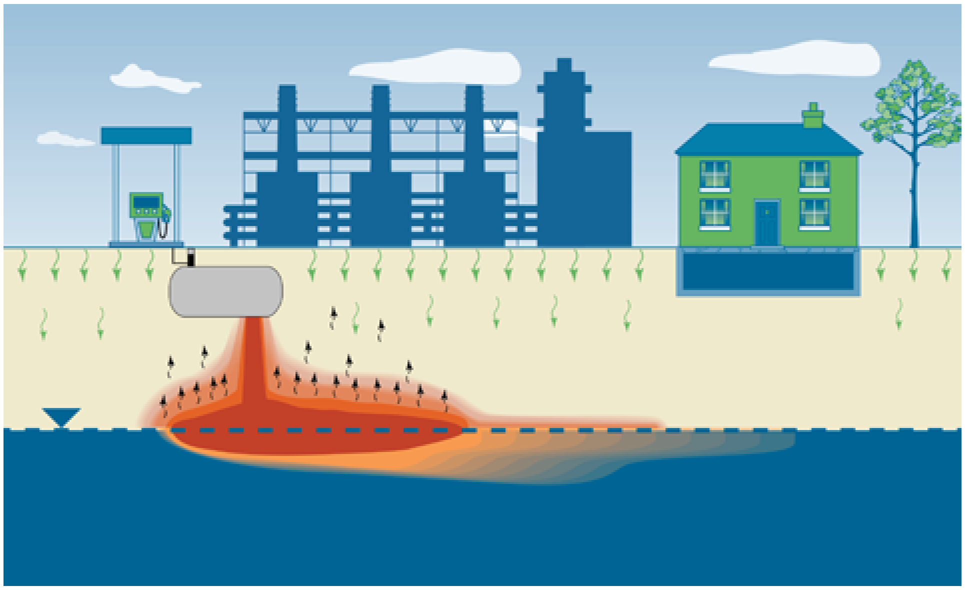
Guidance Document

Petroleum Vapor Intrusion

Fundamentals of Screening, Investigation, and Management



October 2014

Prepared by
The Interstate Technology & Regulatory Council
Petroleum Vapor Intrusion Team

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PVI-1

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50 F Street NW, Suite 350, Washington, DC 20001

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PVI Team, August 2013.

Photo courtesy of: Alyson Boyer Rode of Alycat Photo & Video Services.

First row, seated (left to right): Richard Rago, Dottie Lofstrom, Raymond Montero, Laura Trozzolo, Robin Davis, Sandra Gaurin, Nathan Lewis, Shannon Thompson, Lynn Spence, Frank Camera. **Second row (left to right):** Lila Beckley, Diana Marquez, James Lingle, John Boyer, Mary Yelken, John Menatti, Bruce Bauman, Josh Nagashima. **Third row (left to right):** George DeVaull, Jim Whetzel, Loren Lund, Catherine Regan, Christopher Brown, David Folkes, Mary Siders, Chris Mulry, Matt Williams, David Bennett, Eric Blodgett. **Fourth row (left to right):** William R. Chapman, Michael Hyman, Todd Ririe, J.R. Capasso, Eric Nichols, Ben Martich, Tom Higgins.

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EXECUTIVE SUMMARY

State environmental agencies across the country have consistently listed vapor intrusion as a high-priority topic for sites contaminated with volatile organic compounds. This broad group of organic chemicals includes chlorinated compounds, as well as non-chlorinated compounds such as petroleum hydrocarbons. When contaminant vapors from contaminated soil and groundwater migrate upward into overlying buildings and contaminate indoor air, the process is known as vapor intrusion. The results of vapor intrusion can negatively affect the health of building inhabitants. ITRC's 2007 guidance document, *Vapor Intrusion Pathway: A Practical Guideline*, primarily focused on chlorinated vapor intrusion (CVI) and did not specifically address the fundamental difference in the behavior of petroleum hydrocarbons and vapors from chlorinated organic compounds in the subsurface. This subset of vapor intrusion, or petroleum vapor intrusion (PVI), is the focus of this guidance document.

The fundamental difference between CVI and PVI is biodegradation. Unlike vapor intrusion associated with chlorinated compounds, vapors from petroleum hydrocarbons rapidly biodegrade as they migrate through unsaturated, vadose-zone soils, greatly limiting the potential for the PVI pathway to be complete. Because of the rapid biodegradation of petroleum hydrocarbon vapors, compared to slower anaerobic degradation of chlorinated compound vapors in the subsurface, the number of sites with a completed vapor intrusion pathway is significantly fewer than the number at sites contaminated with chlorinated compounds. Biodegradation of petroleum hydrocarbons by indigenous microorganisms is characteristic of nearly all unsaturated soils. As a result, the potential for biodegradation of petroleum hydrocarbon vapors can be used to evaluate whether a site contaminated with petroleum compounds requires additional investigation of the vapor intrusion pathway.

This ITRC guidance document specifically addresses the need for guidance on the effective screening, investigation, and management of vapor intrusion at sites contaminated with petroleum hydrocarbons. A number of state regulatory agencies and the U.S. Environmental Protection Agency have used various forms of screening tools to evaluate the petroleum vapor intrusion pathway, often without clear, scientific basis. Until recently, empirical data were unavailable to justify an alternative approach. The guidance presents a method of screening petroleum-contaminated sites for potential vapor intrusion, and also provides the tools and strategies that offer the most efficient means of evaluating the vapor intrusion pathway at many different types of petroleum sites. The fundamental principle of this screening method is the "vertical screening distance," which was developed using empirical data from hundreds of petroleum-contaminated sites. Using screening distance to assess petroleum-contaminated sites allows managers to better focus scarce resources on sites with greater potential for petroleum vapor intrusion.

This document describes an eight-step process for screening, investigating, and managing sites contaminated with petroleum hydrocarbons to address the PVI pathway. In addition, the document provides:

- a detailed description of the differences between CVI and PVI
- a screening approach based on a peer-reviewed, empirical data set for evaluating the potential for vapor intrusion at petroleum-contaminated sites
- a discussion of the role of conceptual site models and multiple lines of evidence to support site decision making
- a review of investigative approaches (the "toolbox") and mitigation options
- an evaluation of the various types of petroleum-contaminated sites
- a discussion on community engagement at PVI sites

This guidance also complements the ongoing work of the U.S. Environmental Protection Agency, Office of Underground Storage Tanks, in addressing the PVI pathway.

By following the guidelines and recommendations outlined in this ITRC guidance document, the vapor intrusion pathway can be eliminated from further investigation at most sites where soil or groundwater is contaminated with petroleum hydrocarbons or where LNAPL is present.

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1.0 INTRODUCTION

Chemical contaminants in soil and groundwater can volatilize into soil gas and migrate through unsaturated soils of the vadose zone. Vapor intrusion (VI) occurs when these vapors migrate upward into overlying buildings through cracks and gaps in the building floors, foundations, and utility conduits, and contaminate indoor air. If present at sufficiently high concentrations, these vapors may present a threat to the health and safety of building occupants.

Petroleum vapor intrusion (PVI) is a subset of VI and is the process by which volatile petroleum hydrocarbons (PHCs) released as vapors from light nonaqueous phase liquids (LNAPL), petroleum-contaminated soils, or petroleum-contaminated groundwater migrate through the vadose zone and into overlying buildings. Fortunately, in the case of PHC vapors, this migration is often limited by microorganisms that are normally present in soil. The organisms consume these chemicals, reducing them to nontoxic end products through the process of biodegradation. The extent and rate to which this natural biodegradation process occurs is strongly influenced by the concentration of the vapor source, the distance the vapors must travel through soil from the source to potential receptors, and the presence of oxygen (O_2) in the subsurface environment between the source and potential receptors.

1.1 About This PVI Guidance Document

This PVI guidance document from the Interstate Technology and Regulatory Council (ITRC) builds on existing ITRC VI guidance (2007): *Vapor Intrusion Pathway: A Practical Guideline (VI-1)*. This guidance document serves as a companion to the VI-1 document and also as a standalone resource that provides information and tools specific to PVI. In addition, this guidance is designed to complement the United States Environmental Protection Agency (USEPA) PVI guidance currently under development by the Office of Underground Storage Tanks (OUST). As currently drafted, the USEPA OUST PVI guidance is limited to underground storage tanks (USTs) regulated by Subtitle I of the Solid Waste Disposal Act, whereas this ITRC guidance document applies to various types of petroleum sites and multiple PHC compounds.

This PVI guidance is intended for sites involving VI of PHC compounds and not chlorinated volatile organic compounds (CVOCs) or other aerobically recalcitrant non-PHC compounds. Refer to *Vapor Intrusion Pathway: A Practical Guideline (VI-1)* for guidance on CVOCs and non-PHC compounds.

1.1.1 What Is the Purpose and Scope of This Document?

This guidance provides regulators and practitioners with consensus information based on empirical data and recent research to support PVI decision making under different regulatory frameworks. The PVI assessment strategy described in this guidance document enables confident decision making that protects human health for various types of petroleum sites and multiple PHC compounds. This guidance also provides a comprehensive methodology for screening, investigating, and managing potential PVI sites. The screening method is applicable for different types of petroleum sites with variability depending on whether the site is a smaller site, such as a UST or aboveground storage tank (AST) gas station, or a larger petroleum industrial site, such as a terminal, refinery, pipeline, or manufactured gas plant (MGP) site.

Figure 1-1 conceptually displays three possible outcomes for the PVI pathway.

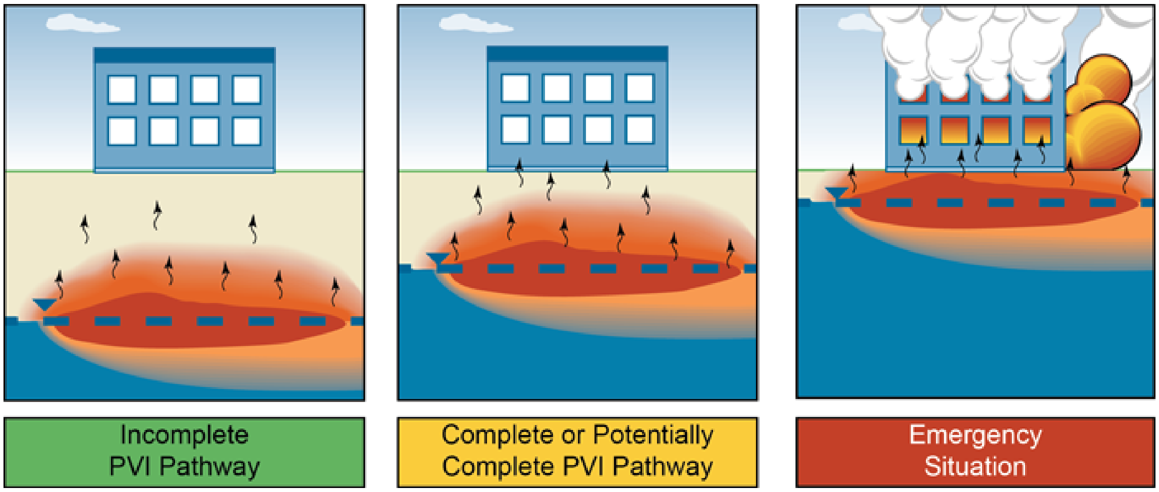


Figure 1-1. PVI conceptual outcomes.

This PVI guidance document applies only to the evaluation of the PVI pathway. Additional characterization and remediation of the PHC source, as well as evaluation of other exposure pathways and associated receptors, may be necessary under the rules and policies of the governing regulatory body and is not addressed in this document. For all pertinent regulations, please contact your local regulatory agency (see Appendix B for a list of PVI-related, regulatory contacts). Furthermore, ITRC has many applicable guidance documents to assist with remedial investigations and corrective actions (see the ITRC documents page).

Emergency Situations

Contact first responders immediately if there are strong petroleum odors or evidence of, or reasons to suspect, combustible, explosive, or oxygen-deficient conditions inside the building.

Finally, this document does not cover emergency response actions related to PVI and assumes that all emergency situations have been handled prior to consulting this text. If strong petroleum odors are detected, or combustible, explosive, or oxygen-deficient conditions may exist inside a building, then first responders should be contacted immediately.

1.1.2 Who Should Use This Document?

The primary audiences for this guidance document are regulators and private sector practitioners who evaluate and manage potential PVI sites. This document also provides responsible parties, site owners, managers, and other stakeholders with a basic understanding of the unique aspects of PVI. This guidance document explains the principles of PVI and assists with the following tasks:

- identifying PVI issues at PHC-contaminated sites
- making informed PVI risk-management decisions, including the use of a PVI screening method to determine the presence or absence of PVI
- selecting appropriate management and control strategies to reduce or eliminate PVI effects on indoor air

1.1.3 Who Developed This Document?

The ITRC PVI Team developed this guidance document. The team included approximately 130 members from state and federal regulatory agencies, consultants, site owners (both private and public sectors), academia, and community stakeholders. Many of these team members are recognized experts in the fields of VI and PVI. See Appendix N for the complete PVI team roster.

1.1.4 Why Is This Document Important?

State environmental regulatory agencies have consistently identified VI as a high priority. For sites contaminated with PHCs, many regulators and practitioners have noted uncertainty about how to best account for biodegradation of PHC vapors when evaluating PVI.

ITRC has developed this PVI guidance to provide a scientifically-based, consensus approach to explain the following key issues for managing PVI:

- how the principle of biodegradation, supported by empirical evidence, justifies the use of a PVI screening method for various types of petroleum-contaminated sites
- how to investigate PVI if the pathway is potentially complete or other factors prevent the use of the screening method
- how to mitigate and manage PVI if the pathway is complete or potentially complete

To support development of this document, the PVI Team conducted a survey of state environmental regulatory agencies to gain insight into the “state of the practice” for addressing potential PVI sites. Survey information was collected in the spring of 2012. Responses were provided from 49 states and the District of Columbia. Some of the key findings from the survey included:

- The PVI pathway is a priority for many states.
- Seventeen states had no PVI guidance.
- Most states addressed PVI as a subsection of general VI guidance.
- All states identified at least one type of petroleum site as important with regard to PVI.
- Forty-four states indicated that PVI had occurred at one or more sites.

Appendix A, PVI Survey – Summary of State Responses, provides a summary of the survey results.

1.2 Petroleum Vapor Intrusion Assessment Strategy

A consistent approach to PVI that fits any regulatory framework and type of petroleum site is critical for confident decision making that protects human health. Figure 1-2, PVI strategy flowchart, presents a consistent, flexible approach. This strategy is a stepwise process, beginning with development of a preliminary conceptual site model (CSM) and site screening. This phase may be followed by a more detailed site investigation and refinement of the CSM or, if chosen, immediate vapor control. If the detailed investigation is chosen, depending on the outcome, site management specifically for PVI (such as vapor controls, long-term monitoring, and institutional controls) may be required. In addition, community engagement is a critical component of the strategy that should be considered throughout the PVI assessment process.

Iterations within each of the strategy phases may be warranted, and investigators must decide whether to continue data collection and interpretation within a particular phase or to proceed to the next phase. The following subsections highlight key aspects of the strategy and introduce the more detailed discussions in subsequent chapters.

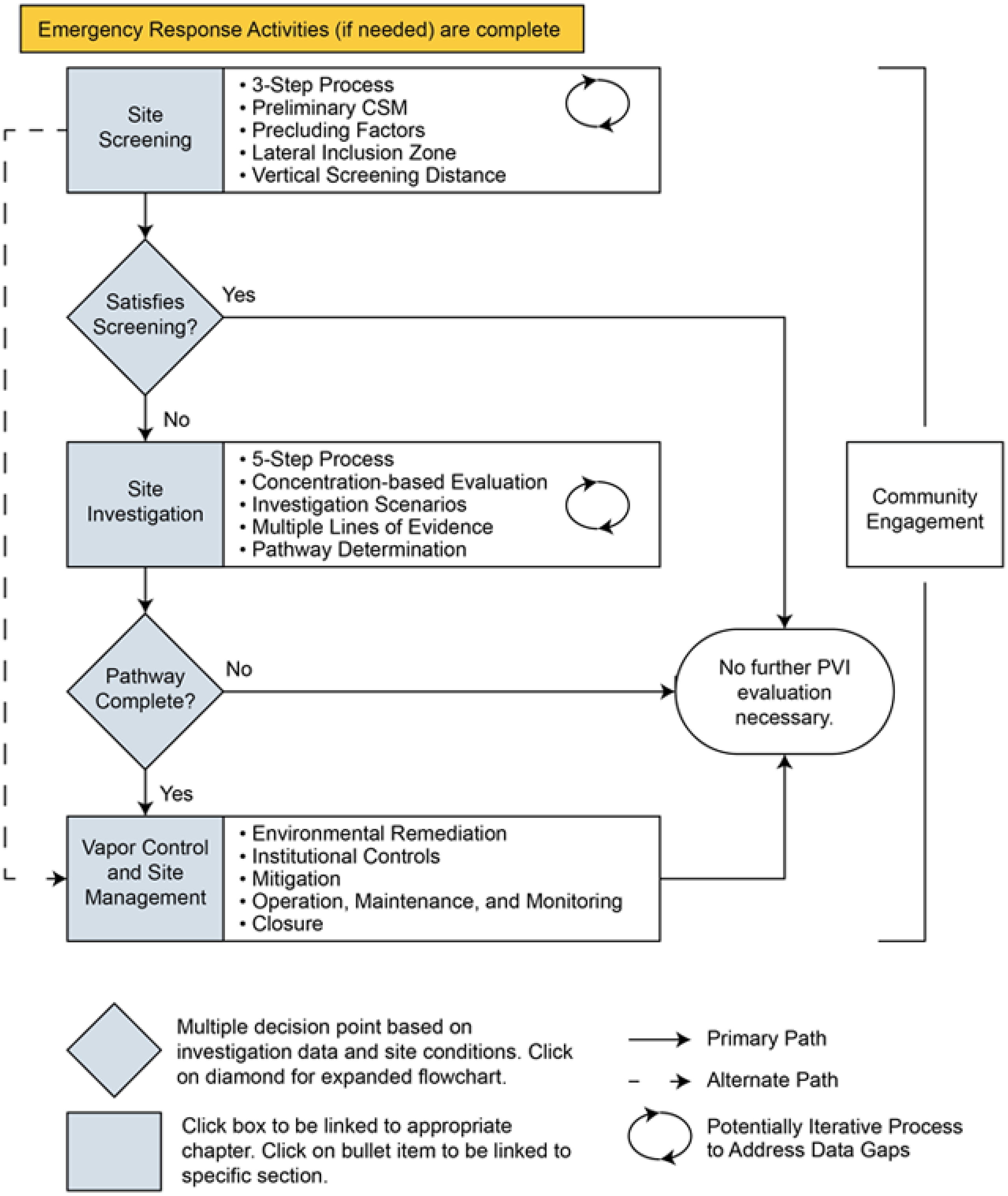


Figure 1-2. PVI strategy flowchart.

