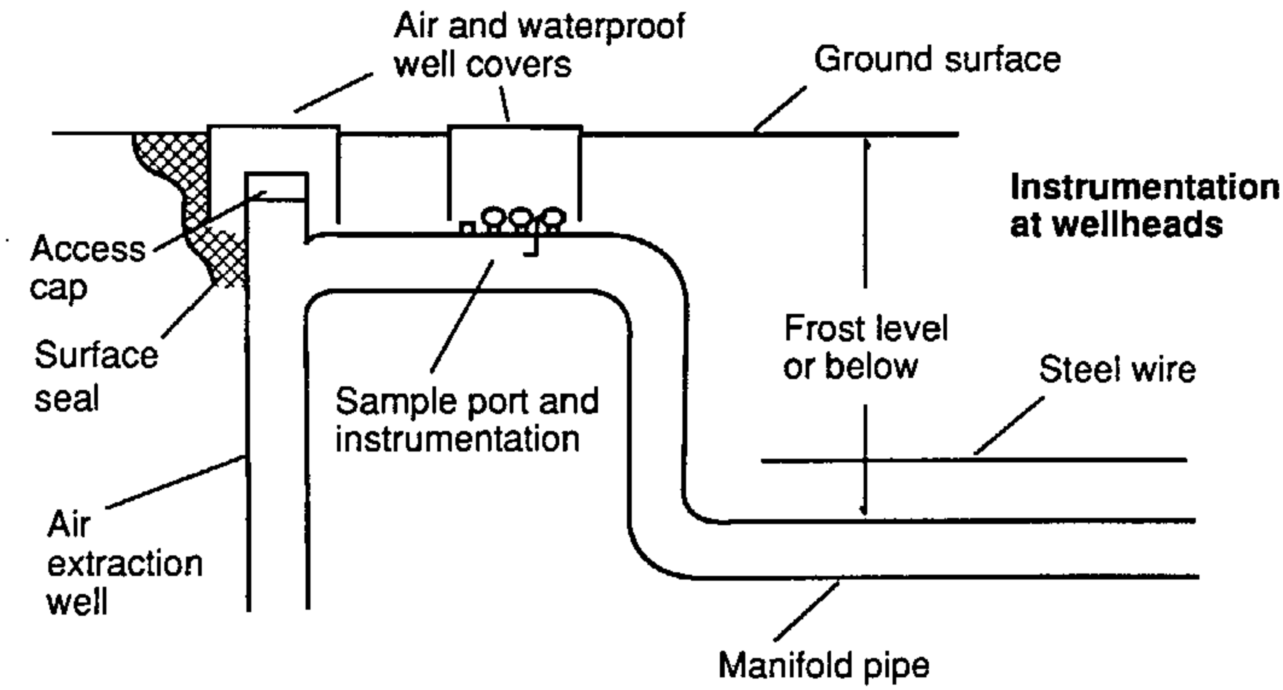
Install a flowmeter, a vacuum gauge or manometer, a thermometer, and valve at locations where samples are collected. These devices are described as follows:

- <u>Valves.</u> Each well should be installed in a manner that allows the well to be isolated from the rest of the system. PVC ball valves or gate valves are generally used to isolate each well. If the flow rate through the pipe is expected to be over 100 scfm, the valve should not be smaller in diameter than the manifold pipe. In lower-flow systems, the valve may be smaller to reduce costs.

  A dilution or bleed valve is also needed on the manifold immediately before the air enters the air filter or blower (if

Figure 4-3
**Wellhead details with buried manifold**



no filter is used). The dilution valve allows atmospheric air into the blower, when opened, and relieves vacuum to reduce overall air-extraction rates from the wells. Do not install the dilution valve between the wells and the sample ports, because the sample results would not represent extracted air concentrations. A dilution valve is more energy efficient than a throttle valve that restricts air flow because blowers require the least amount of electrical power when the pressure differential across the blower is relatively low, . In addition to a dilution valve, install an automatic pressure relief valve if the blower may overheat under a blocked flow condition. A silencer on the inlet to the dilution valve may be needed in some cases. If the dilution valve is opened to the atmosphere, an air filter on the blower is needed, even if it is a centrifugal blower.

An alternative to installing the dilution valve that opens to atmosphere is to install a bypass valve to draw air from the blower exhaust. This allows air to circulate from the exhaust back to the blower inlet. This alternative does not need a silencer on the intake which lowers equipment costs. A bypass valve, however, does not allow the system operator to dilute the airstream at the stack to reduce the concentration to below the lower explosive limit.

- <u>Sample Port.</u> The sample port design is specific to the sample container and the field procedure for collecting samples. It may have a septa fitting for direct syringe insertion, or it may be as simple as a hose barb for a piece of plastic tubing. The sample ports may have to be fabricated for the specific sampling devices.

- <u>Flow Meter.</u> Averaging pitot tubes or regular pitot tubes are generally used to measure air flow. Pitot tube manufacturers specify that a number of transverse readings are collected at different points within the air stream when pitot tubes are used. Averaging pitot tubes are designed to only require a single reading. In general, manufacturers recommend 10 or more straight unobstructed pipe diameters upstream and five or more diameters downstream of the pitot tube or averaging pitot tube. (Example: A pitot tube on a 2-inch pipe requires 20 straight unobstructed inches upstream of the pitot tube and 10 inches downstream.) A minimum of approximately 1,000 feet per minute of air velocity is needed to get accurate readings, therefore, the pipe diameter may need to be reduced at the location within the manifold where the flowmeter is installed.

  Orifice plate meters are also acceptable if they are installed in accordance with manufacturers specifications.