1.2.1 Site Screening Using Vertical Screening Distance

Vertical Screening Distance

Vertical screening distance is the minimum thickness of soil between a petroleum vapor source and building foundation needed to effectively biodegrade hydrocarbons below a level of concern for PVI.

Site screening is the initial phase in the PVI assessment strategy for determining whether the PVI pathway is potentially complete or not. The PVI screening method detailed in Chapter 3, Site Screening, uses the concept of vertical screening distance to make this determination. The vertical screening distance is defined as the minimum thickness of soil between a petroleum vapor source and building foundation needed to effectively biodegrade hydrocarbons below a level of concern for PVI. This distance is based on empirical studies involving data collected at hundreds of petroleum release sites. The analysis of the data confirmed that all PHCs studied were aerobically biodegraded within the vertical screening distance. The vertical screening distance is determined based on whether the petroleum vapor source is LNAPL in the vadose soil or groundwater, or dissolved phase in groundwater.

Using this PVI screening method helps to minimize investigative efforts at sites where there is little risk of a complete PVI pathway. To use the PVI screening method based on the vertical separation distance, an investigator follows a stepwise procedure to construct a preliminary CSM with key site-specific information (see Section 3.1). For many sites, the key information may be available from previous or current investigations.

Note that the application of this PVI screening approach is not based on chemical-specific screening levels. Other screening tools, such as attenuation factors or target concentrations for groundwater or soil gas, are concentration based and either do not account for biodegradation of PHCs or use a generic bioattenuation factor.

1.2.2 Site Investigation

An outcome of the site screening process may be that additional investigation of the site is necessary to evaluate pathway completeness for PVI. Chapter 4, Site Investigation, and Chapter 5, Modeling, describe approaches and tools for conducting the site investigation phase of the PVI assessment strategy, along with specific issues related to investigation of PHCs.

1.2.3 Vapor Control and Site Management

If the site screening or site investigation steps determine that the pathway is complete or likely complete, then site management of the PVI pathway may be necessary. Management tools may include one or more options such as environmental remediation, institutional controls, and building mitigation. Regardless of the management tools used, the CSM should be refined and the PVI pathway reevaluated as conditions change or new information becomes available. Chapter 6, Vapor

Control and Site Management, discusses these tools in detail, with specific attention to issues found at petroleum sites.

2.0 CHARACTERISTICS OF PETROLEUM VAPOR INTRUSION

VI occurs when vapors from contaminated groundwater or other subsurface sources migrate upward through vadose zone soils and into overlying buildings. Figure 2-1 depicts a general CSM for the VI process. A CSM is a summary of site-specific conditions and describes the relationship between contaminant sources, contaminated media, migration pathways, and potential receptors.

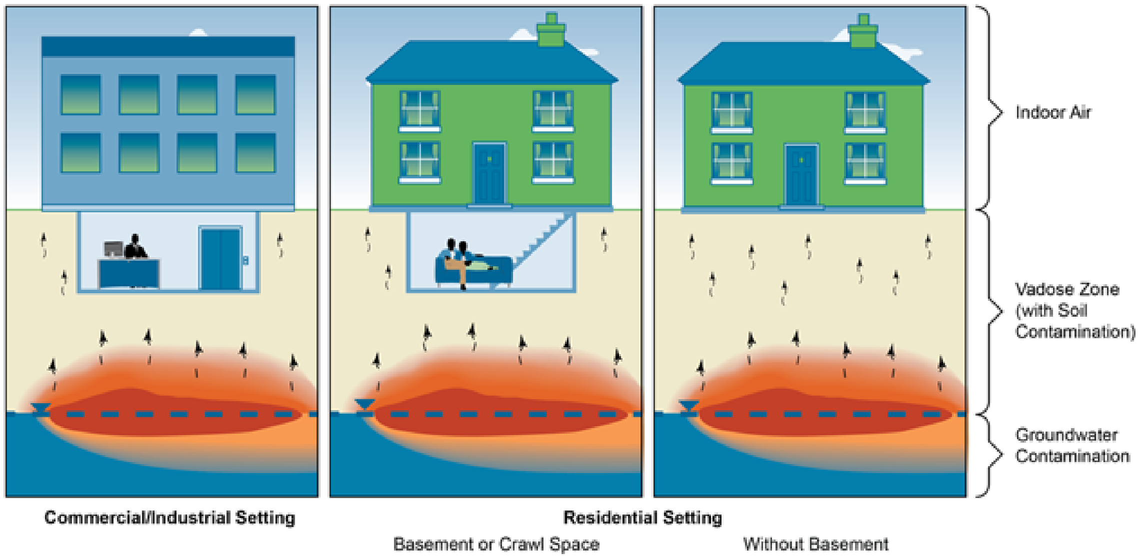


Figure 2-1. General conceptual site model for the VI pathway.

Some vapor effects in indoor air are not related to the VI pathway. Examples of these effects include:

- ambient outdoor air quality
- vapors off-gassing from tap water
- affected water or product inside a building
- household or commercial products stored or used in a building
- building materials containing volatile compounds
- household activities

Most of the available guidance on VI has focused on contamination from CVOCs, such as tetrachloroethene (dry cleaning fluid). PHCs have more recently been a topic of interest because of recent advances in the science. While PVI has similarities to chlorinated vapor intrusion (CVI), recent research and analysis has increased the understanding of the significant differences between PVI and CVI.

2.1 Differences Between PVI and CVI

The defining feature of PVI that distinguishes it from VI of other volatile chemicals, most notably CVOCs, is the relatively rapid rate of attenuation of petroleum hydrocarbons (PHCs) because of aerobic biodegradation in vadose zone soils.

Many studies have documented the subsurface biodegradation of PHC vapors (McAlary et al. 2007; Ririe, Sweeney, and Daugherty 2002; Hers et al. 2000b; Ostendorf et al. 2000). Recent evaluations (USEPA 2013i; Lahvis et al. 2013a; Davis 2009) of empirical soil gas data have demonstrated that biodegradation can limit the migration of PHC vapors from a subsurface source. These studies indicate that the potential for PVI is reduced because biodegradation minimizes the flux of PHC vapors in soil gas from a source to overlying buildings. Although PVI may be possible under certain environmental conditions, McHugh et al. (2010) note that "the most common cause of petroleum vapor intrusion is dissolved PHCs or LNAPL in direct contact with building structures such as sumps, basements, or elevator pits."

Table 2-1 summarizes key differences between PVI and CVI. Much of the information is presented in the document *Petroleum Hydrocarbons and Chlorinated Hydrocarbons Differ in Their Potential for Vapor Intrusion* (USEPA 2012g). These differences form the basis for the PVI-specific site screening approach, as introduced in Section 1.2.1 and detailed in Chapter 3, Site Screening Using Vertical Screening Distance.

Table 2-1. General differences between PHCs and CVOCs (USEPA 2012g)

Property	PHCs	CVOCs	PVI-related details
Distribution in groundwater	A significant portion of the source mass can reside above the water table as LNAPL.	The majority of free-phase product (DNAPL) migrates below the water table to a less penetrable layer.	• LNAPL will be mostly above groundwater and spreading with changes in groundwater elevation. • Risk of PVI decreases when only dissolved phase is present. • Length of dissolved phase plumes is typically limited by biodegradation.
Biodegradation	Primarily aerobic; relatively rapid; biodegradation interface is small (from a few inches up to 5 or 6 feet) – see Figure 3-1	Primarily anaerobic (except vinyl chloride); relatively slow; generally limited to anoxic zones	• O_2 in soil and water will promote biodegradation. • Biodegradation will limit the size of the PHC vapor plume in the vadose zone. • Biodegradation will occur rapidly over a short distance in the presence of >2% O_2 in soil gas. • Atmospheric O_2 replenishment in the vadose zone is usually sufficient to continually support biodegradation. • Lack of O_2 (<2% O_2 in soil gas): ◦ significantly decreases biodegradation rate ◦ extends the distance vapors can travel before being biodegraded ◦ may promote production of meth-

Table 2-1. General differences between PHCs and CVOCs (USEPA 2012g) (continued)

Property	PHCs	CVOCs	PVI-related details
Bio-degradation products	Aerobic conditions: carbon dioxide (CO_2) and water. Anaerobic conditions: methane and carbon monoxide (CO).	Degradation chemicals generally are toxic.	ane • Terminal biodegradation products are non-toxic. • Methane is a potential explosion hazard in presence of ignition source. • Methane production is generally increased by the presence of ethanol in fuels.

2.2 Biodegradation

The following fate and transport mechanisms explain the behavior of PHC vapors and describe how this behavior affects the PVI pathway:

- partitioning of PHC vapors from contaminated soil, groundwater, or LNAPL into soil gas
- diffusion of PHC vapors in soil gas from the source toward the ground surface
- biodegradation in an aerobic biodegradation zone
- advection into a building
- mixing of vapors with building indoor air

Biodegradation, discussed below, is of critical importance for understanding PVI and is the basis for the site screening strategy presented in Chapter 3. The processes of partitioning, diffusion, advection, and mixing are the same for PHCs and other compounds, including CVOCs. Further details on these processes and the biogeochemical behavior of PHCs are discussed in Appendix M, Fate and Transport of Petroleum Vapors, and Appendix C, Chemistry of Petroleum.

2.2.1 The Process of Biodegradation

Biodegradation is the breakdown of organic chemicals, including PHCs, by microorganisms. Microorganisms that biodegrade PHCs are ubiquitous in most subsurface soils. Although PHCs can be biodegraded in the absence of O_2, the most rapid rates of biodegradation typically occur under aerobic conditions. The vadose zone above an area contaminated by a petroleum release is normally an aerobic environment in which O_2 can be readily replenished from the atmosphere. Because rates of petroleum vapor biodegradation usually exceed the rates of petroleum transport via diffusion, petroleum vapors are typically, but not always, fully attenuated by aerobic biodegradation processes in the vadose zone.

Biodegradation

PHC-degrading bacteria are found in all environments and can consume hydrocarbons rapidly in the presence of O_2. This activity can limit transport and VI effects of PHC vapors.

A notable feature of aerobic biodegradation of PHCs in soils is the short acclimation time for this process, which can be measured in hours and days (Turner et al. 2014). The acclimation time is the time required for the microbial community to start consuming PHCs after the initial introduction of these chemicals. This short acclimation time indicates that PHC biodegradation is a common physiological trait of soil microorganisms.

2.2.2 Environmental Effects on Biodegradation

Despite the general reliability of aerobic biodegradation in reducing PVI, several environmental factors can hinder this process. The most significant factor is the availability of O_2, which is a necessary electron acceptor and enzyme reactant in the aerobic biodegradation of PHCs. Some state regulations/guidance documents indicate that O_2 levels only need to be greater than 2–4% by volume to support aerobic biodegradation. In addition, Roggemans, Bruce, and Roggemans (2001) showed oxygen concentrations of 2% by volume to be supportive of aerobic biodegradation.

Some factors that may hinder the recharge of O_2 in the vadose zone are soils with high moisture content; soils with high organic content; soils with low permeability; large building foundations; and the presence of high PHC concentrations, such as near LNAPL sources, that consume O_2 from biodegradation itself. In the absence of O_2, anaerobic microorganisms can use other electron acceptors to support PHC biodegradation. Anaerobic biodegradation of PHCs is typically slower than aerobic biodegradation, and the rates of biodegradation in the presence and absence of O_2 can differ substantially.

Acclimation of Microorganisms

Microbial communities can start consuming PHCs within hours or days of the introduction of PHCs into the subsurface.

Other factors that can potentially limit the biodegradation of PHCs include low moisture content, nutrient availability, temperature, and heavy metals. In the vadose zone, sufficient moisture and nutrients usually are present to support microbial PHC biodegradation. However, in more extreme circumstances (such as arid environments), insufficient moisture can potentially limit PHC biodegradation even when sufficient O_2 is available. In general, the rates of biological processes decrease with decreasing temperature. Cold climates, however, do not preclude the potential for biodegradation because some specific PHC-consuming microorganisms thrive in temperatures ranging from 20ºC to 0ºC (Margesin and Schinner 2001). Similarly, heavy metal contaminants can be toxic to PHC-degrading bacteria and can decrease PHC degradation rates (Babich and Stotzky 1985). Many microorganisms, however, have the capability to resist the toxic effects of heavy metals and have high activity in environments affected by these common inorganic contaminants.

2.2.3 Generation of Methane and Effects on Biodegradation

When PHCs are present at sufficiently high concentrations or in large source areas, O_2 and other electron acceptors may become depleted. PHCs may then be biodegraded through the activities of methanogenic microbial communities. Because methane is not a component of gasoline or other liquid hydrocarbon products, the presence of methane indicates that insufficient O_2 is available for aerobic PHC biodegradation.

Methane Production

Methane may be produced when O_2 is depleted in the presence of high PHC concentrations or large source areas, or by the breakdown of petroleum products containing ethanol.

The presence of methane can also further affect PHC biodegradation, because methane itself can be readily biodegraded under aerobic conditions. The consumption of O_2 for methane biodegradation can limit the amount of O_2 available for biodegradation of other PHCs. O_2 levels can also be reduced in the presence of ethanol by a similar mechanism, resulting in further methane production. However, the effect of methanogenic degradation of ethanol in this context is limited in fuels containing 10% or less ethanol by volume (Wilson et al. 2012; Wilson et al. 2013). The vertical screening distances discussed in Chapter 3 were developed in part from empirical site data for fuel releases that included 10% ethanol.

2.2.4 Effects of PHC Chemical Structure on Biodegradation

The chemical structures of PHCs and their physicochemical properties can also influence their biodegradation. Generally, for PHCs dissolved in the water phase, microorganisms biodegrade n-alkanes (straight-chain alkanes) more rapidly than cyclic and aromatic compounds, and biodegrade shorter chain n-alkanes more slowly than longer chain n-alkanes (Alexander 1977). The structure of the chemical (for example, more branching) and the presence of specific substituents or functional groups (for example, the ether group on methyl tert-butyl ether, or MTBE) can also strongly affect biodegradability.

Another important factor that affects the biodegradability of a chemical based on its structure is the air-to-water partitioning coefficient. For petroleum chemicals, because the air-to-water partitioning of aromatic compounds is less than n-alkanes, a greater fraction of the aromatic compounds are partitioned into water, are more readily available to be biodegraded, and therefore may be more significantly attenuated by microbial biodegradation than n-alkanes (DeVaull 2007).

A summary of the effects of chemical structure on aerobic hydrocarbon biodegradation rates is presented in Section 5.3.1.3, First-Order Biodegradation Rate Constants. For more information about the chemistry of petroleum, see Appendix C, Chemistry of Petroleum.

2.3 Petroleum Vapor Intrusion Conceptual Site Model

A CSM is a visualization of site conditions that allows for evaluation of contaminant sources and affected media, migration pathways, and potential receptors. This tool provides an iterative representation of the site and guides decision making while assessing the PVI pathway.

A CSM for PVI incorporates biodegradation and is used to determine whether a complete PVI pathway exists or, if needed, the information required to make this determination. Information to construct the CSM is acquired from historical research, site characterization, and an understanding of contaminant behavior, among other sources. The CSM is a dynamic tool that should be refined throughout the life of the project as new information is acquired.

An example of a CSM for the PVI pathway is shown in Figure 2-2. The CSM for a site with a potential for PVI will evolve as the assessment progresses through the assessment strategy summarized in Figure 1-2. However, in order to use the screening method described in Chapter 3, only a limited set of key information and data (what is termed a "preliminary CSM"), must be compiled. Section 3.1.1 describes the preliminary CSM in conjunction with the site screening process.