  Hot wire anemometers are also used in soil venting systems, but may be inaccurate if there are liquid water droplets in the air stream. These devices must be classified as "intrinsically-safe" when working with ignitable contaminants.

  For a discussion of flow meters, see Ginesi and Grebe (1987).

- <u>Vacuum.</u> Measure the vacuum with a manometer, a magnehelic, or a vacuum gauge. Most soil venting systems operate at a low enough vacuum that the measurements are read in inches of water column. Higher vacuum units may use inches of mercury as vacuum measurement units. Note: 1 inch of Hg = 13.55 inches of water column. Vacuum gauges should be to two digits of accuracy.

- Temperature. The temperature is usually read with a bimetal dial-type thermometer that is installed through a hole in the manifold pipe.

- Relative Humidity or Dew Point. Relative humidity or dew point measurements are not required, but may be beneficial when evaluating moisture content for biodegradation or carbon filters. Use a wet bulb thermometer or digital meter to measure relative humidity or dew point.

4.5 Water Trap.

A water trap (also called a separator tank or demister) may be necessary. In general, a water trap should be included in the design if the up-hole air velocity in the air-extraction wells is greater than 1,000 feet per minute or if a rotary lobe blower is used. If in situ air sparging (see *Guidance on Design, Installation and Operation of In Situ Air Sparging Systems*) is used, a water trap should be included because the sparging process can cause water to enter the air-extraction wells.

Water trap configurations include the following:

- A vertical pipe, cap, and tee in a manifold that is capable of holding less than 5 gallons;

- A large tank in line with the manifold;

- An engineered trap that uses a cyclone action to separate the water droplets from the air stream.

It is necessary to address the water that accumulates in water traps. If a groundwater extraction system is also used at the site, the accumulated water can be added to the pumped groundwater that is treated and/or disposed of. If no groundwater extraction system is used at the site, it is necessary to arrange for proper disposal of the water.

4.6 Blower (or Vacuum Extractor) Type and Size.

The following are three common types of blowers for soil venting systems:

- Centrifugal. Centrifugal blowers perform best in high flow, low vacuum applications. Advantages of centrifugal blowers include low equipment cost, low electrical costs, and minimal maintenance requirements. The main disadvantage is that they cannot develop a high vacuum. These units are only usable in sand and gravel environments or in trenched systems that have a very high length of perforated pipe. Due to the small vacuum they develop, long manifold systems may need large-diameter manifold piping to reduce pipe friction.

- Regenerative. Regenerative blowers develop higher vacuums than centrifugal blowers (up to 8 inches of mercury). These are the most common blowers for smaller sand and gravel sites.

- Rotary Lobe. The rotary lobe blowers are capable of producing very high vacuums (up to 15 inches of mercury is not uncommon), which is the primary advantage of this blower type. Disadvantages include higher cost, high electrical demands, high noise levels, and frequent maintenance requirements. Soil venting systems in silt or clay soils require the rotary lobe's high vacuums.

Figure 4-4 shows performance curves for these three blower types. Each curve on the figure is for comparison purposes only; larger and smaller models are available for each blower type. It is apparent that the rotary lobe units have a very high vacuum capability and are the best choice for sites that need a high vacuum. It is also readily apparent that a centrifugal unit is the best choice for sites that have high-flow rates that are achievable with a low vacuum. Regenerative blowers have characteristics between the rotary lobe and centrifugal units.

Other blower types, such as liquid ring, may also be used when conditions warrant.

The type and size of the blower determines the electrical requirements. Some of the rotary lobe units are large enough to require three-phase power.

A discharge muffler should be used to reduce noise for larger soil venting systems, especially systems that use rotary lobe blowers.

Size the circuit breaker for the motor to trip the circuit breaker if the rotor is locked. The motor and all controls should be explosion-proof if there is ANY POSSIBILITY of igniting the contaminants. Sensors should be intrinsically-safe and controllers need to be in explosion-proof enclosures or located in non-hazardous locations.

Rotary lobe blowers and other blower types that have close tolerance clearances should be equipped with a particulate air filter. Regenerative blowers may also need an air filter. A centrifugal blower is usually best used without an air filter because the filter restricts air flow.

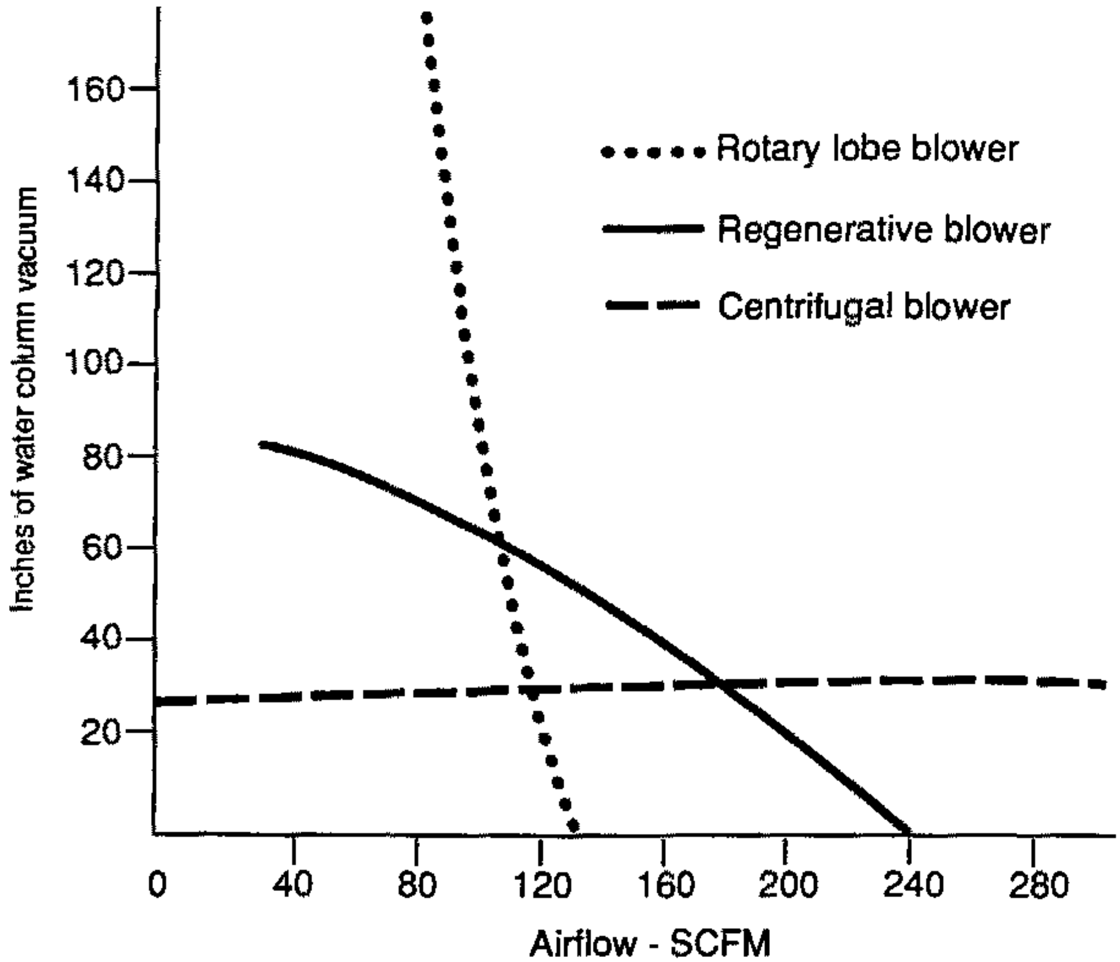
It is recommended that the discharge stack be constructed with CPVC or other materials that retain strength at high temperatures on the higher vacuum systems. The higher discharge temperatures on the high vacuum systems may weaken PVC. Most blower manufacturers include methods for estimating the discharge temperature from the blower. If the discharge temperature reaches approximately 140 degrees fahrenheit (or higher), PVC may become too weak. In general, PVC is acceptable on all centrifugal blower systems. A drain at the base of the stack is useful to drain any accumulated moisture.

## 4.7 Emission Control Devices.

If emissions exceed the table value of any contaminants listed in Table 3 of Chapter NR 445, then 95 percent contaminant removal or destruction capability is required. Sources requiring air treatment devices that exceed table values in Table 3 need DNR Bureau of Air Management permits. The following are three types of air treatment devices for controlling

Figure 4-4

**Performance curves for three types of blowers**




Notes:

Centrifugal blower type shown is a New York model 2004A at 3500 rpm

Regenerative blower type shown is a Rotron model DR707

Rotary lobe blower type shown is a M-D Pneumatics model 3204 at 3000 rpm

The DNR does not endorse these blower manufacturers; performance curves shown for discussion purposes only emissions from petroleum projects:

- Incineration. Incineration is most cost-effective with high contaminant levels because the contaminants provide a significant amount of fuel for the incineration process.

- Catalytic Destruction. Catalytic units generally are used with high contaminant levels, but lower contaminant levels compared to the incineration units. If the contaminant level is too high, the catalyst becomes too hot and burns out. Pilot test data is necessary to assess if it is appropriate to use catalytic destruction units.

- Granular Activated Carbon (GAC). GAC units are not used frequently in Wisconsin compared to other states. At the levels where GAC is most cost effective, the emission limits in Wisconsin generally allow a direct discharge. If carbon filters are used, a device to dehumidify the air may be needed.

Other treatment devices, such as bio-filters or internal combustion engines may also be acceptable to the DNR on a site-specific basis. This should be discussed with the DNR project manager before purchasing and installing.

Greater blower-pressure capacity is needed with off-gas control systems because of the flow restriction within the system. Manufacturers of off-gas control equipment may provide pressure and flow requirements for equipment.

## 4.8 Air Injection.

Some projects use air injection to direct air flow through a specific part of the contaminated soils. It is usually used to help create more flow near the capillary fringe, which is often the hardest part of the soil column to remediate.

In general, do not use air injection if the injected air temperature is lower than the normal groundwater temperature. The colder air reduces the volatility of the contaminants and also reduces the biodegradation rate.

### 4.8.1 Passive Vents.

Some projects use passive air injection to help direct air flow through contaminated zones. Passive air vents are venting wells that inject air under atmospheric pressure without using a blower. The driving force is the induced vacuum in the subsurface that is created by the soil venting system. Only a small percent of the air that is extracted from a soil venting system is from passive injection. Air-flow rates in passive injection wells typically cannot be accurately quantified because of the low rate of air flow into the well. The wells can be constructed for the purpose of air injection, uncapped water-table monitoring wells, or air-extraction wells that are valved off of the manifold and open to the atmosphere.

Generally, passive injection is not very effective. However, converting existing wells to passive injection may be appropriate if useable wells already exist at the site.

### 4.8.2 Forced Injection.

In some cases, clean (contaminant-free) air is injected into the soil through a series of wells or trenches. Designers should justify the use of forced injection in the workplan on a site-specific basis.