Appendix D provides a checklist to assist in the development of a CSM for the PVI pathway.

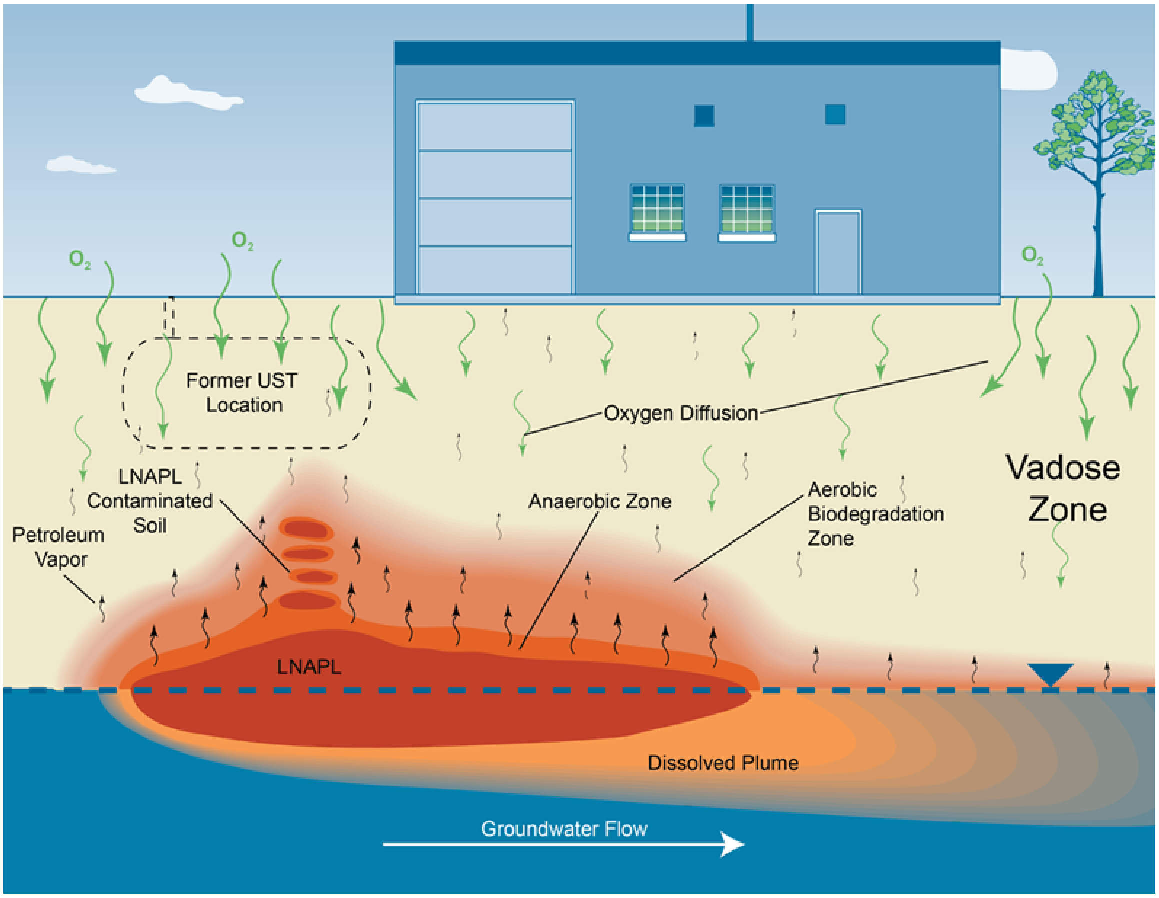


Figure 2-2. General conceptual site model for the PVI pathway.

2.4 The Petroleum Vapor Intrusion Source

Understanding and properly characterizing the petroleum source is an important part of the CSM for PVI. Petroleum fuels can be broadly categorized as “gasolines,” “middle distillates,” and “residual fuels,” with the middle category including diesel, kerosene, Stoddard solvent and some types of jet fuels (API 1994). The general makeup of common petroleum fuels in terms of the number of carbon molecules per compound is depicted in Figure 2-3. The detailed chemistry of petroleum fuels has been extensively studied (Potter and Simmons 1998, USEPA 2009f). These fuels are primarily composed of hundreds of nonspecific, aliphatic hydrocarbon compounds with a small, variable amount of aromatic compounds, including BTEX and naphthalene. Collectively, all of these hydrocarbons are referred to as “Total Petroleum Hydrocarbons” (TPH). The vapors associated with petroleum fuels are similarly dominated by aliphatic compounds with smaller amounts of aromatic compounds (USEPA 2013a, Brewer et al. 2013). The actual vapors above the petroleum source will depend on the constituent composition of the vapor source, vapor pressures of the constituents, and temperature. A more detailed overview of the chemistry of petroleum and its vapors is provided in Appendix C.

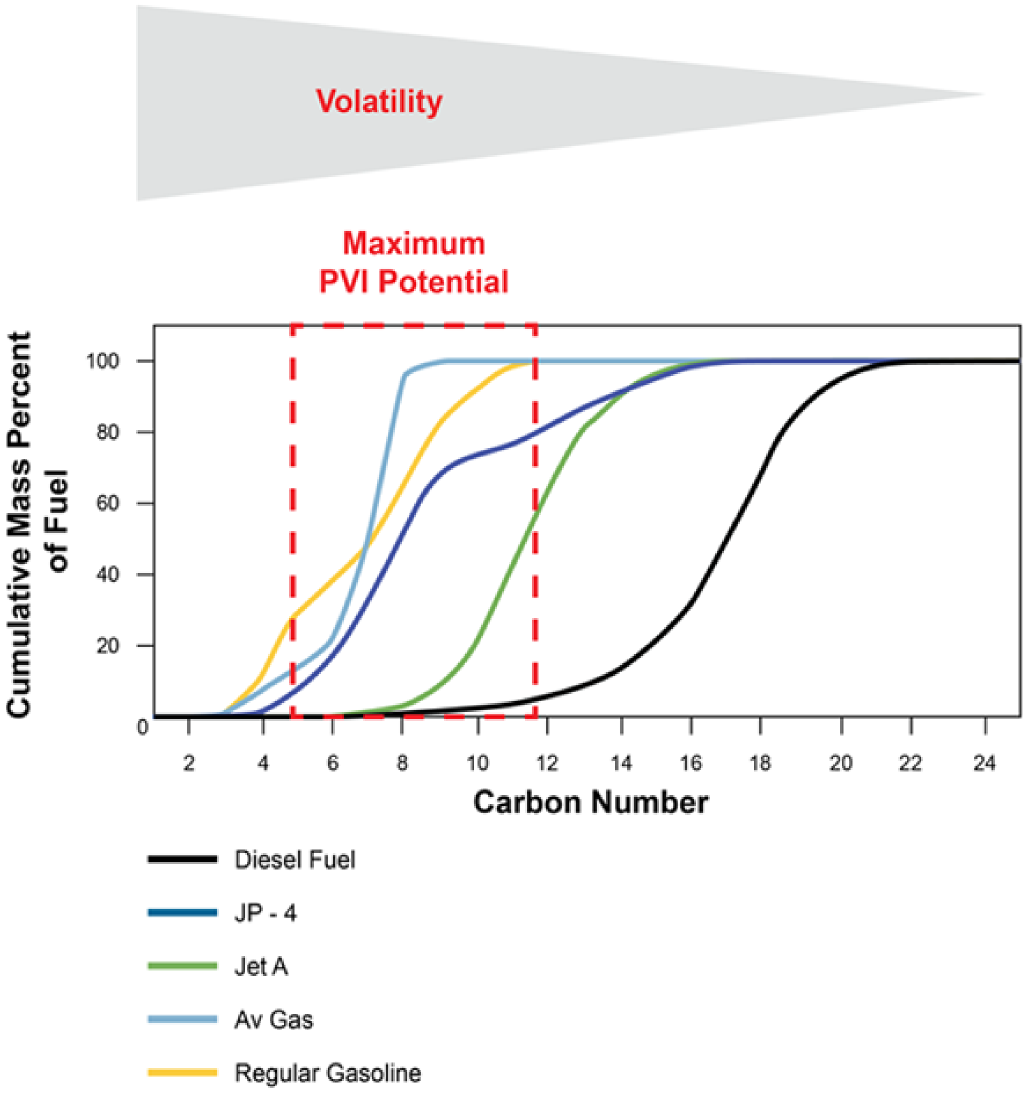


Figure 2-3. Composition of typical petroleum fuels with respect to the number of carbon molecules in individual compounds.

2.5 Common Types of Petroleum Sites

Petroleum products may be released to the environment at industrial, commercial, and residential properties. The type of site and PHC, as well as the nature of the release and subsurface lithology, influences the distribution of PHC in the subsurface.

The ITRC PVI survey of 49 states and the District of Columbia identified nine common types of petroleum release sites. Table 2-2 summarizes common types of petroleum sites and general features of each that may be related to the potential for PVI. The site type examples detailed in Table 2-2 are examples of common petroleum site types and may not cover all site type possibilities or all site-specific scenarios. Components of the sites listed may not be applicable to other types of petroleum sites. The characteristics summarized in Table 2-2 are characteristics as they relate to the potential for PVI. For example, the indicator compounds listed in the Table are compounds that may be important in evaluating the potential for PVI. The indicator compounds summarized are not an exhaustive list of possible compounds that may be detected on the particular petroleum site type.

The discussion of indicator compounds for PVI generally focuses on a small number of individual, well-studied, aromatic compounds such as benzene, toluene, ethylbenzene, xylenes, and naphthalene that are traditionally considered in human health risk assessments. The role of nonspecific, petroleum-related aliphatic and aromatic compounds in PVI has only recently come under more scrutiny (for example, Brewer et al. 2013). These compounds are collectively measured and assessed in terms of TPH or in more detail as specific groups of aliphatic and aromatic carbon ranges (such as C5–C8 aliphatics, C9–C12 aliphatics, or C9–C18 aromatics). Some regulatory agencies (for example, Hawaii Department of Health) may require a more detailed evaluation of the role of TPH in PVI. Approaches for providing these detailed evaluations, however, are beyond the scope of this document. Refer to the local regulatory agency for further guidance.

Table 2-2. Types of petroleum sites

Petroleum site type (link to Appendix E)	Common indicator compounds	Potential release sources
Gasoline and Diesel UST Locations	Gasoline: BTEX, trimethylbenzenes, naphthalene, methane Diesel: naphthalene, methane	USTs, product lines, dispensers, service bays
Commercial and Home Heating Oil Locations	Naphthalene, benzene	USTs, ASTs, product lines
Refineries	BTEX, naphthalene, methane	Underground or aboveground piping, USTs (former and current), ASTs, loading areas, tank pits (current and former), processing units, historical disposal sites
Bulk Storage Facilities	For oil/-petroleum/gasoline: BTEX, naphthalene, methane	Underground or aboveground piping, ASTs, oil/water separators, loading areas
Pipelines/Transportation	For oil/petroleum: BTEX, naphthalene, methane For natural gas: methane, butane, propane, benzene	Pipeline, pipe joints, valves, flanges, weld points
Oil Exploration and Production Sites	BTEX, methane	Wells and well area, pipelines, gathering lines, mud pits, USTs and associated piping, ASTs and associated piping, maintenance facilities, oil/water separators
Former Manufactured Gas Plants (MGP)	BTEX, indane, indene, naphthalene, trimethylbenzenes	Tar holders, oil/water separators, gas holder foundations, purifying boxes, tar wells

Table 2-2. Types of petroleum sites (continued)

Petroleum site type (link to Appendix E)	Common indicator compounds	Potential release sources
Coal Tar/Creosote Facilities	Naphthalene, alkyl-naphthalene derivatives, benzene	Drip pads, product storage areas, unlined pits, lagoons
Dry Cleaners Using Petroleum Solvents	BTEX	Outside building (especially windows and doors), storage areas, dry wells, drains

Additional detailed information about common types of petroleum sites is contained in Appendix E, Common Types of Petroleum Sites. Site type information includes:

- site descriptions
- schematic figures
- carbon chain range(s)
- potential release sources
- relative site size compared to other site types
- site-specific preferential pathways
- site-specific key assessment factors

3.0 SITE SCREENING USING VERTICAL SCREENING DISTANCE

This chapter describes a method for PVI screening based on the vertical distance from a petroleum vapor source to a building foundation (vertical separation distance). Application of the method is expected to improve PVI screening and reduce unnecessary data collection at numerous petroleum release sites. The vertical screening distance is the minimum thickness of soil between a petroleum vapor source and building foundation necessary to effectively biodegrade hydrocarbons below a level of concern for PVI (see Figure 3-1). The vertical screening distances are based on empirical studies involving data collected at hundreds of petroleum release sites (see Appendix F). Method application requires the development of a preliminary CSM based on soil and groundwater data collected as part of an initial site investigation or from valid preexisting data.

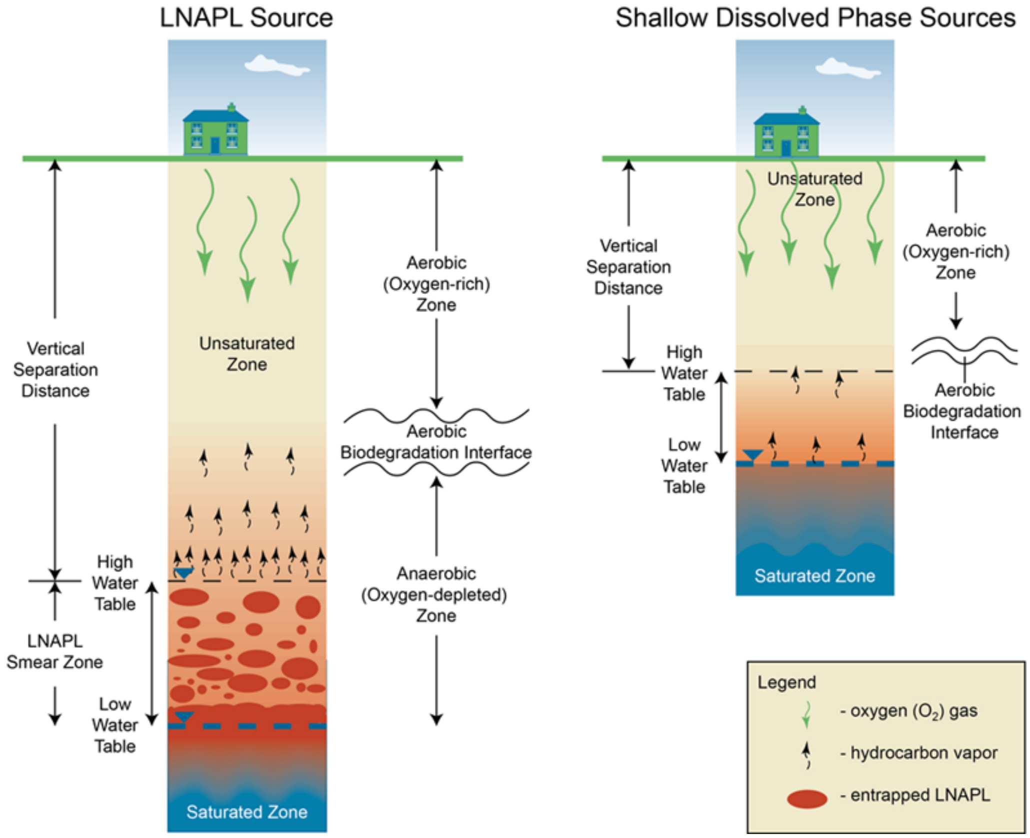


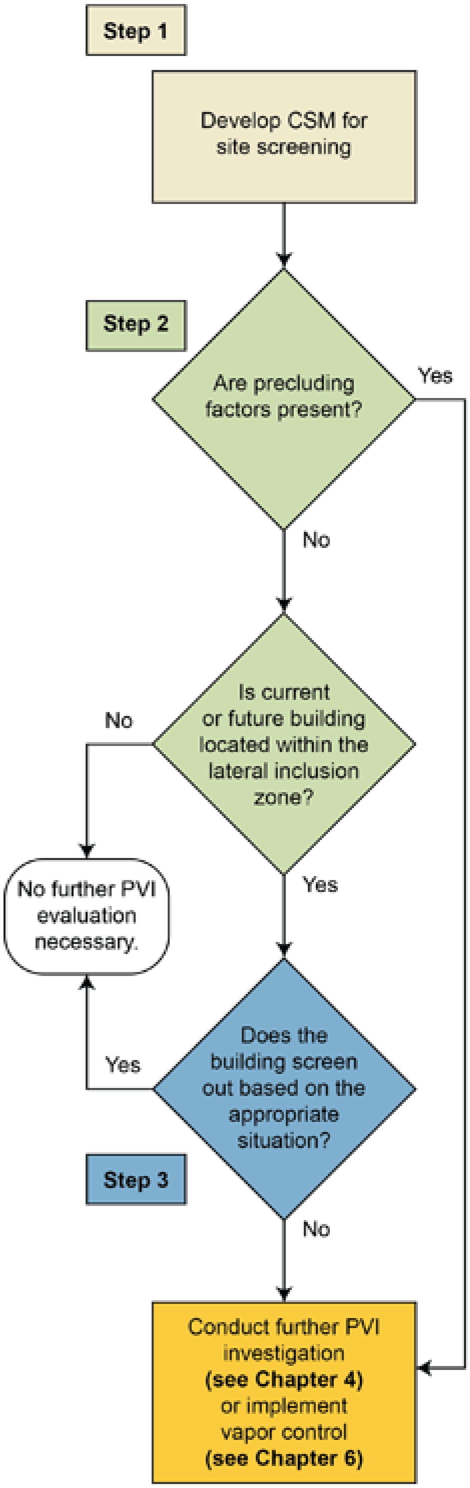
Figure 3-1. Conceptual model of petroleum vapor transport for an LNAPL source and a dissolved phase source.