To assure that the injected air is extracted by the extraction system, the injection rate should be no more than one quarter of the extraction rate. If the proposed ratio of injection to extraction is greater than 0.25, provide justification in the work plan. Air injection wells must inject air at very low air-flow rates if they are within the zone of contamination. Otherwise, they may force contamination outward to uncontaminated areas or through the ground surface. If air injection is proposed within the zone of contamination, air modeling is needed to evaluate flow paths.

Air that is oxygen deficient should not be injected at sites with aerobically degradable contaminants because it could slow the biodegradation rate.

To assure that there is no positive pressure in the subsurface near basements or other structures where vapors may collect, gas probes may be needed with air injection on a site-specific basis.

It is possible to heat air to increase the volatility of the contaminants. If heat is added, the temperature must be low enough so that it does not disinfect the soils, which adversely affects natural biodegradation.

4.8.3 In Situ Air Sparging.

Air sparging is a form of forced air injection into the saturated zone. If air sparging is used, include a water trap in the design of the soil venting system. The sparging process may cause excessive amounts of water to enter the air-extraction wells. See *Guidance on Design, Installation and Operation of In Situ Air Sparging Systems* for a detailed discussion of air sparging.

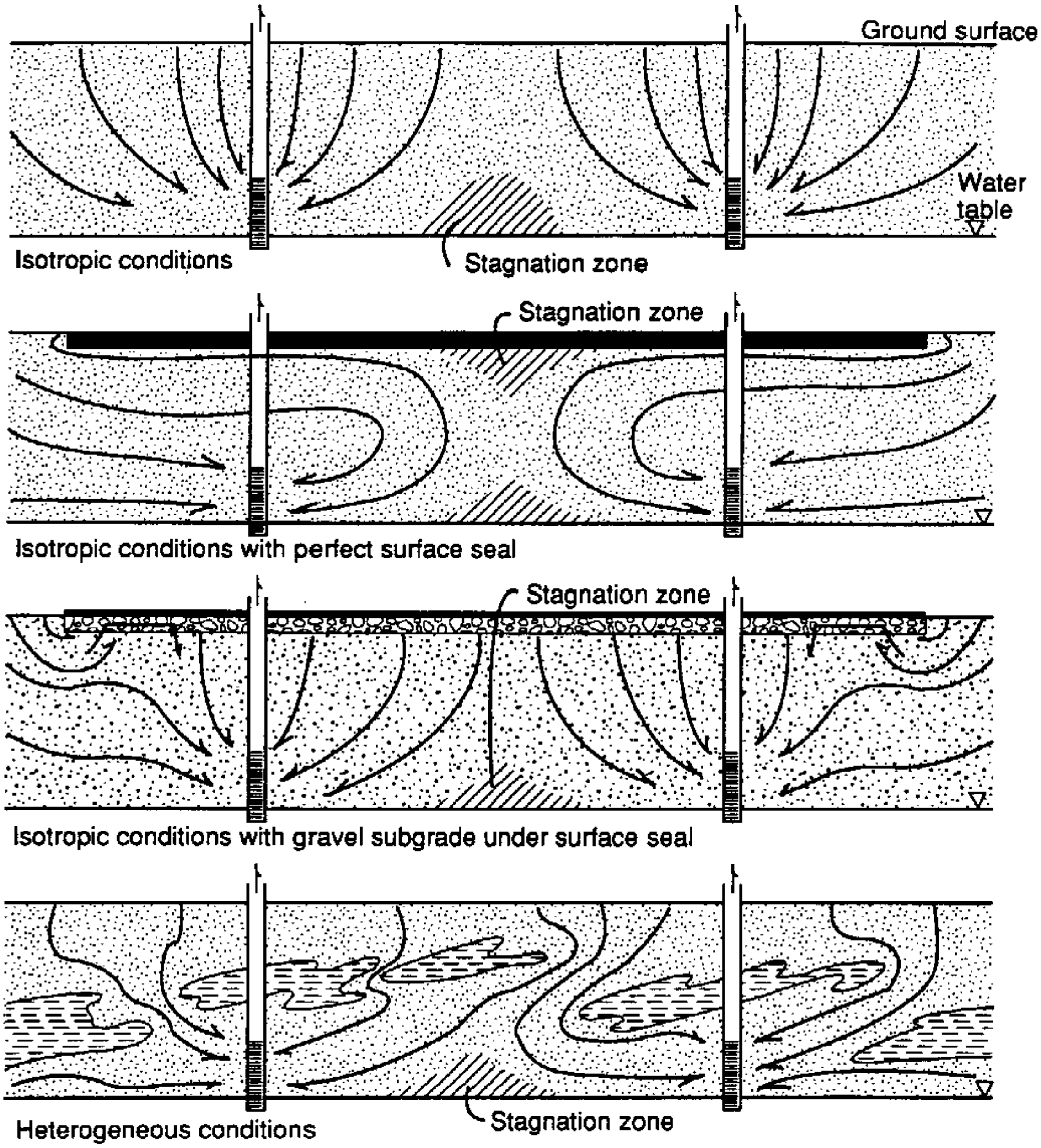
4.9 Other Design Considerations.

4.9.1 Surface Seal.

A surface seal, such as a pavement layer, is often recommended in the literature. A surface seal directs air flow horizontally and restricts vertical air flow from the ground surface near the extraction well(s). Sites that are highly stratified, or sites that have a high Kh/Kv ratio do not need surface seals because the natural geologic conditions force the air-flow patterns horizontally. Sites without a high Kh/Kv ratio or stratification may benefit from a surface seal. Figure 4-5 indicates air-flow patterns with a quality surface seal, a poorly constructed surface seal and no surface seal.

If surface seals are used, it is important to construct them properly. There is usually a gravel subgrade below pavement. Significant quantities of air can flow horizontally through a highly permeable subgrade toward the extraction well(s), even though the subgrade is less than a foot thick. The propensity of the subgrade to act as a short circuiting route is directly proportional to the ratio of horizontal permeability of the subgrade to the vertical permeability of the underlying soils.

## Figure 4-5
## Typical air flow patterns




Note: Not to scale, for conceptual discussion purposes only
Flow is three dimensional. Recharge also occurs in the dimension perpendicular to the drawing.

Surface seal modeling is described by Krishnayya et al. (1988). In the Krishnayya article, Figure 9 indicates the increased horizontal flow and reduced, near-extraction well recharge that occurs with a very high quality surface seal.

It is difficult to properly install a quality surface seal, especially in finer-grained soils, because of the potential for horizontal short circuiting immediately below the seal.

4.9.2 Stagnation Zones.

Stagnation zones are areas that have little or no air flow because two or more wells are pulling the air in different directions. This is very similar to the groundwater stagnation points that develop downgradient of a groundwater extraction well.

Remediation will generally occur at slower rates in stagnation zones than at other areas of a site due to the low velocity of air flow through these soils. Because stagnation zones are created by the location of one air-extraction well relative to another well (or possibly by other site features), increasing the total blower flow rate is unlikely to remove stagnation zones.

Since stagnation zones exist in all soil venting systems with multiple wells, efficient system operation requires periodic changes in flow rates from each well. Designers should change flow rates from different wells over time, so the stagnation points are not always in the same locations. Initially, a soil venting system can be operated with all air-extraction wells on-line. As some wells "clean up" contamination, these wells can be converted to passive injection wells or valved off.

As discussed in Subsection 2.1, stagnation zones can also be anaerobic zones where aerobic biodegradation is slowed due to limited oxygen.

4.9.3 Vacuum-Enhanced Product Recovery.

Vacuum-enhanced product recovery refers to using product-recovery wells for air extraction, groundwater extraction, and liquid-phase product recovery. There is evidence in the literature that extracting air from the product-recovery wells increases the rate of liquid product recovery. The thickness of the smeared zone is also reduced because the vacuum tends to lift the water table, counteracting the drawdown of the cone of depression that is created by pumping. The *Guidance for Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems* provides a detailed discussion of the advantages and disadvantages of vacuum-enhanced product recovery.

In practice, the vacuum that is applied to the recovery well should not be greater than the drawdown that is created by pumping. This minimizes the smeared zone thickness.

> Example: Assume that the submerged portion of the recovery well is 100 percent efficient to groundwater flow, and the unsaturated screen portion of the well is 100 percent efficient to air flow. A 10 gpm pumping test indicates that the specific capacity of the recovery well is 12 gpm per foot of drawdown. The hydraulic conductivity determined from the pumping test is used to calculate the capture zone. It is determined that 50 gpm is required to capture the plume.

The predicted drawdown at start-up of the recovery system is:

$$\frac{50 \text{ gpm}}{12 \text{ gpm per ft of drawdown}} = 4.17 \text{ feet or 50 inches of water column}$$

Therefore, the maximum vacuum that should be applied to the well is 50 inches of water column.

If the specific capacity is unknown, it can be estimated. See Attachment 3 to the *Guidance on Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems* for estimating drawdown.

Volatilization of liquid product will take place because vacuum-enhanced product recovery passes the air flow through a well that has liquid phase product in it. This raises the possibility that the air emissions may be quite high, possibly exceeding air emission limits. Designers should evaluate the cost efficiency on a site-by-site basis to compare the costs of air emission control with the advantages of vacuum-enhanced product recovery.

Also see Subsection 4.9.4 in the *Guidance on Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems* for a discussion of well design.

4.9.4 Groundwater Extraction from Air-Extraction Wells.

In some situations, air-extraction wells may also be used for groundwater extraction. In most cases, air-extraction wells are used for groundwater extraction because they are in a convenient location and drilling costs are reduced by using one well for two purposes. In other cases, the vacuum is used to increase the yield of the well. Occasionally, the water is pumped out of the well to counteract the effects of upwelling, and to lower the groundwater table to expose the smeared zone to air flow (Johnson, et al., 1992).

If a well serves these two purposes (groundwater and air extraction), it must be designed for both purposes. Construct the lower portion of the well that is used for groundwater extraction with a well screen and filter pack sized for groundwater extraction. If the slot size or filter pack is too large, the well may pump sand. See *Guidance for Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems*.

If the formation is highly permeable, enormous quantities of groundwater have to be extracted to significantly lower the water table. If the primary purpose of groundwater extraction is to lower the water table to expose contaminated soil to the air flow (and not to extract dissolved phase contaminants), it may not be cost-effective to pump and treat groundwater at some sites. In this situation, in situ air sparging or other techniques may be preferable. See *Guidance on Design, Installation and Operation of In Situ Air Sparging Systems*.

4.9.5 Enhanced Biodegradation of Petroleum Compounds in Soil.

Petroleum based contaminants readily biodegrade during operation of a soil venting system. Biodegradation for petroleum projects is an important part of the remediation process because a significant quantity of the contaminants are destroyed by natural bacteria ( Hinchee and Miller, 1990 and Miller, 1990). Generally, the degradation rate is much faster under aerobic conditions than anaerobic conditions. The level of oxygen is usually the limiting factor under static conditions. The venting system provides oxygen when using active venting, and moisture or nutrient supply become the limiting factors.