The PVI screening process is divided into three steps (see Figure 3-2):

Step 1: Develop a Preliminary CSM: The preliminary CSM is based on critical data obtained from an initial site investigation or valid preexisting data. Critical data include soil and groundwater data, type of site (petroleum UST/AST or petroleum industrial), type of vapor source (dissolved-phase or LNAPL), vertical separation distance, and the presence of site-specific factors that would preclude the use of the screening process. Note that if COC concentrations in soil and groundwater are below existing PVI regulatory criteria, the development of a preliminary CSM and use of a vertical screening distance are not required and no further PVI evaluation is needed.

Step 2: Evaluate Site for Precluding Factors and Lateral Inclusion: If precluding factors are present, then investigate the site further (Chapter 4, Appendix G) or implement vapor control and site management (Chapter 6). If there are no precluding factors, evaluate whether current or future buildings are located within the lateral inclusion zone. If buildings are located within the lateral inclusion zone, continue to Step 3 for further screening. Buildings outside of the lateral inclusion zone require no further PVI evaluation.

Step 3: Screen Building Using Vertical Separation Distance: Assess whether further site investigation is necessary based on the measured vertical separation distance between the building foundation and the top of the petroleum vapor source in soil or groundwater.



Step 1: Develop CSM (Section 3.1)

- **Site Type:** identify the site as either Petroleum UST/AST (e.g., gas station) or Petroleum Industrial (e.g., terminal, refinery)
- **Petroleum Vapor Source:** determine the type of petroleum vapor source (dissolved-phase or LNAPL) underlying each building of interest
- **Extent of Source:** determine the location and lateral and vertical extent of the petroleum vapor source in soil or groundwater
- **Precluding Factors:** determine the presence of precluding factors, including:
  - Preferential pathways - natural (e.g., karst or fractured geology) or anthropogenic (e.g., sanitary sewers, piping corridors)
  - Expanding/advancing plume
  - Certain fuel types (e.g., lead scavengers or > 10% vol/vol ethanol)
  - Certain soil types (e.g., peat or excessively dry soils between the source and building)
- **Lateral Inclusion Zone:** determine zone as 30 feet from the edge of the petroleum vapor source (in soil or groundwater)
- **Vertical Separation Distance:** determine the distance between the bottom of the building foundation and the top of the petroleum vapor source

Step 2: Evaluate Building for Precluding Factors and Lateral Inclusion (Section 3.2)

- **Precluding Factors:** Are factors present?
- **Lateral Inclusion Zone:** Is any portion of the current or future building foundation within the lateral inclusion zone?

Step 3: Conduct Screening with Vertical Separation Distance (Section 3.3)

LNAPL Sources:
Vertical separation distance between top of LNAPL source (in soil or at water table) and bottom of building foundation is > 15 ft (petroleum UST/AST sites) or > 18 ft (petroleum industrial sites)

Dissolved-Phase Sources:
Vertical separation distance between water table and bottom of building foundation is > 5 ft

Figure 3-2. Flowchart for PVI screening application.

3.1 Step 1 - Develop Preliminary CSM

The preliminary CSM is developed by collecting soil and groundwater data as part of routine initial site investigations. The CSM necessary for PVI screening has the following components:

- site type
- petroleum vapor source
- extent of source
- lateral inclusion zone
- vertical separation distance
- precluding factors

3.1.1 Site Type

USEPA (2013a) has published empirical studies that reported different LNAPL screening distances based on facility type:

- LNAPL sources at petroleum UST sites
- LNAPL sources at fuel terminal, refinery, and petrochemical (non-UST) sites

This document addresses all petroleum facilities (see Appendix E), and therefore a slightly modified site classification is needed to guide selection of the appropriate LNAPL vertical screening distance:

- *Petroleum UST/AST sites*. Petroleum UST/AST sites generally include facilities used for vehicle fueling (such as gas stations, municipal fleet yards, bus terminals, and fire stations) and commercial/home heating oil tanks. Fuel at these sites is typically stored in USTs, but could be stored in similarly-sized ASTs.
- *Petroleum industrial sites*. Petroleum industrial sites include: (a) bulk fuel terminals; (b) refineries; (c) exploration and production sites; (d) crude oil and product pipelines; and (e) former MGPs.

Differences in the vertical screening distances according to site type may relate to the volume of the LNAPL release or extent of the LNAPL plume. Large releases of petroleum can result in a large oxygen demand, which reduces biodegradation of the PHCs. Petroleum industrial sites tend to have large infrastructure and may have multiple releases from different locations, which can also exert a high oxygen demand. Given that LNAPL release volumes and plume extents may not always correlate with the site type, a good CSM and professional judgment are needed to select the most appropriate LNAPL vertical screening distance. Note that there is more uncertainty associated with the industrial sites because a relatively small data set of industrial sites was used in the empirical study (USEPA 2013a).

3.1.2 Petroleum Vapor Source

The empirical studies of Lahvis et al. (2013a) and USEPA (2013a) found that vertical screening distances are longer for LNAPL sources than for dissolved-phase sources. Greater vertical source separation is necessary to biodegrade PHC vapors below a level of concern for PVI for LNAPL sources than for dissolved-phase sources because LNAPL sources can generate higher concentrations of vapors. As a result, there is greater demand for O_2 in the vadose zone during aerobic biodegradation of LNAPL sources compared to dissolved-phase sources. Both LNAPL and dissolved-phase sources may be present from a single release.

Source identification can be challenging at locations where LNAPL is present as a residual-phase source in soil or groundwater because the LNAPL may not be readily apparent unless there is measurable thickness of LNAPL in a nearby groundwater monitoring well. In these cases, a multiple-lines-of-evidence approach can be used for LNAPL identification (see Table 3-1). The LNAPL indicator criteria and parameter ranges are values reported in the literature. Presence of LNAPL may be indicated by one or more of the parameters shown in Table 3-1. Measurable PHC concentrations in groundwater less than those indicative of LNAPL are consistent with a dissolved-phase petroleum vapor source. PHC concentrations in soil or groundwater can vary widely depending on the LNAPL type (gasoline, diesel, jet fuel) and the degree of weathering. The indicator criteria provided in Table 3-1 should thus be used as general guidance. Regulatory agencies may have their own set of criteria for LNAPL identification.

Table 3-1. General LNAPL indicators for PVI screening

Indicator [1]	**Comments**
Groundwater	
• Benzene: > 1 - 5 mg/L [2,3] • $\text{TPH}_{(gasoline)}$: > 30 mg/L[4] • BTEX: > 20 mg/L[5] • Current or historical presence of LNAPL (including sheens) [2,3]	There is not a specific PHC concentration in groundwater that defines LNAPL because of varying product types and degrees of weathering.
Soil	
• Current or historical presence of LNAPL (including sheens, staining) [2,3] • Benzene > 10 mg/kg [2] • $\text{TPH}_{(gasoline)}$ > 250[2] - 500[5] mg/kg • Ultraviolet fluorescence (UV) or laser induced fluorescence (LIF) fluorescence response in LNAPL range [6] • PID or FID readings > 500 ppm [7]	• The use of TPH soil concentration data as LNAPL indicators should be exercised with caution. • TPH soil concentrations can be affected by the presence of soil organic matter. • TPH soil concentrations are not well correlated with TPH or O_2 soil gas concentrations (Lahvis and Hers 2013b).

Table 3-1. General LNAPL indicators for PVI screening (continued)

Indicator [1]	Comments
Location relative to UST/AST	
• Adjacent (e.g., within 20 feet of) a known or suspected LNAPL release area or petroleum equipment [2]	The probability of encountering LNAPL increases closer to a known or suspected release.

Notes:
[1] One or more of these indicators may be used to define LNAPL.
[2] Value used in the derivation of screening distances by USEPA (2013a) and Lahvis and Hers (2013b).
[3] Value used in the derivation of screening distances by Peargin and Kolhatkar (2011).
[4] Value used in the derivation of screening distances by USEPA (2013a).
[5] Value recommended by Lahvis and Hers (2013b).
[6] Value is from ASTM E2531-06.
[7] Value recommended by USEPA (2013a) and Lahvis and Hers (2013b).

3.1.3 Extent of Source

Proper delineation of the petroleum vapor source in soil or groundwater is critical in determining which buildings are within the lateral inclusion zone (see Section 3.1.5) and the vertical separation distance (Section 3.1.6). There is a higher probability of encountering LNAPL in the vadose zone near and below former or current UST/AST equipment, in known or suspected release areas, along perching units or low-permeability soil layers, or in a smear zone near the water table. The LNAPL smear zone may extend well above the water table at some sites with large (several feet) water-table fluctuations. Soil sampling and soil screening using a photoionization detector (PID) or flame ionization detector (FID) are recommended for delineating vadose zone sources. For dissolved-phase sources, the edge of the plume should be defined according to governing state or local regulatory requirements.

3.1.4 Precluding Factors

The presence of any of the precluding factors listed below will direct the investigator out of the site screening process and require either further investigation (Chapter 4) or vapor control and site management (Chapter 6). Typical precluding factors include the following:

Utilities in LNAPL Zones

*There is a **significantly** greater risk of PVI from utilities located within LNAPL zones than there is with dissolved groundwater plumes.*

1. Preferential pathways that intercept both the source (either LNAPL or dissolved phase) and building foundations (see Figure 3-3). The preferential pathways may be artificial or engineered, such as utility conduits with improper seals and connections to a building, or natural, such as karst geology or fractured rock (see Figure 3-4). The source material need not be in contact with the building foundation to pose a potentially complete PVI pathway.
2. Ongoing releases of petroleum products that result in expanding or mobile contaminant plumes. These releases are precluding factors because it is not feasible to identify the lateral inclusion zones in these cases.

3. Certain fuel types preclude the use of screening distances because the empirical research (Appendix F) has insufficient data to draw confident conclusions for these fuel types. These fuel types include:
    - gasoline containing lead scavengers
    - gasoline containing greater than 10% vol/vol ethanol
4. Soils with a naturally high content of organic matter or excessively dry soil conditions between the source and building foundation also preclude application of the screening method discussed in this document. These soils are precluding factors for the following reasons:
    - High organic matter in soil can exert a high oxygen demand, and thus reduce the O_2 available to biodegrade PHCs. DeVaull (2007) identifies soil organic carbon greater than 4% w/w as a possible indication of high soil oxygen demand. Such soils include peat, bay muds, and wetland and delta soils; however, these soils are usually removed and replaced with engineered fill for building construction. These soils also adsorb petroleum vapors.
    - Excessively dry soils (less than 2% by volume or 1.2% by weight moisture) may have insufficient moisture to support biodegradation (DeVault et al. 1997); however, this condition has rarely been documented to occur below the surface, even in arid regions.

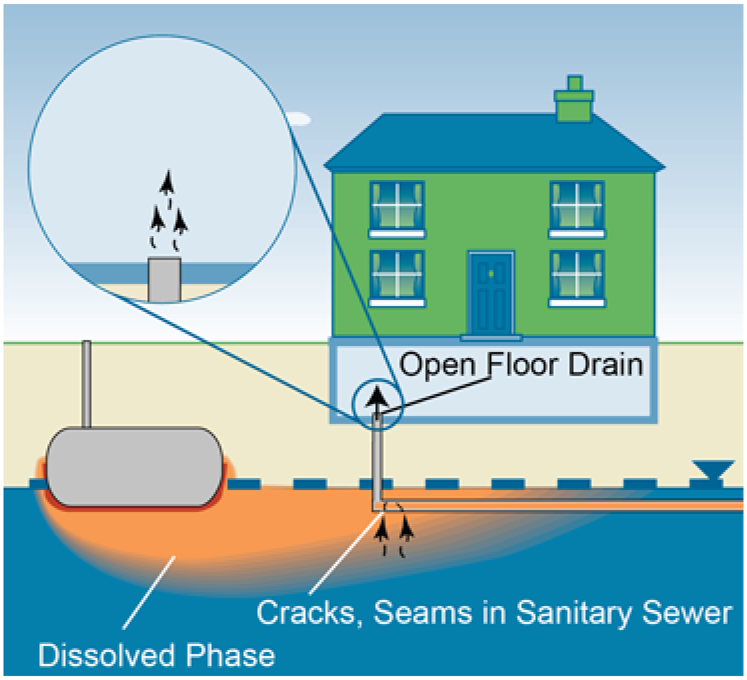


Figure 3-3. Precluding factor: conduit intersecting source and entering building.

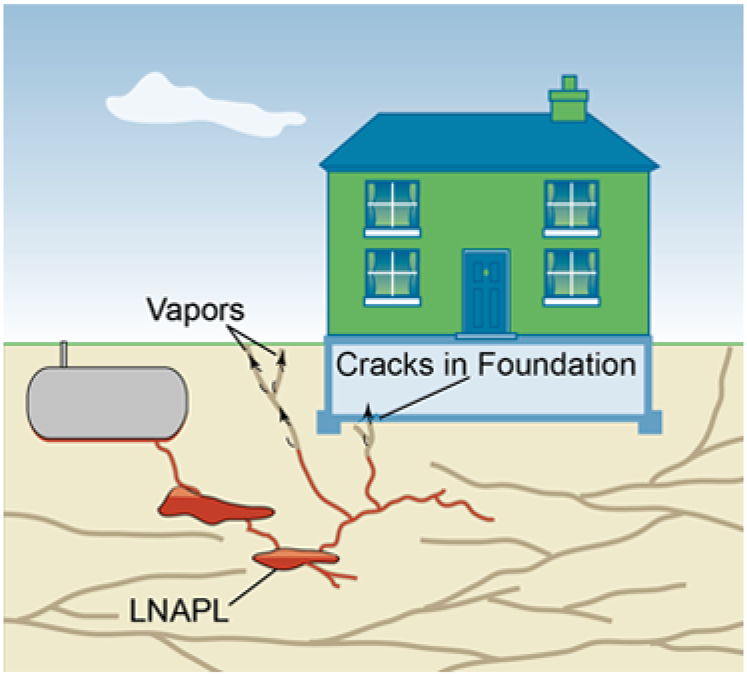


Figure 3-4. Precluding factor: fractured or karst geology.

3.1.5 Lateral Inclusion Zone

The lateral inclusion zone is used to determine whether a building is close enough to the lateral edge of a petroleum vapor source to be considered for PVI screening. The lateral inclusion zone is defined as the area from the edge of the petroleum vapor source to the edge of a building foundation. Identifying the edge of the petroleum vapor source depends on how the extent of the source is defined by individual governing state or local regulatory requirements. Wilson et al. (2013) describe an interpolation method for sites where plume delineation and lateral inclusion zone are uncertain. This method is based on interpolation of contaminant concentrations between monitoring locations.

Little empirical data are available from the literature to help define the lateral inclusion zone or distance of vapor attenuation in the lateral direction. Nonetheless, lateral inclusion distances and vertical screening distances should be approximately the same, because the physical processes acting on PHC vapor plumes (mass flux from the source, oxygen demand, and biodegradation) are generally the same in the vertical and horizontal directions (USEPA 2013n). The vertical screening distances are expected to apply laterally in the absence of preferential pathways or significant hydrogeologic barriers (such as perched water tables or low-permeability soil lenses) that could enhance lateral migration of PHC vapors. Modeling studies by the American Petroleum Institute (API 2009) support this assumption. The lateral edge of a contaminant plume, however, is generally not known with the same degree of certainty as the vertical edge because plume delineation is conducted over a scale of tens of feet laterally, compared to a only a few feet vertically.

A conservative, 30-foot lateral inclusion distance may be considered appropriate to incorporate the uncertainty. If a high degree of confidence exists in the delineation of the lateral edge of the source, it may be appropriate to use the applicable vertical screening distance to define the lateral inclusion zone.

3.1.6 Vertical Separation Distance

The vertical separation distance is measured from the top of the petroleum vapor source to the bottom of the building foundation for each building located within the lateral inclusion zone. Seasonal and long-term fluctuations in groundwater levels should be considered when determining the depth to the LNAPL smear zone or dissolved phase source. A consideration of current and historical land use is recommended for buildings located in the lateral inclusion zone in order to assess the potential for additional (secondary) sources that are not associated with the primary release under investigation. Vertical separation distance should be determined from the top of the source closest to the building foundation where these additional (secondary) sources are identified.

Note that the soil within the vertical separation distance may contain detectable concentrations of PHCs, which typically do not interfere with biodegradation (because the soil does not contain LNAPL source material). This condition is consistent with the petroleum vapor transport CSM shown in Figure 3-1.

3.2 Step 2 - Evaluate Building for Precluding Factors and Lateral Inclusion

Vertical screening distances can only be applied in the absence of any precluding factors identified in the preliminary CSM (Section 3.1.4). If precluding factors are present, then further site investigation is necessary (Chapter 4). If no precluding factors are present, then determine whether the edge of the building foundation is within the lateral inclusion zone that extends 30 feet from the edge of the petroleum vapor source. If the building is located within the lateral inclusion zone, then vertical screening distances can be applied in Step 3. Buildings located outside of the lateral inclusion zone require no further PVI evaluation.

3.3 Step 3 - Conduct Screening with Vertical Separation Distance

Several empirical studies have defined vertical screening distances for LNAPL and dissolved-phase sources (see Appendix F). As previously noted, there is more uncertainty with the industrial sites because of the relatively small data set of industrial sites in the empirical study (USEPA 2013a). Although the values derived for dissolved-phase and LNAPL sources vary slightly among the studies, they can be conservatively defined as:

- 5 feet: dissolved-phase sources
- 15 feet: LNAPL sources (petroleum UST/AST sites)
- 18 feet: LNAPL sources (petroleum industrial sites)

Determine whether the vertical separation distance between the top of the petroleum vapor source and the bottom of the building foundation exceeds these vertical screening distances for either an

LNAPL source (see Figure 3-5) or a dissolved-phase source (see Figure 3-6). If so, then no further evaluation of the PVI pathway is necessary. If not, then further site investigation (Chapter 4) or vapor control and site management (Chapter 6) is necessary.

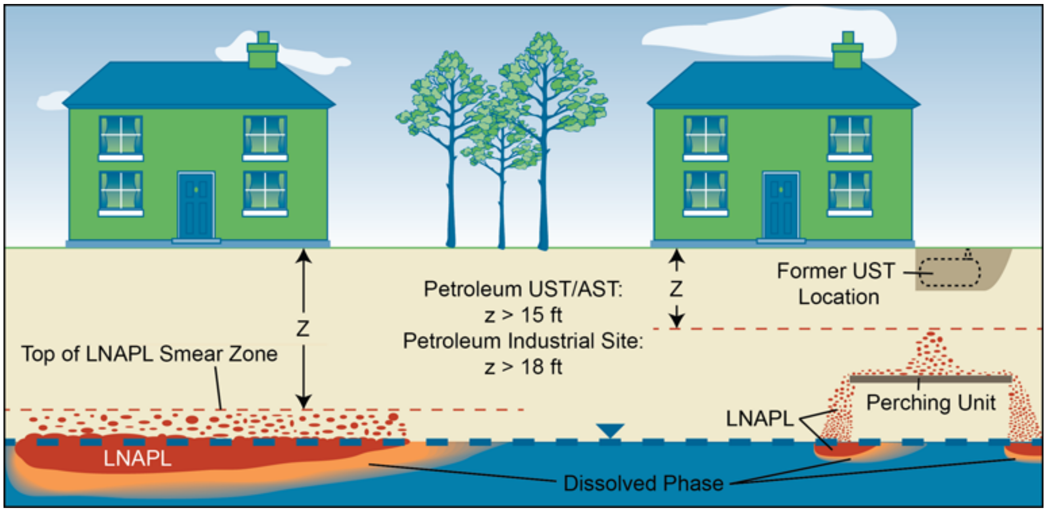


Figure 3-5. Vertical screening distances for LNAPL source.

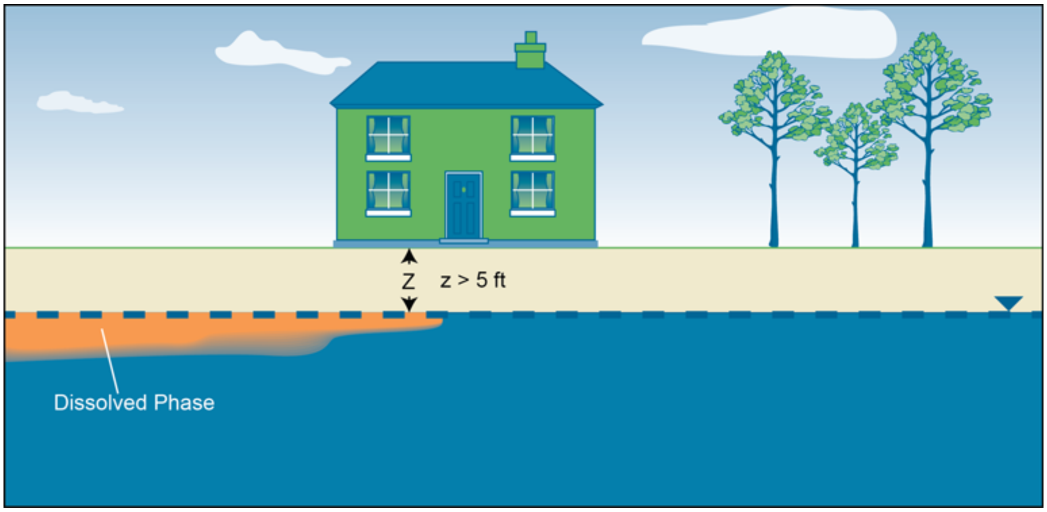


Figure 3-6. Vertical screening distances for dissolved-phase source.

4.0 SITE INVESTIGATION

The five-step process for investigating PVI applies in the event that a building does not satisfy the screening process and allow elimination of the exposure pathway. The site investigation phase starts with Step 4 - Implementing a concentration-based evaluation using existing data (Section 4.1). If necessary, Step 5 involves conducting a PVI investigation which includes selecting the applicable CSM scenario (Section 4.2.1), determining the corresponding sampling approach (Section 4.2.2), and addressing analytical considerations (Section 4.2.3). Data evaluation (Section 4.3) is Step 6. Since PVI is an iterative process, Step 7 determines whether additional investigation is warranted (Section 4.4). Finally (Step 8), a conclusion on the completeness of the PVI pathway must be made (Section 4.5). These steps are illustrated in Figure 4-1. The decision to implement vapor controls (Chapter 6) in lieu of further site investigation can be made at any time in the PVI investigation process.

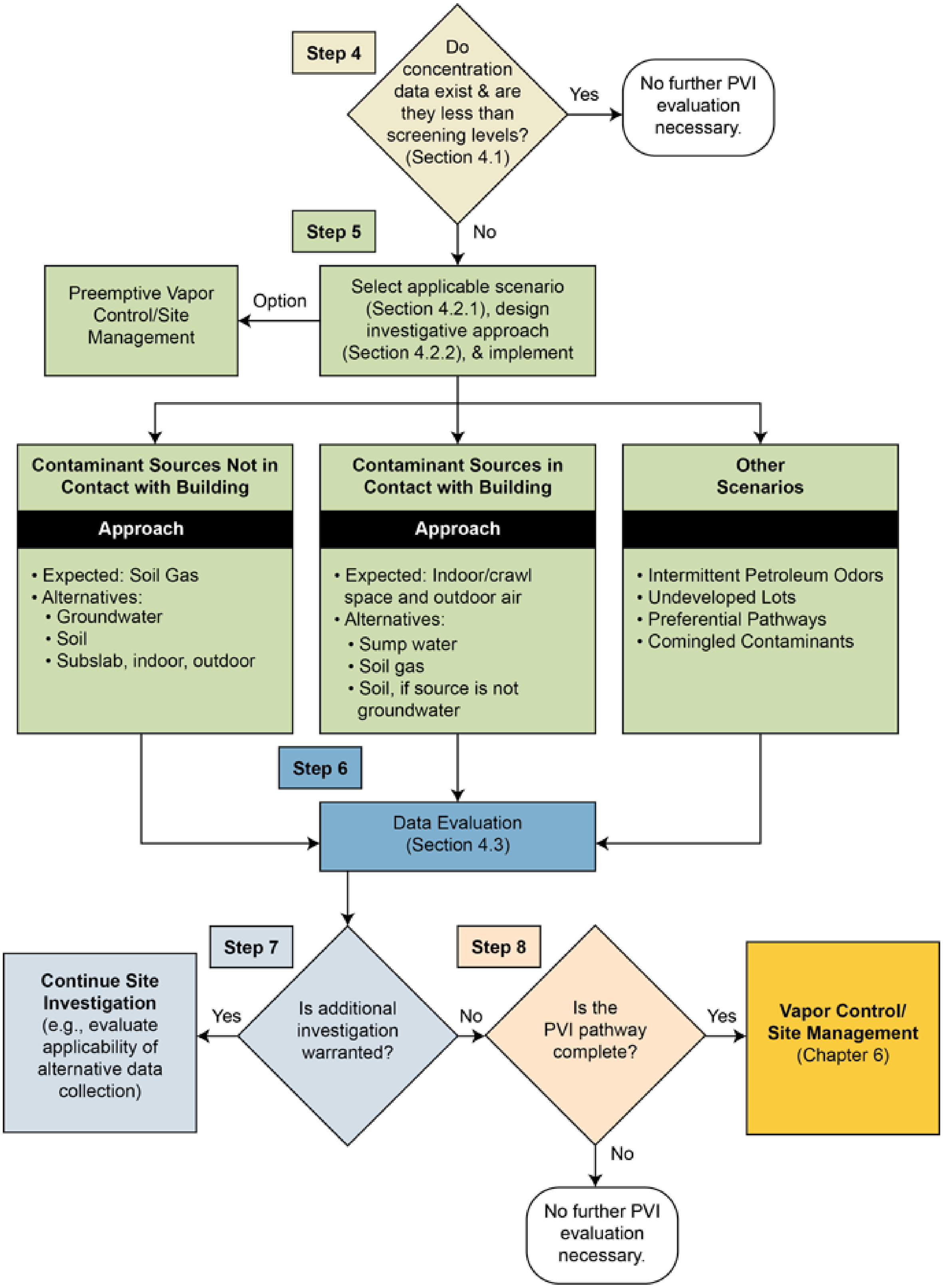


Figure 4-1. Site investigation approach flow chart.

The level of effort and the type of data required depend on site conditions in order to answer key questions such as:

- Are concentrations of COCs in soil or groundwater low enough that vapor intrusion is unlikely? This question requires a concentration-based evaluation.
- Are concentrations of COCs in soil gas low enough that vapor intrusion is unlikely? This question requires a pathway-based evaluation.
- Are concentrations of COCs in indoor air the result of vapor intrusion? This question requires a receptor-based evaluation.

One or more lines of evidence are needed when evaluating complex relationships between groundwater, soil, and air. When more than one line of evidence is collected, the process is referred to as a "multiple-lines-of-evidence" approach. It is up to the investigator to gather, evaluate, and weigh different types of data and information. Different, but not necessarily all, media can be sampled to evaluate multiple lines of evidence.

Soil gas sampling is a common approach used for PVI evaluations because of the influence of biodegradation on PHCs in the subsurface and the prevalence of indoor PHC sources (see Appendix L) that make indoor air data difficult to interpret. If the concentration of COCs in soil gas decreases to below action levels within the vadose zone, then the transport pathway is likely incomplete and additional sampling (for instance, indoor air) unnecessary. Section 4.2 focuses on investigation strategies (what to sample) and includes a summary of investigative approaches. Additional details of investigative approaches are presented in Appendix G, including field procedures for sampling soil gas, groundwater, soil, near-slab and subslab soil gas, outdoor (ambient) air, and indoor air. Appendix G also covers supplemental tools and other data that can be useful for VI investigations, including the use of tracers, differential pressure measurements, real-time and continuous analyzers, and forensic (“fingerprinting”) analysis, among others.

4.1 Step 4 - Conduct a Concentration-Based Evaluation Using Existing Data

The criteria for determining if the PVI pathway is complete can vary by state, region, and stakeholder. Existing concentration data can be compared to applicable vapor intrusion screening criteria (look-up values) to evaluate whether the pathway can be eliminated. This determination can be made independent of the vertical screening distance method outlined in Chapter 3. Check with the local regulatory agency for applicable concentration-based criteria (also see the ITRC PVI state survey, summarized in Appendix A).

4.2 Step 5 - Select and Implement an Applicable Scenario and Investigative Approach

4.2.1 Investigative Scenario

Most PHC sites fall under one of the scenarios depicted in Figure 4-1. These scenarios are described in more detail in this section and can be used in selecting investigation strategies and approaches for the site.

An overview of the relevant investigative approaches is provided in Section 4.2.2. Regulatory agencies may have requirements or guidance specific to investigating the vapor intrusion pathway. Some agencies may also require specific analytical methods and the use of certified laboratories. Understanding these applicable regulatory requirements is part of designing a successful investigation.

Scenario 1: Contamination Not in Contact with the Building

At PHC sites with contamination not directly in contact with the building, the initial investigation approach will most likely be soil gas sampling, since soil gas data reflect the processes that occur in the vadose zone (partitioning, sorption, biodegradation), from the contamination source to the overlying building. Alternative approaches may include collection of groundwater, soil, subslab soil gas, or indoor air and outdoor air data.

Scenario 2: Contamination in Contact with the Building

At PHC sites with contamination directly in contact with the building, collection of subslab soil gas samples may not be possible because of soil pore-space saturation. The initial investigation approach will most likely be indoor air or crawl space sampling and outdoor air sampling. In buildings with basements, near-slab soil gas samples may be collected around the perimeter or subslab soil gas samples collected below slab-on-grade garage floors. Alternative approaches may include collection of samples within the slab and flux chamber samples. If sumps are present, alternatives include the collection of sump water samples, sump headspace samples, or flux chamber samples.

Other Scenarios

- *Intermittent petroleum odors*. Assuming there is not an emergency situation, the initial investigative approach will most likely be a building walk-through, potentially followed by indoor air sampling to verify the presence of PHCs. If verified, a more detailed investigation may be necessary.
- *Undeveloped lots*: The soil gas and groundwater sampling methods described above apply for undeveloped land use, recognizing that structure sampling is not possible.
- *Comingled contaminants*: For sites with volatile contaminants other than solely PHCs, refer to the ITRC VI guidance (2007).

Focus the Investigation

It may not be necessary to investigate all media shown in Figure 4-1. Focus only on the lines of evidence needed.

4.2.2 Investigative Approach

The following sections describe investigative approaches and sampling methods for the evaluation of PVI. The order of the investigative approaches described in the sections below does not reflect their priority. Details of the sampling methods presented are included in Appendix G.2 through Appendix G.5.

4.2.2.1 Groundwater Sampling

Groundwater data exist at most sites, typically from monitoring wells, but may only provide limited spatial coverage (both on and off site) and may be from wells screened over large depth intervals (10 feet to 15 feet). For evaluating the PVI pathway, it is best to use the groundwater data that have been collected from the most recent sampling event and that are representative of monitoring wells near the area of concern.

Additional groundwater samples may be collected to further characterize the potential for PVI. For evaluating the VI pathway, it is best if the groundwater samples are collected in a shallow interval across the top of the groundwater and as close to buildings as possible. Discrete sampling methods or small diameter wells are more suitable for VI investigations than conventional monitoring wells with long screens (see Appendix G.2).

If groundwater data indicate no potential for PVI risk, and if there are no sources in the vadose zone, then the pathway can be considered not of concern and further PVI assessment is not needed. If groundwater concentrations indicate LNAPL and the source is not in contact with the building, then further soil or soil gas sampling is recommended.

4.2.2.2 Soil Gas Sampling

At many PHC sites, the initial investigation approach will most likely be soil gas sampling, since soil gas data reflect the processes that occur in the vadose zone (partitioning, sorption, biodegradation), from the contamination source to the overlying receptor. Three primary options are available for characterizing soil gas. These three options differ mainly by the sampling location relative to the building under investigation:

- *Exterior soil gas*. These subsurface sampling points are located at some distance (usually 10 linear feet or more) away from the building of interest, or, in the case of the future building scenario, in the footprint of the proposed building. The distance used to define the maximum distance away from a building that an external soil gas sample may be collected and still be considered applicable to the building varies by state. This distance can be affected by access or other physical constraints. Sample points are installed within the vadose zone. Factors considered for selecting sampling depth include (1) fluctuations in water table depth; (2) thickness of capillary fringe; and (3) regulatory preference (some states specify minimum sampling depths). In general, regulatory agencies prefer subslab or near-slab soil gas samples over exterior samples.
- *Near-slab soil gas*. These subsurface sampling points are located around the perimeter of the building (typically less than 10 feet from a building). As with exterior soil gas samples, the distance used to define near-slab samples varies by state or can be affected by access or other physical constraints. In addition to the sampling depth considerations for external soil

gas points, building features (such as depth of foundation) should be considered when selecting near-slab sampling depths. In general, regulatory agencies prefer subslab soil gas samples over near-slab soil gas samples.

- *Subslab soil gas*. These sampling points are located within the footprint of the building and are installed by drilling through the building slab. Sampling depths are typically less than 1 foot below the bottom of the slab.

Methods for collecting soil gas samples, and additional factors in sample placement are provided in Appendix G.8. General advantages and disadvantages for each type of soil gas sampling are provided in Table G-6.

Vertical soil gas profiles can be acquired by installing a series of nested or clustered exterior or near-slab soil gas points at a range of depths. Such soil gas data may be useful for defining the zone of active biodegradation and demonstrating that the decrease in PHC concentrations with distance from the source is due to biodegradation.