To quantify biodegradation rates based on oxygen or carbon dioxide emissions, it is necessary to measure background oxygen and/or carbon dioxide in the soil. Ideally, the background measuring point is one or more upgradient water-table well(s), and/or gas probe(s) that are located in an uncontaminated part of the site which is/are not used for air extraction. Measuring the ambient background levels of oxygen and/or carbon dioxide in the soils is necessary whenever oxygen or carbon dioxide samples are collected because the ambient levels may change seasonally (Wood et. al., 1993; Solomon and Cerling, 1987). The change in the carbon dioxide or oxygen levels, relative to background, is the value to use when quantifying biodegradation rate. Attachment 1 includes a sample method to quantify the biodegradation rate based on carbon dioxide.

The advantage to using carbon dioxide measurements to measure biodegradation is that carbon dioxide can be quantified with a high level of precision at very low levels. It is difficult to precisely measure a very small oxygen deficiency. Two disadvantages to measuring biodegradation with carbon dioxide are that carbonates in the soil can dissociate or precipitate, and carbonic acid can form which reduces the accuracy of the estimate. Generally, the literature indicates that practitioners prefer to use oxygen to quantify biodegradation, instead of (or in addition) to carbon dioxide because oxygen is less affected by the soil geochemical properties.

Also, see Subsection 5.1 for a discussion of oxygen breakthrough.

4.10 Soil Venting System Design Report.

In some cases, the design of a soil venting system is included in a comprehensive report with the results of a pilot test. In other cases, the design is submitted separately. A report that includes the design of a soil venting system should include the following:

<u>Discussion.</u>

- A discussion of the system design and a desc ription of capabilities for remediating the soil at the site. Include a brief discussion of the geological conditions at the site.
- Describe the logic used to determine well placement and spacing.
- Details of the air-extraction well design include the screen length and diameter, slot size, depths and specification of the filter pack and seals, and the drilling method. If multiple well depths are needed, discuss the logic for determining well-screen depths.
- Justify a horizontally-trenched system if it is proposed in the design report.

- Details of the manifold design including pipe type, diameter, and a description of instrumentation for measuring flow and vacuum. Indicate the depth of the manifold, if it is buried.

- Blower specifications including total anticipated air-flow rate, vacuum levels, type and size of blower.

- Discuss the Wisconsin air emission limits, anticipated flow rates, pilot test results, and the possible need for air emission control devices. If air emission control is proposed, discuss the type of system and the status of any air permitting requirements. The discussion should include an estimate of total VOCs in the unsaturated zone.

- Discuss options for water disposal, if a water trap is proposed.

- The height of the stack.

- Monitoring plan.

    — Non-petroleum sites. There are no specific requirements for non-petroleum sites. The designer should propose a monitoring plan in the workplan. In most cases, reporting frequency and sampling frequency will be the same as the one in Attachment 1. Sampling parameters, methods, etc. are determined on a site-specific basis.

    — Petroleum sites. Attachment 1 is a generic plan for petroleum sites. The designer should prepare a site-specific plan based on Attachment 1. Deviations from Attachment 1 should be identified and justified. If a photoionization detector is used, see Robbins et al, (1990).

<u>Figures.</u>

- A map of proposed well locations drawn to scale. The map should include the following:

    — locations of proposed and existing air-extraction wells;

    — locations of the manifold, instrumentation, and sample port;

    — location of blower and other equipment;

    — suspected and/or known source location(s) (if differing contaminant types are present at a site, the locations should identify the contaminant type);

    — extent of soil contamination;

    — paved areas, buildings, and structures that may act as a surface seal or an infiltration barrier;

    — buried utility trenches that may act as zones of higher permeability;

- scale, north arrow, title block, site name, and key or legend; and

- any other pertinent site information.

- A current water-table map and a table of water levels. Indicate the date of water-level measurements on the map.

- A process flow diagram indicating piping network, instrumentation and key components.

Appendices.

- Engineering calculations for determining the well spacing and zone of influence measurements from the pilot test, if any. Clearly state any assumptions. Hand written (if legible) calculations are acceptable. Include the initials or name of the author and the quality control-checker. Include references for any formulas used.

- If an air-flow model is used, include the results of the model and any assumptions that the model uses.

- Engineering calculations predicting the total air-flow rate. Include the performance curve that is provided by the manufacturer of the blower. Note the manufacturer and model of the blower. Note the rpm of the blower if it is belt driven.

- A description of sampling procedures and analytical methods.

- Form 4400-120 for LUST sites.

# 5.0 Operation of a Soil Venting System.

## 5.1 Overview.

Operation of a soil venting system requires ongoing monitoring and system adjustment to maximize performance.

Immediately after start-up, VOCs associated with the glue from the manifold are discharged from the system. Samples for compound-specific testing should not be collected until at least one or two hours after start-up to allow the VOCs from the glue to be discharged from the system.

For safety purposes, air should not be discharged from the stack at or above the lower explosive limit. The use of a dilution valve may be necessary at some sites during the pilot test or upon start-up.

Immediately after start-up of a soil venting system, a large mass of VOCs are rapidly removed because the concentration of VOCs in the extracted air is very high. During this initial phase, air-flow advection through the coarse-grained soils rapidly extracts VOCs from coarse-grained soil. If there is a significant amount of stratification or other geologic heterogeneities in the site soils, the extraction rate will rapidly decline to a non-zero asymptotic rate of extraction. Buscheck and Peargin (1991) and Johnson et al. (1990) have an excellent discussion about the reduced extraction rate over time.

Small fluctuations in the extraction rate are normal with soil venting systems.

A slow contaminant-extraction rate may occur even if soil sample results indicate there is a significant amount of contaminants remaining in the soil. The slow extraction rate can be due to a number of factors:

- Fine-grained soil units or layers readily retain significant quantities (relative to coarser-grained units) of contaminants. Clay soils will commonly retain contaminants at concentrations that are orders of magnitude higher than the coarser-grained soils.

- The fine-grained soil layers in stratified soils are generally parallel to the direction of the air flow. Therefore, the pressure gradient induced by the vacuum does not force the air flow (and VOCs) through the fine-grained soil layers. Instead, the air flow is around the fine grained layers. In many cases, the VOCs diffuse very slowly out of the fine-grained soils into the coarser layers for advective transport to the extraction well.

- Even if the geology is largely homogenous, the distribution of the most highly contaminated soil in the unsaturated zone is typically near the water table. The extraction of VOCs is slowed in the most highly contaminated soil because the air-flow rate is relatively slow near the capillary fringe due to the reduced effective porosity to air flow.

- Remaining contaminants are relatively non-volatile. See Subsection 2.1 for a discussion of vapor pressure and Raoult's Law.

The following are reasons that extraction rates can increase significantly:

- A new loss of product.
- Higher air temperature raises the volatility of contaminants. If there is a high air-flow rate and a low air residence time in the soil, the ambient temperature in the warmer months can increase the volatilization rate. Use temperature trends over time at the wellheads to assess this effect.
- Water-table fluctuations can expose additional contamination that was previously submerged.

After the system has operated for a few months to a few years, the emissions fall to a very low level, relative to initial concentrations. At this point, significant contaminant reduction at petroleum sites is due to biodegradation. In these cases, the soil venting systems provide oxygen to the bacteria. Aerobic biodegradation is not significantly inhibited until oxygen levels have dropped below 5 percent. See Attachment 1 for a sample method for determining the biodegradation rate based on carbon dioxide.

It is possible that oxygen deficiency in stagnation zones could exist, even if extracted air is quite low in carbon dioxide and high in oxygen because of dilution. If most of the air passes through relatively clean soil and only a small amount of the extracted air passes through biologically active contaminated zones, there could be oxygen deficient parts of the site that go undetected because of oxygen breakthrough. Therefore, at larger sites that have the potential for oxygen breakthrough, it may be prudent to install gas probes near predicted stagnation zone locations to assess oxygen and carbon dioxide. Gas probes in those locations may also be useful for assessing contaminant concentrations or methane.

On a site-specific basis, if significant biodegradation rates are necessary to complete the cleanup (for a site with significant levels of aerobically biodegradable, but relatively non-volatile compounds), an evaluation of methane may also be needed to assess the presence of anaerobic zones.

Biodegradation requires a high moisture content in the soil. During colder months the atmospheric dew point is likely to be lower than the soil temperature. In this case air that is drawn through the ground can remove significant amounts of moisture from the soil. When the atmospheric dew point is higher than the soil temperature (which occurs occasionally during the summer months) drying the soil with an excessive air-flow rate is less likely.

Because biodegradation requires a fairly high moisture content, it is possible that using a slower air-extraction rate late in a project is more productive than a high rate of air flow. A high air-flow rate may remove too much moisture and inhibit bacteriological activity. Opening the dilution valve to reduce the flow rate may be necessary to reduce the drying effects of the air flow. Another option is to use a timer to operate the system for only a few hours per day. If the blower is very large, it may be practical to purchase and install a smaller blower because of reduced electrical demand and/or reduced maintenance costs.

Stagnation zones that develop between the air-extraction wells in multi-well systems inhibit the ability of a soil venting system to operate efficiently throughout the entire site. Changing the flow rates from different wells on a periodic basis improves overall system performance.

Some consultants use temporary or permanent gas probes to evaluate air quality within the subsurface at points other than the extraction wells. Water-table wells can also be used for air sample collection. If the trend of air samples from the probe(s) over time indicate that high levels of VOCs and/or biodegradation products (carbon dioxide or methane) are remaining, it is a clear indication that the part of the site where the probe(s) is/are located is not being cleaned up. Either the probe(s) is/are located in or near a stagnation zone, or something else is not working correctly.

Some operators cycle soil venting systems by operating the system intermittently. In the literature, there is no clear advantage or disadvantage to cycling soil venting systems. If the consultant chooses to cycle the system, the sampling plan should acknowledge that cycling causes inconsistent contaminant-extraction rates over time. Increased sampling frequency may be necessary to accurately evaluate the extraction rate.

## 5.2 As-Built Submittal.

After a soil venting system is constructed, the "as-built" information should be included in a report. Since most of the information is in a design report, a separate submittal is not always necessary. The "as-built" information can be included in the first progress report after start-up. The "as-built" submittal should include the following:

- Any deviations from the specifications in the design report.
- A map of actual-well locations drawn to scale. The map should include the following:
  - locations of existing air-extraction wells;
  - the manifold, instrumentation, and sample port locations;
  - location of blower and other equipment;
  - suspected and/or known source location(s) (if differing contaminant types are present at a site, the contaminant types should be identified per location);
  - zone of soil contamination;
  - paved areas, buildings, and structures that may act as a surface seal or an infiltration barrier;
  - buried utility trenches that may act as zones of higher permeability;
  - scale, north arrow, title block, site name, and key or legend; and
  - any other pertinent site information.
- A table with the air-flow rate, vacuum levels, and temperature at all sampling locations at start-up.