When concentrations of PHCs in soil gas (5 feet bgs or greater) exceed allowable screening values, shallower soil gas samples (< 5 feet bgs) may potentially demonstrate that biodegradation is active and concentrations do not exceed screening levels at these locations. If field instruments or other on-site methods are used, step-out sampling locations and depths may be selected during a single mobilization. Alternatively, additional shallower samples may be collected during the same mobilization and analyzed in an off-site laboratory if results for the deeper samples exceed screening levels.

4.2.2.3 Indoor Air Sampling

Indoor air data provide measurements at the point of exposure and represent the sum of influences of sources that contribute contaminants to indoor air. These sources may include ambient outdoor air and indoor sources (such as consumer products, petroleum vapors from cars in an attached garage, or petroleum vapors from home repair and remodeling), as well as the contribution from subsurface sources through VI. Indoor air measurements often complicate data interpretation when the data are collected without careful planning and well-documented execution.

Interpretation of indoor air sampling results for PHCs may be challenging when assessing the VI pathway for two primary reasons:

- Ambient (outdoor air) levels of benzene and other PHCs can exceed applicable screening levels in many urban areas.
- The indoor air sources for benzene and other PHC compounds in inhabited structures are ubiquitous (see Appendix L, Indoor Air Background).

For these two reasons, indoor air sampling is unlikely to be the initial method used for a PVI investigation.

Conduct a building survey in advance of indoor air sampling to identify potential background sources. Removing the identified background sources (to the extent practical) before the sampling begins may be prudent, but be aware that additional, unidentified background sources may remain. A survey also provides an opportunity to educate occupants on what to expect during the sampling event and inform them of the activities that should be avoided immediately before and during the sampling period. Examples of building surveys can be found in ITRC's 2007 guidance.

An 8-hour indoor air sampling period is often selected for commercial buildings. A 24-hour sampling interval is usually selected for residential structures. Stainless steel canisters are generally used for sampling intervals from 5 minutes to 24 hours. Alternative sampling devices (such as passive samplers) can be deployed for longer periods to reduce the effects of short term variability. However, PHC results for samples collected over longer periods are susceptible to false positives, potential interferences from occupant activities, and background sources, because hydrocarbons are ubiquitous in consumer products and ambient air.

Samples of indoor air represent the air quality at the time of sampling. Although indoor air is generally well mixed, temporal and seasonal variations occur in indoor air quality. Document conditions at the time of sampling, including heating, ventilation, and air conditioning (HVAC) system operation. Additionally, review the resulting laboratory data for representativeness and usability, according to the data quality parameters specified in the sampling and analysis plan.

Indoor air samples may be collected with the HVAC system on or off, depending on the sampling objectives. To evaluate whether vapor intrusion is possible, sample with HVAC turned off and after the building has equilibrated for a few hours. This method represents a worst-case building scenario for VI. If assessing human risk exposure, indoor air samples should be collected under normal conditions.

Sample Duration

The sample duration for indoor air samples should be selected in an effort to provide the best estimate of the time-integrated average concentration to which an occupant may be exposed.

Concurrent sampling of indoor air, ambient air, and subslab soil gas may provide data that allow a more detailed understanding of site conditions. Collecting multiple lines of evidence is particularly helpful at PHC sites because of the complex nature of the transport and exposure pathway, and because PHCs are ubiquitous in indoor air from background sources.

4.2.2.4 Ambient (Outdoor) Air Sampling

When indoor air is sampled, concurrent ambient air samples should also be collected. Collect ambient air samples at locations upwind of the building being investigated. Additionally, document information on significant point or nonpoint sources on the day of sampling (such as gasoline stations, automobiles, gasoline-powered engines, fuel and oil storage tanks, and locations that may generate significant petroleum vapors) when selecting ambient sample locations and interpreting the data. The ambient air data can be used as a tool to provide information regarding outdoor influences on indoor air quality (California DTSC 2011).

4.2.2.5 Crawl Space Sampling

Air within a crawl space can be collected using indoor air sampling methods. These data may provide an additional line of evidence to evaluate whether vapor intrusion is occurring. A number of states and regions compare results for crawl space air samples to indoor air screening levels, which assume no attenuation between the crawl space and the indoor air. Detection of higher concentrations of PHCs in a crawl space than in indoor air samples collected in basement or upper floor areas may indicate a subsurface source.

Air exchange between the crawl space and ambient air may also vary significantly depending on construction and should be considered before sample collection. Methods for sampling in crawl spaces are described in Appendix G.

4.2.2.6 Soil Sampling

ITRC's *Vapor Intrusion Pathway: A Practical Guideline* (2007) notes that analytical data for soil samples are not ideal for evaluating VI risk because of the uncertainty associated with partitioning from soil to soil gas and the potential loss of VOCs during and after sample collection. To evaluate VI, contaminant concentrations measured in the soil sample must be converted to soil gas concentrations using assumptions about the partitioning of the contaminant into the gas phase. Soil- to-soil gas partitioning equations are readily available, but empirical data show a poor correlation between predicted soil gas values from soil data and actual measured values for PHCs (Golder Associates 2007).

Golder Associates has found that, in the case of PHCs, calculating soil gas values from contaminant concentrations measured in soil samples typically overestimates the actual concentrations in soil gas by orders of magnitude. This calculation overpredicts the risk for PVI (Golder Associates 2007). Several state agencies, however, have soil criteria for the VI pathway (Eklund et al. 2012).

If vapor transport modeling is conducted, then consider analyzing samples for physical properties in the scope of work (see Chapter 5).

4.2.3 Analytical Considerations

The chemicals selected for analysis at a potential PVI site depend on the source and type of PHC contamination (see Appendix E, Types of Petroleum Sites), as well as the objectives of the investigation and the requirements of the agency providing regulatory oversight. The sampling and analysis plan should describe objectives of the investigation, analytical methods to be used, and quality requirements for the data.

A site-specific analyte list typically includes PHCs, but also might include TPH fractions and indicator compounds to assist in identifying and differentiating subsurface sources of volatile chemical contamination (Table 4-1).

Table 4-1. Indicator compounds

Source	Compounds
Gasoline	Benzene, toluene, ethylbenzene, xylenes, trimethylbenzenes, individual C–4 to C–8 aliphatics (such as hexane, cyclohexane, dimethylpentane, or 2,2,4-trimethylpentane) and appropriate oxygenate additives (such as MTBE and ethanol)
Middle distillate fuels (No. 2 fuel oil, diesel, and kerosene)	N-nonane, n-decane, n-undecane, n-dodecane, ethylbenzene, xylenes, trimethylbenzene isomers, tetramethylbenzene isomers, and naphthalene
Manufactured gas plant sites	Benzene, toluene, ethylbenzene, xylenes, indane, indene, naphthalene, and trimethylbenzene

An assessment of biodegradation in soil gas usually includes the analysis of O_2, CO_2, and CH_4. After oxygen is depleted, methanogenic bacteria convert petroleum hydrocarbons to methane and carbon dioxide. If methane is above 1%, then conditions are anaerobic, and sampling is likely near an LNAPL source. CO_2, on the other hand, is typically the complement of oxygen, meaning that the combined sum should be around 21%. If there is an excess of CO_2, then anaerobic biodegradation is likely occurring, and methane is being oxidized to CO_2 under anaerobic conditions. Additionally, nitrogen may be considered an indicator as to whether there is replenishment of air or an advective flow of soil gas that flushes out the air. If nitrogen is displaced (much less than 79%) then either the bulk soil gas is migrating or the sample was collected under a vacuum.

Appendix G provides a detailed discussion of analytical methods for PVI investigations, and Table G-3 is a summary of analytical methods used for evaluation of petroleum hydrocarbons in the vapor phase. G.12.3.4 provides a discussion of naphthalene collection and analysis, which presents challenges such as contaminant carryover and variability in recovery.

Many regulatory agencies have requirements or guidance related to UST sites and remediation programs. Some agencies may also require specific analytical methods and the use of certified laboratories. Understanding these applicable regulatory requirements is part of designing a successful investigation.

Some PHC sites may require a detailed analysis of hydrocarbon sources. Forensic chemistry uses hydrocarbon profiling or fingerprinting for this purpose and is available in some commercial laboratories. Methods have been developed to analyze for vapor-phase PHC compounds (paraffins, isoparaffins, aromatics, naphthalenes, and olefins—also known as the PIANO analysis), including for air-phase matrices in VI investigations (Plantz et al. 2008).

4.3 Step 6 - Evaluate Data

The following section describes data quality considerations and factors to consider when evaluating the data.

4.3.1 Data Quality

If the project was planned using the Data Quality Objective (DQO) process (USEPA 2006b) or other standard project planning process, then the quantity and quality of data, including the measurement quality objectives, will have been specified in the sampling and analysis plan. Some common data quality issues are listed in Table 4-2. All of the data should be examined for these types of issues to ensure that data are of adequate quality prior to using the data to evaluate the VI pathway.

Table 4-2. Data quality issues to consider

Data quality issue	Factors to keep in mind
Detection limits	• Ensure that detection limits are less than the applicable screening values for the compounds of concern. • Consider whether more than one compound is of concern at the site, screening levels might be lower to account for cumulative effects and hence, detection limits must also be lower.
False positives	• Be aware of the potential cross-contamination from probes, canisters, other materials, and from indoor sources. • Remember that screening levels for VI are low and the chances for false positives increase as contributions from other sources increase.
False negatives	Consider that false negatives can be due to losses in sampling equipment, leaks, and other factors. Ask yourself: • Was the leak-detection compound detected in the sample? • Is O_2 higher in deeper samples of soil gas? • Was the proper type of tubing used in the soil gas probe? • Was the proper type of sample container used? • Were the chain of custody documents completed properly?
Sampling errors	• Remember to keep sampling hardware properly checked and maintained. • Minimize operator errors by properly training field staff. Ask yourself: ◦ Did canisters fill to the target pressure? ◦ Was the leak detection compound applied and measured correctly? ◦ Were canister pressures recorded, for both start time and end times? • Ensure that sampling durations are adequate.

4.3.2 Evaluating the Data

Evaluating data to assess the completeness and significance of the PVI pathway typically uses one or all of the following comparisons, as described in detail in ITRC's VI guidance (2007):

1. Comparison of concentrations to generic screening levels published by the regulatory agency. Many states have developed and tabulated screening levels for groundwater, soil gas, subslab soil gas, indoor air, and in some states, soil data. Many USEPA regions have adopted regional screening levels, which summarize indoor air screening levels for residential and commercial or industrial receptors. Soil and groundwater regional screening levels, however, are not necessarily protective of the VI pathway.
2. Comparison of concentrations to screening levels calculated from attenuation factors. These screening levels typically are higher (less conservative) than the generic screening levels.
3. Comparison of concentrations to screening levels calculated from models, such as BioVapor, or an agency-specific model. These screening levels allow more site-specific adjustments to default parameters and, as a result, are typically higher (less conservative) than the screening levels from the previous two approaches.

Issues to consider when evaluating PVI data include:

- Screening levels for PHCs in groundwater generally do not account for biodegradation. As a result, use of groundwater models or attenuation factors generally overpredicts the potential for PVI.
- Soil data are usually not an acceptable line of evidence in many states for the VI pathway in general because predicted soil vapor concentrations from soil data are not reliable. In general, soil data overpredict the potential for PVI for vadose zone PHC sources where there is adequate separation between the source and the receptor, and biodegradation is occurring.
- PHC concentrations in soil gas also decrease with distance from the source because of biodegradation if sufficient O_2 is present. For states that use conservative soil gas attenuation factors or models that do not account for biodegradation, the calculated indoor air levels and corresponding risk from the soil gas data will be overpredicted. Vertical profiles of the soil gas PHCs between the source and receptor can be an effective approach to document the effect of biodegradation on soil gas concentrations and whether the VI pathway is complete.
- Subslab soil gas concentrations are often evaluated using a default attenuation factor or by comparing the measured concentrations to the overlying indoor air concentrations. Spatial heterogeneity of subslab concentrations and inaccuracy of default attenuation factors can complicate the interpretation of subslab data and lead to incorrect conclusions. Since slabs are known to “breathe” in both directions because of fluctuations in barometric pressure and building factors, measured PHCs in samples might also come from the indoor air of the overlying structure and from leaking drains and other utilities.
- Indoor air data are typically compared to indoor air screening levels and to ambient (outdoor) air levels. If the measured values are below the applicable screening values, then the VI pathway is considered not significant. Typically, more than one sampling round is required to confirm this conclusion. When measured indoor values exceed screening levels, typical

evaluation approaches include comparison of indoor air concentrations to subslab concentrations. If the indoor air levels exceed subslab levels, then an indoor source may be assumed. If subslab levels exceed indoor levels, a subsurface source may be assumed. In this latter case, other potential subsurface sources should be considered in addition to vapor migration from subsurface contamination. Forensic vapor intrusion approaches may be helpful. The evaluation may become more complex if there is contribution of PHCs from indoor air background sources, outdoor air sources, occupant activities, building materials, or other nonsubsurface sources. Appendix L includes information and references for background concentrations of PHCs.

4.3.3 Modeling

Vapor-transport modeling can be used during data evaluation to simulate the fate and transport of contaminant vapors from a subsurface source, through the vadose zone, and potentially into indoor air. Modeling at a potential PVI site can help guide vapor intrusion investigations, identify critical factors affecting transport, and help evaluate whether the aerobic biodegradation interface is likely to exist between the source and building foundation. The use of modeling, as well as a tiered analysis of increasing complexity, is described in greater detail in Chapter 5.

4.4 Step 7 - Determine whether Additional Investigation is Warranted

This step reflects the iterative nature of the PVI investigation in determining whether the site has been adequately characterized (ITRC 2007). Other questions to consider include the following:

- Have the site contaminants been properly delineated?
- Has the potential for PVI at all possibly affected buildings been assessed?
- Are there sufficient data to reach a vapor control decision at the site?

If the conclusion is that data gaps still exist that prevent a decision on the potential for PVI, refer to Appendix G for additional tools to investigate the PVI pathway (such as building construction and HVAC operating conditions or vapor flux).

4.5 Step 8 - Decide whether the PVI Pathway is Complete

Once it has been determined that sufficient data have been collected, the final step in site investigation is the determination on the completeness of the PVI pathway. If the pathway is incomplete, no further evaluation of the PVI pathway is necessary. If the pathway is complete, however, the investigator must assess vapor control approaches as discussed in Chapter 6.

5.0 MODELING

A modeling assessment is one of a number of optional methods applied in site investigation and evaluation (Chapter 4). This chapter includes guidance on the use of PVI models and reporting of modeling results (Section 5.0); a summary of VI model types; steps in using the models and the reporting of results (Section 5.2); and, lastly, a discussion of the BioVapor Model (Section 5.3).

The discussion of specific model use is focused on the relatively simple PVI model BioVapor, a one-dimensional analytical model that includes aerobic biodegradation (DeVaull, McHugh, and Newberry 2009; API 2010), but also applies for the similar PVIScreen model (Weaver 2012). Other PVI models may also be appropriate for use; a list of models is included in Appendix H. Both BioVapor and PVIScreen are similar in concept to the broadly applied Johnson and Ettinger (J&E) model (Johnson and Ettinger 1991; USEPA 2009d), but, in addition, include the significant effects of aerobic biodegradation. The J&E model has been widely used for assessing the effects of contaminated vapors on indoor air, but is not recommended for evaluation of PVI because it does not include aerobic biodegradation (USEPA 2013a), and is therefore overly conservative.

BioVapor and other models that incorporate biodegradation show distinct behavior for aerobically-degradable petroleum vapors. This behavior is illustrated in Figure 5-1, which includes model results for both BioVapor and a similarly-applied, three-dimensional numerical model (Abreu and Johnson 2006; Abreu, Ettinger, and McAlary 2009a; Abreu, Ettinger, and McAlary 2009b) in a typical basement scenario. Figure 5-1 shows the significant effects of biodegradation on benzene, both with increasing vertical building-source separation distance and with lower source vapor concentrations, as compared to results which neglect biodegradation. Modeling of other petroleum chemicals (not shown in Figure 5-1) exhibits results similar to Figure 5-1, but the precise estimates will vary.