- A table of water levels in all wells.
- Air-extraction well construction diagrams.
- Boring logs and any other documentation required by Chapter NR 141.
- Any other pertinent information.

5.3 Reporting.

The reporting frequency for most sites are as follows:

- Petroleum sites. As described in Attachment 1. The DNR project manager may specify a different reporting schedule.
- Non petroleum sites. The reporting frequency will be established on a site-specific basis by the DNR project manager.

Progress reports should be sequentially numbered starting with the first report after the remediation system start-up. In general, the progress reports do not need to be detailed documents. In most cases, only one or two pages of text in a letter format with supporting tables and figures is sufficient.

The progress reports should include the following information:

- A brief discussion of the progress of the remediation system including:
  - Contaminant extraction totals to date in pounds or gallons of contaminant(s) removed.
  - System operation details, periods of shut down, equipment malfunctions, etc.
  - Overall evaluation of the system effectiveness.
  - Recommendations for future activities, if appropriate.
- Graphs that include data through the life of the project are very useful to evaluate trends. Graphs may include:
  - Total contaminant removal graph with time on the horizontal axis and cumulative contaminant removal on the vertical axis. The consultant may provide a graph with this information on a per well basis for smaller systems (four wells or less), but a graph on a per well basis typically is not required unless requested by the DNR.
  - Contaminant level time graph, with time on the horizontal axis and mass per volume values on the vertical axis. A graph on a per well basis is recommended for smaller systems, but typically is not required for larger systems.
- Tables that include data throughout the project are useful to

establish trends. Include the following tables:

- Field data and flow-rate measurements.
- Contaminant levels and extraction rates at each sampling point. (This table can be combined with the field data table if space allows).
- Table of water levels and product levels or thicknesses.

- If analytical data is available from a laboratory, include the lab reports.
- A discussion of sampling procedures, analytical procedures, etc. is not required, but include a reference to the report that lists the procedures.
- Any other pertinent information or data.

5.4 Case Close Out.

When to Consider a Site for the Close Out Process. The volatilization rate on a pounds-per-day basis needs to be calculated prior to sampling before terminating operation of a soil venting system. If the contaminants are aerobically biodegradable, the sum of the current rate of both volatilization and biodegradation — on a pound-per-day basis — should be included in the mass removal calculation. It is premature to consider the site for case close out if the mass-removal rate is significant, relative to the remaining contamination mass.

Methods For Determining the Biodegradation Rate. To determine the biodegradation rate, the DNR recommends the methods discussed in the April 5, 1991 guidance on air monitoring for LUST sites, or other scientifically-valid methods, such as a soil respiration test. Background carbon dioxide levels, oxygen levels, or both are necessary to evaluate the biodegradation rate. High carbon dioxide levels do not always mean a high biodegradation rate.

Site-Specific Data Necessary to Consider Terminating Operation of a Soil Venting System. The DNR will evaluate soil venting system termination on the basis of confirmation borings. Soil samples need to be analyzed for the appropriate contaminants, as follows:

- For petroleum contaminated sites, soil samples for PVOCs and GRO and/or DRO need to be collected as appropriate for the site.
- For non-petroleum contaminated sites and sites that have a mixture of petroleum and non-petroleum contamination, the system operator must use sampling protocols that are appropriate for the site. The system operator should consult the DNR project manager to determine appropriate laboratory methods.

Number of Soil Borings Per Site. The number of soil borings will vary from site to site. Generally, two soil borings are the minimum number to determine a soil venting system operation termination. For larger, more complex sites, approximately one soil boring for every three air-extraction wells is sufficient. In some cases, site-specific factors may determine more soil borings that need to be sampled (e.g., a site where the water table is very deep). In such situations, reducing the number of borings, or reducing the depths may be appropriate.

Soil Boring Locations. The DNR recommends that soil borings be located in a minimum of two places:

- Mid-point between the air extraction wells because these locations are most likely to be the areas least influenced by the systems (e.g., stagnation zones); and

- In the zone(s) that contained the highest initial contamination.

Sample Depth. The DNR recommends that system operators utilize the following guidelines when taking samples:

- Samples should be collected at 2.5 feet intervals to the water table for field screening with a field headspace test. The headspace readings should be included on the boring logs.

- Two samples should be collected per boring for analytical testing unless otherwise directed by the DNR, or the water table is less than 10 feet below the ground surface. If the water table is less than 10 feet below the ground surface, one sample is generally sufficient. In most cases, one sample should be collected at the water table and another at the zone that exhibits the highest levels of contamination based on field screening. If no samples exhibit any headspace readings, sample at the water table and approximately 5 to 7.5 feet above the water table.

Further Action the DNR May Require. Based on the residual levels of soil contamination and the data provided on the asymptotic level, the DNR project manager may deem the case appropriate for close out. However, the DNR may direct the responsible party to conduct other actions based on site-specific characteristics, including one or more of the following:

- Continue operating the soil venting system and/or modify the system;

- Monitor the soil or groundwater, rather than continue operating the soil venting system;

- Construct an engineering control; or

- Conduct a remedial options analysis to identify other appropriate site-specific actions.

Project close out criteria are described in Chapter 10 of the *Guidance for Conducting Environmental Response Actions.* Note: Chapter 10 was not completed when this document was finalized.

If a system operator has any questions about when to recommend a case for close out, contact the DNR project manager at sites that are actively managed by the DNR. At sites that are not assigned DNR project managers, contact the appropriate Emergency and Remedial Response Unit Leader in the district where the site is located.

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Wisconsin DNR - Guidance on Design, Installation and Operation of Groundwater Extraction and Product-Recovery Systems.

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