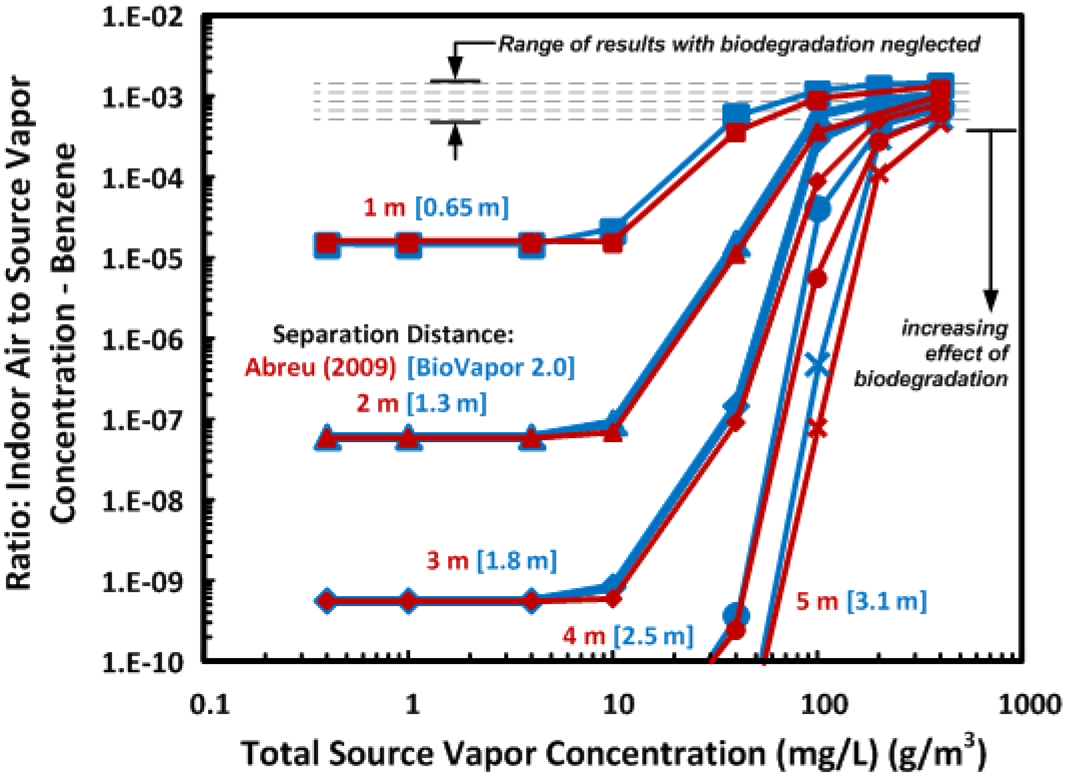


Figure 5-1. Example model results illustrating the effects of biodegradation on chemical concentrations reaching indoor air. Significantly lower indoor air concentrations occur for both lower source vapor concentrations and at increased separation distance, as compared to model results which neglect biodegradation. Both three-dimensional (Abreu, Ettinger, and McAlary 2009b; API 2009) and BioVapor model results are shown in a typical basement scenario for benzene.

Another observation from Figure 5-1 is that the range of PVI scenarios can lead to high, transitional, and low ratios of indoor air to source vapor (indoor-to-source) concentration or attenuation factor. Three groups of site conditions and their potential for VI are evident:

1. At high source concentrations and short distances, high indoor-to-source concentration ratios are predicted, which may present potential concerns.
2. In the transitional range, small changes in site and scenario conditions and related parameters may significantly affect the indoor-to-source concentration ratios predicted and thus the potential for indoor VI.
3. At low source concentrations and greater distances, very low indoor-to-source ratios are predicted, indicating no potential concern or need for further evaluation of any kind (beyond delineation of a spill zone).

These scenarios illustrate the need for a sensitivity analysis when using VI models, particularly for model applications in the transitional range, for which small changes in input parameters may significantly change the potential for PVI. Sensitivity analysis is discussed in greater detail in Section 5.1.5 and, for the BioVapor model, in Section 5.3.2.

5.1 Use of Models for Assessing PVI

PVI models may be useful for sites that require further assessment based on the screening and application of the vertical screening distances described in Chapter 3, Site Screening. The complexity of modeling applications can vary greatly depending on the objectives of the modeling and availability of project-specific information. In general the steps indicated in Figure 5-2 should be followed and documented in the modeling report.

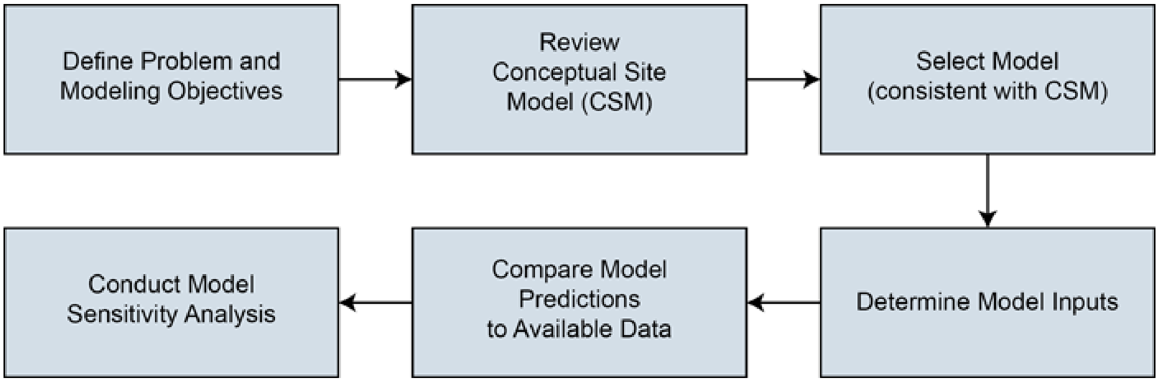


Figure 5-2. Steps in the modeling process.

5.1.1 Define the Problem and the Modeling Objectives

Prior to conducting any model simulations, the purpose and objectives of the modeling should be clearly understood and defined. The modeling objectives and purpose play a role in model selection. The objectives can also influence selection of parameter values and can help to determine the level of detail and accuracy required in the model simulations.

The following list includes example applications of PVI modeling, along with typical objectives for each modeling application:

- *Site-specific predictive modeling to assess current or future conditions*. Modeling in this context is typically conducted in conjunction with a risk assessment. Input parameter values are selected to represent site conditions, but tend to be conservative because of the risk context. In some instances, such as where buildings do not currently exist but are planned for the future, modeling can predict vapor migration and attenuation for the future conditions anticipated at the site.
- *Site-specific modeling to help develop a CSM*. PVI models can be used to explain key processes and data and to test and verify the CSM through comparison to available data. At petroleum release sites, a biodegradation model, such as BioVapor, may be used to match measured O_2 and PHC profiles in soil gas. Used in this way, a model can help to test and verify the CSM and evaluate the significance of vapor attenuation processes. In addition, PVI models can be used to evaluate the possible contribution of background sources to indoor air relative to the contribution from subsurface vapor sources.

- *Inverse modeling to develop site-specific cleanup goals*. Some agencies may allow the derivation of site-specific cleanup goals through inverse modeling. With inverse modeling, acceptable concentrations of contaminants in indoor air are first identified. Then, a site-specific model is used to back-calculate the predicted concentrations needed in soil gas, soil, or groundwater to attain the acceptable contaminant concentrations in indoor air.
- *Remedial design and selection*. A PVI model can be used to assess the O_2 flux to the subsurface that is required to achieve cleanup goals as part of a soil gas mitigation evaluation and technology selection process.
- *Modeling to support the development of PVI screening criteria and distances*. Modeling in this context may be relevant or applicable when conditions or assumptions differ from those presented in Chapter 3. An example is a petroleum vapor source composition that differs significantly from gasoline. The screening criteria may include site-specific vertical screening distances or modified source-to-indoor air ratios, which apply when specific conditions are met.

For modeling, a tiered process is generally used. Initially, when site-specific data may be lacking, a model may rely on generic, conservative assumptions. Predictions at this tier are intentionally conservative and based on a simplified CSM, thus the model tends to overestimate exposure and risk. If site management decisions cannot be made at this stage, or the model estimates an unacceptable level of risk is present at this stage, then the modeling may progress to a refined tier, where some of the conservatism is addressed with additional site-specific data.

5.1.2 Review Conceptual Site Model

A model application should be consistent with the CSM developed for a site, summarizing the source of vapors, the expected migration pathways, important processes affecting vapor migration and attenuation, and the receptor that may be potentially exposed to the vapors. Clearly document components of the CSM and how they apply to the model. The CSM may contain areas of uncertainty because of a lack of field data. These areas of uncertainty and how they affect the modeling objectives should also be documented.

5.1.3 Select an Appropriate Model

An appropriate model should be selected to simulate the physical system defined in the CSM and for which site-specific data are available to populate the model. More complex models demand more input parameters, and the requirements for site-specific data collection increase with model complexity. It is critical that the model formulation and assumptions are consistent with site conditions and the CSM. For example, if the PVI source is not beneath the building, and depending on model objectives, selection of a one-dimensional upward transport model may not be appropriate.

Section 5.2 and Appendix H discuss models that incorporate biodegradation, and are thus appropriate for potential PVI sites. BioVapor is described in greater detail in Section 5.3.

The computer code selected for the modeling application should be well documented and have been tested for the intended use. A brief description of the model code should be provided in a report along with citations for model documentation.

5.1.4 Determine Model Inputs, Compare Model Predictions to Data, and Calibrate Model

In matching models to data, the ranges of model parameter values should be consistent with the CSM and based on empirical data. In model calibration, model estimates are compared to available data then, if they differ significantly, the model and the data are reevaluated, and the model inputs are adjusted as warranted. Typically, model comparisons focus on soil vapor data because indoor air may be affected by background sources of PHC chemicals.

Model calibration may or may not be part of the modeling application, depending on the modeling purpose, objectives, and available data. Where a model is not calibrated to field data, choose input parameter values that result in overestimates of concentrations and indoor exposure.

If a model is calibrated, then document the calibration criteria, procedure, and results, as well as the source and relevance of the observed data used in the calibration.

5.1.5 Conduct Model Sensitivity Analysis

Some degree of uncertainty is associated with predictive modeling results; understanding this uncertainty allows better interpretation of these results. Uncertainty can be assessed by performing a sensitivity analysis, which identifies those parameters that most significantly influence the modeling results.

Sensitivity analysis assesses the effect of parameter variation on model results and can be performed during model simulations and during model calibration. The reliability of the model can be assessed by evaluating the sensitivity of model responses to changes in parameter values that reflect plausible parameter uncertainty. The uncertainty may be bounded by selecting worst-case and best-case input values. Sensitivity analysis can also be performed to help identify data deficiencies.

Model applications should address the sensitivity of model outcomes to the choices made in the model inputs. Uncertain parameters that have a strong influence on model results should be identified and discussed. A notable example is the aerobic biodegradation rate, which can exert a significant influence on modeling results for a PVI site.

Parameter uncertainty and sensitivity analyses are critical components of any modeling exercise and are often recommended as best practices (USEPA 2004; ITRC 2007). These practices are especially valuable for screening assessments, in which model input parameters (such as pressure differential, soil permeability, ventilation rate, and moisture content) are not easily measured and are generally unknown for a specific site. The difficulty in obtaining measurements for some parameter inputs has forced investigators to rely heavily on literature values or professional judgment. To aid in selecting inputs, default parameter ranges and look-up tables have been defined (Johnson et al.

2002; Johnson 2005; USEPA 2004; Tillman and Weaver 2007). Where parameters are both uncertain and sensitive, it is generally best to choose conservative values.

5.2 Models for Petroleum Vapor Intrusion

The use of PVI models in regulatory programs varies, and continues to vary, as rules and regulations are revised. A recent U.S. state survey (MADEP 2010) indicates that, in states where VI modeling may be applied, it: (1) may be used as the sole basis for eliminating consideration of the VI pathway (11 states); (2) it may be applied as a line of evidence in the investigation (7 states), or (3) if applied, it may require confirmatory sampling (8 states).

Three types of models are used to evaluate PVI:

- empirical models, which use predictions based on observations from other sites (such as bioattenuation factors)
- analytical models, which are mathematical equations based on a simplification of site conditions (such as the J&E model)
- numerical models, which allow for simulation of multidimensional transport and provide for more realistic representation of site conditions

This section provides an overview of PVI models that incorporate aerobic biodegradation, with additional details provided in Appendix H.

5.2.1 Empirical Models

Empirical models use an appropriate distance or attenuation factor derived from a compilation of relevant data to screen a site for PVI potential or to estimate an indoor air concentration. The vertical screening distances discussed in Chapter 3 are the result of empirical modeling.

5.2.2 Analytical Models

Analytical models for assessment of PVI exclusively consist of one-dimensional or compartmental models with a uniform planar subsurface source at a specified depth. A primary distinguishing feature of analytical models for PVI application is whether they incorporate biodegradation. A comparison of models for evaluation of VI both for CVOCs and for PHCs is presented in the Bekele study (Bekele et al. 2013).

The BioVapor model (DeVaull 2007; API 2010) is a modification of the J&E model incorporating O_2-limited biodegradation and includes improvements on earlier models (Johnson, Kemblowski, and Johnson 1998, 1999; Spence and Walden 2011). These improvements include options for setting several different boundary conditions for O_2 recharge to the subsurface, as well as accounting for all PHC present. The O_2-limited model only simulates biodegradation in soil zones when there is sufficient O_2, which is an important feature for biodegradation models. The BioVapor model has been extensively reviewed (Weaver 2012) and the USEPA is currently developing a version of this model (PVIScreen). The BioVapor model is described in greater detail later in this chapter.

5.2.3 Numerical Models

Numerical models offer potential advantages for simulation of conditions requiring additional detail, such as heterogeneity, geometric complexity, and temporal variability. PVI numerical models have typically been applied to obtain a more detailed understanding of causes and effects of vapor transport and attenuation (specific models are identified in Appendix H). Because of their complexity, numerical models require more data and effort (and therefore increased cost) than analytical models and thus, for practical applications, are rarely used.

5.3 BioVapor Model

The BioVapor model (DeVaull 2007; API 2010) is a one-dimensional model based on a CSM similar to the J&E model, but it includes aerobic biodegradation. The BioVapor model has been reviewed and accepted by USEPA (Weaver 2012) and is the basis for the USEPA PVIScreen model (2014a). Currently, BioVapor has been cited by a number of regulatory agencies and programs (for example USEPA OUST, California, Michigan, Illinois, and Australia). BioVapor evaluates O_2-limited aerobic biodegradation using an analytical solution to calculate the aerobic depth below ground surface. This calculation describes a shallow aerobic layer where first-order biodegradation occurs and a deeper anaerobic layer where biodegradation does not occur (see Figure 5.3). In the absence of biodegradation, the BioVapor model produces equivalent results to the J&E model.

The BioVapor model helps to assess the significance of data for groundwater, soil vapor, and soil, when PHC concentrations exceed applicable screening criteria. The BioVapor Model should not be used when LNAPL or contaminated groundwater is in contact with a building, or directly entering a building, because the model does not simulate these conditions. The conceptualization for the BioVapor model is based on constant, uniform contamination source, diffusion-dominated transport and a single, homogeneous soil layer. There are certain conditions outside of this conceptualization where BioVapor should generally not be used such as significant pressure-driven flow (for example, a landfill setting) or transport through preferential pathways (for example, sewers directly connecting an LNAPL source to a building). There may be other conditions where BioVapor may be applied conservatively or to portions of the site, such as heterogeneous soil layers or nonuniform contamination sources. For BioVapor, as for any model, consult the applicable regulatory agencies to determine whether the model results will be accepted.

5.3.1 Model Input Parameters

BioVapor (and PVIScreen) are conceptually similar to the broadly applied J&E model and share many similar (often identical) defined model parameters. Default values and applicable ranges for model input parameters, including the additional parameters specific to the BioVapor model are provided in Table 5-1, along with a qualitative description of the sensitivity of BioVapor model to input parameters. Other guidance on the selection of J&E model input parameters is also available (see Hers et al. 2003; USEPA 2004; Weaver and Tillman 2005; Johnson 2005).

Input parameters for the BioVapor model that affect biodegradation aspects of the model are:

- O_2 supply beneath the building
- chemical parameters and concentrations, including all PHC sources or degradation products with oxidative demand (such as methane)
- chemical-specific, first-order biodegradation rate constants
- baseline rate for O_2 respiration in soils
- minimum O_2 for aerobic respiration
- distance from bottom of building foundation to contamination source
- type of building foundation (which affects the O_2-supply boundary condition)

Information on key input parameters for biodegradation modeling is provided below.

Table 5-1. Relevant model parameters, ranges, and parameter sensitivities for the BioVapor model

Parameter	Default value	Normal range	Parameter sensitivity	Reference
Values for building parameters				
Indoor mixing height, L_{mix} (cm)	244 (Residential) 300 (Commercial)	(-)	Low	USEPA 2004 ASTM 2000
Air exchange rate, ER (1/day)	6 (Residential) 12 (Commercial)	Min: 1.3	Moderate	USEPA 2004 ASHRAE 2004
Foundation thickness, L_{crack} (cm)	15	(-)	Low	USEPA 2004
Foundation area, A_b (cm^2)	1.06E+6	(-)	Moderate	USEPA 2004
Foundation crack fraction, η (cm^2-cracks/cm^2-total)	3.77E-4	0–1	Low to moderate	USEPA 2004
Total porosity (soil-filled cracks), $\theta_{T,crack}$ (cm^3-void/cm^3-soil)	1.00	0–1	Low	USEPA 2004
Water-filled porosity (soil-filled cracks) $\theta_{w,crack}$ (cm^3-void/cm^3-soil)	0.00	0–1	Low	USEPA 2004
Airflow through foundation, Q_s (cm^3-air/sec)	83	Min: 0	High	USEPA 2004
General comments – effect of building parameters on model results: • relatively insensitive, unless biodegradation is negligible • sensitive to airflow through foundation, Q_s, if O_2 in the subsurface (and therefore aerobic biodegradation) is limited • residential: (single-family house, slab-on-grade); commercial: (small office or retail building, slab-on-grade)				
Values for vadose zone parameters				
Soil porosity, θ_T (cm^3-void/cm^3-soil)	0.375	0.1 – 0.5	Low	USEPA 2004, Johnson 2005
Soil water content, θ_w (cm^3-water-/cm^3-soil)	0.054	0 – 0.5	High	USEPA 2004, Johnson 2005
Soil organic carbon fraction, f_{oc} (cm^3/cm^3-soil)	0.005	0.0001 – 0.1	See Baseline Respiration	Nominal
Soil density – bulk, ρ_s (g-soil/cm^3-soil)	1.7	1.5 – 2	Low	ASTM 2000

Table 5-1. Relevant model parameters, ranges, and parameter sensitivities for the BioVapor model (continued)

Parameter	Default value	Normal range	Parameter sensitivity	Reference
Airflow through foundation, Q_s (cm^3-air/sec)	83	(-)	High	Hers et al. 2003, USEPA 2004
Air flow underneath foundation, Q_f (cm^3-air/sec)	(-)	≥ Qs	High	No Default
O_2 concentration below building, at soil surface (atmospheric, for dirt-floor, otherwise apply if measured below foundation)	Optional	0 – 21%	High	
Aerobic depth, L_a (cm)	Optional	0 – L_T	High	
Minimum O_2 concentration for aerobic biodegradation, $O_{2\text{-min}}$	1%	0 – 1%	Low	DeVaull, 2007
Annual median soil temperature, T (°C)	10	0 – 30	Low	USEPA 2004
Baseline soil O_2 respiration rate, Λ_{base} (mg-O_2/g-soil-sec); function of f_{oc}	1.956E-7	Minimum: 0	Low to Moderate	DeVaull, 2007
Depth to source (from bottom of foundation), L_T (cm)	300	(-)	Moderate to high	None
First order aerobic biodegradation rates, k_w (1/sec)	Chemical-specific	See text	Moderate to High	DeVaull 2011
Generally, model results can be sensitive to: • parameters affecting subsurface O_2: airflow (Q_s, Q_f); O_2 at soil surface; baseline O_2 demand (f_{oc}, Λ_{base}); and diffusion (θ_T - θ_w). • parameters affecting degradation: kinetic degradation rates (k_w); depth to source (L_T); diffusion (θ_T - θ_w); and moisture (θ_w)				
Values for source zone parameters				
Chemical-specific source vapor concentration (mg/m^3)	Scenario-specific	0–100,000	Moderate	See text
Total source vapor concentration (mg /m^3)	0.054	0–100,000	High	See text
Generally, model results can be sensitive to higher total source vapor concentrations, for which O_2 may be limited. Any source chemicals which may aerobically biodegrade contribute to total O_2 demand (including methane).				

References:

USEPA 2004. *User's Guide for Evaluating Subsurface Vapor Intrusion into Buildings*, Table 9. February 22, 2004. Online at itrcweb.org/FileCabinet/GetFile?fileID=6921.

ASTM 2000. ASTM E-2081-00: *Standard Guide for Risk-Based Corrective Action*. American Society for Testing and Materials, Philadelphia, PA.

ASHRAE 2004. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). 2004. *Ventilation for acceptable indoor air quality*. ASHRAE Standard 62.1-2004.

DeVaull, G.E. 2007. "Indoor vapor intrusion with O_2-limited biodegradation for a subsurface gasoline source." *Environ. Sci. Technol*. 41: 3241-3248.

5.3.1.1 O_2 Supply Below Building

BioVapor has three options for identifying the O_2 supply or flux below the building foundation (see Figure 5-3).

- Constant airflow rate is typically used for solid foundations (basement or slab-on-grade), where air flow is induced by stack effect (or other mechanisms causing building depressurization) or by the effect of wind on buildings.
- Constant O_2 concentration at surface below the building applies to earthen-floor foundations or dirt-floor crawl spaces, or where subslab O_2 concentrations are measured
- Fixed aerobic depth below grade applies when measurement data on this depth are available.

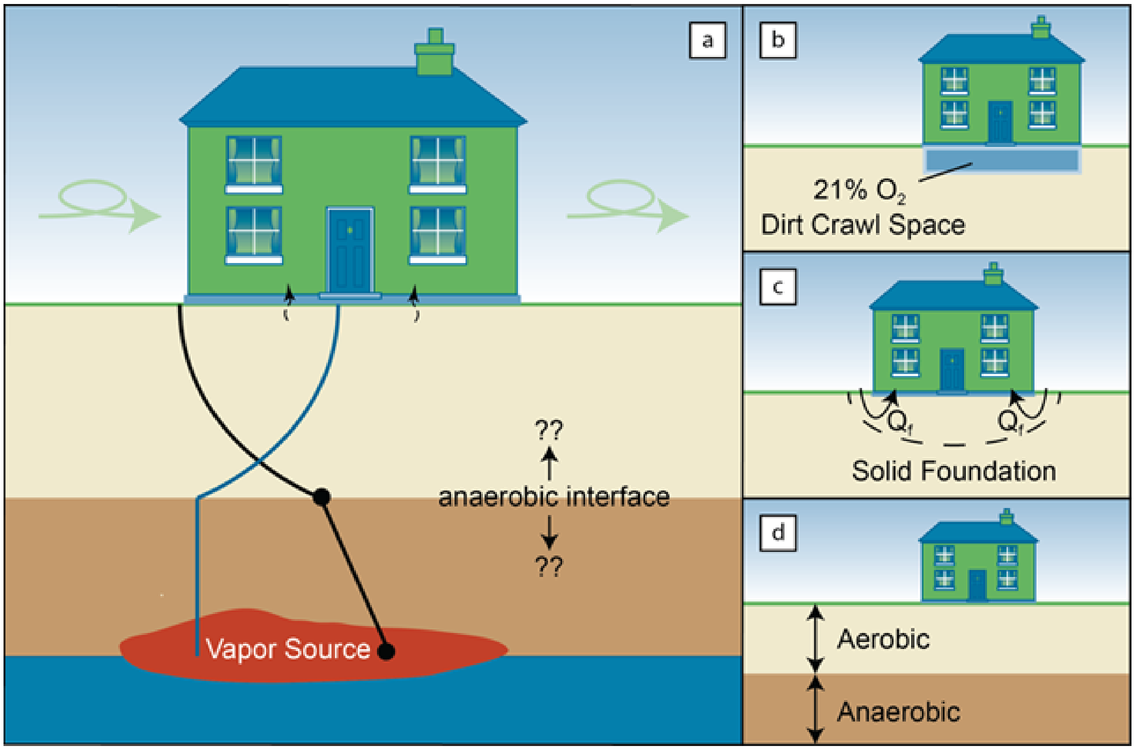


Figure 5-3. (a) BioVapor model biodegradation conceptualization; (b) O_2 boundary conditions consisting of constant O_2 concentration; (c) constant air flow; (d) fixed aerobic zone depth.

Source: Adapted from API (2011).

In the BioVapor model, two different airflow rates may be specified: airflow through the foundation (Q), and airflow under the foundation (Q_f). The Qs parameter relates solely to soil gas advection and is used to calculate the mass transfer of chemicals through the foundation as soil gas is drawn into a depressurized building. The Q parameter describes the advective airflow rate to below the foundation (Figure 5-3c), and is used solely for calculating the O_2 supply or flux into soil below the foundation that is available for aerobic biodegradation (based on airflow rate, assuming atmospheric O_2 concentration). Guidance on estimating the Qs parameter or soil gas advection rate, a common parameter for input into the J&E model, is provided in Hers et al. (2003) and USEPA (2004).

The *BioVapor User's Guide* recommends that Q_f be assumed greater or equal to Q_s, because soil gas advection below and into the building also supplies O_2. In addition, O_2 mass flux by diffusion, both through the building foundation and through lateral migration from the sides of the building, will also supply O_2 for biodegradation. Modeling by DeVaull (2012) showed that when the foundation permeability is low (and thus the soil gas advection rate is low), the diffusive mass transport is proportionally high. In qualitative terms, this means that when Q_s is low, it generally is appropriate for Q_f to be higher than Q_s to account for O_2 diffusion.

5.3.1.2 Chemical Concentrations

The BioVapor model also requires information about PHCs. PHCs are a mixture of aliphatic and aromatic compounds (see Appendix C). Aliphatic compounds are composed of straight-chain, branched, or cyclic compounds and can be saturated (alkanes) or unsaturated (alkenes, alkynes, and others), whereas aromatic compounds contain one or more benzene or other conjugated heterocyclic rings within their structures. In general, aliphatic and aromatic hydrocarbons of moderate molecular weight (such as hexane or heptane) are more toxic than both lighter and heavier molecular weight aliphatic compounds commonly present at significant concentrations in soil vapors (USEPA 2009b). Aliphatic hydrocarbons are the primary components in vapors near petroleum sources such as gasoline and diesel.

The BioVapor model requires input of chemical concentrations for three groups of PHCs:

- risk drivers (such as BTEX or hexane)
- other PHC compounds, which are not risk drivers but represent an oxygen demand
- hydrocarbon surrogates, which include multiple chemicals (for example, hydrocarbon ranges) and which may also not be risk drivers, but represent an oxygen demand

Contaminant concentrations for both soil gas or groundwater sources may be entered, and new chemicals may be added to the database. Concentration data for groundwater may be used for a dissolved PHC source, but soil vapor data are recommended for an LNAPL source.

BioVapor offers several options for estimating chemical concentrations. The oxygen demand required by the total hydrocarbons in soil gas should be accounted for by entering input data on PHC concentrations. The best practice for estimating source concentrations for BioVapor input uses PHC concentrations in soil gas estimated by one of the following methods:

1. Estimate concentrations of individual BTEX compounds and other risk drivers as warranted by an approved analytical method, and use empirical relationships to estimate concentrations of other aliphatic and aromatic hydrocarbons. These estimates may be obtained from either literature values that are based on representative TPH concentration for product type (such as DeVaull, McHugh, and Newberry 2009) or measured TPH (such as USEPA Method TO-

3). This method is acceptable when the type of product at the site is known.
2. Estimate concentrations of individual BTEX compounds and other risk drivers as warranted by an approved analytical method and measure aliphatic and aromatic hydrocarbon ranges (for example, Massachusetts APH method for aliphatics and aromatics).
3. Use USEPA Method TO-15 analysis with an extended PHC analyte list, including tentatively identified compounds, modified to account for C5 and C6 aliphatics to provide a reasonable accounting of total hydrocarbons present.

For all methods, analyze methane and other fixed gas concentrations according to an accepted method.

Guidance on estimating petroleum vapor composition and vapor concentrations in LNAPL source zones is provided in Table 5-2. For example, if the source is fresh gasoline and BTEX concentrations are measured and either the measured or estimated TPH concentration is 200 mg/L, then the concentration of the aliphatic hydrocarbons would be the difference between the TPH and the sum of BTEX compounds. As shown, the concentrations of TPH vapors in diesel source zones are significantly lower than those in gasoline source zones. The concentrations of individual hydrocarbon components and TPH in soil vapor directly above dissolved-phase TPH plumes in groundwater are generally at least 100 to 1,000 times lower (and often much greater than 1,000 times lower) than those within LNAPL source zones (USEPA 2013a).

Table 5-2. Petroleum vapor composition (adapted from API 2010)

Compound	Fresh gasoline	Moderately weathered gasoline	Diesel
Benzene	0.25–1%	1–2%	<<1%
Toluene, ethylbenzene, xylene	1–4%	5–15%	<1%
Other aromatic hydrocarbons	<0.1%	<1%	<10%
Aliphatic hydrocarbons	95–99%	83–94%	>90%
Total hydrocarbons	≈200 mg/L	≈100 mg/L	≈1–5 mg/L

5.3.1.3 First-Order Biodegradation Rate Constants

In the BioVapor model, degradation is defined in terms of a first-order water-phase aerobic degradation rate, k_w (hr^{-1}). Degradation is assumed to occur only in the water phase of the soil matrix (and only when O_2 is present), at a rate proportional to chemical concentrations in the water phase. A statistical compilation of first-order water-phase biodegradation rates from laboratory and field studies (DeVaull 2007; DeVaull 2011) for air-connected vadose zone soils is shown in Table I-2 in Appendix I. The geometric mean first-order biodegradation rate constants for commonly considered chemicals are 0.3 hr^{-1} for benzene and 13 hr^{-1} for trimethylpentane. The median or geometric mean rate constants in Figure 5-4 or listed in Table I-2 are a reasonable starting point for modeling. As part of a sensitivity analysis, a range of rate constants should be simulated. The most likely rates in the distribution are the median (or geometric mean) values. The lowest rates in this empirical data set may have been derived, in some cases, for soils which were not actually uniformly aerobic soils.

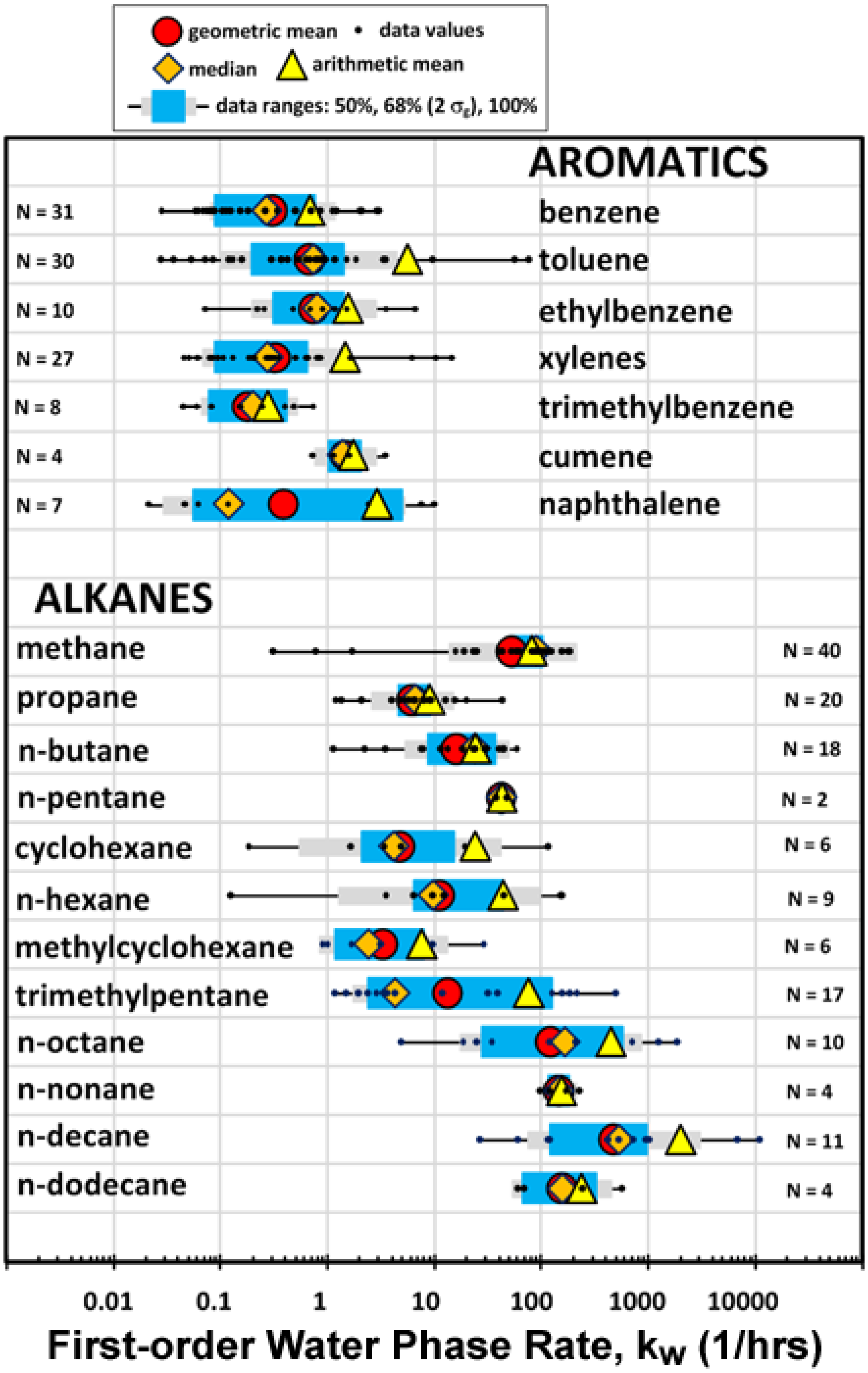


Figure 5-4. First-order water phase biodegradation rates (hr^{-1}) in aerobic vadose zone soils.

Source: *DeVault 2011*.

5.3.1.4 *Baseline Soil O_2 Respiration Rate*

The baseline soil O_2 respiration accounts for the natural oxygen demand from the soil and may be specified directly or estimated from the soil organic carbon level (f_{oc}) based on an empirical relationship developed by DeVaull (2007), as follows:

$$\text{Baseline Soil } O_2 \text{ Respiration Rate} = 1.69 \text{ (mg } O_2/g_{oc} \text{ day) x } f_{oc}$$

For the range $0.0004 < f_{oc} < 0.4$, errors in the O_2 respiration estimate are within a factor of approximately 10 of the correlation at a 95% confidence level (DeVaull 2007). This equation is the BioVapor default value and is recommended in the absence of site-specific data.

5.3.1.5 Minimum O_2 for Aerobic Respiration

The BioVapor model default of 1% is reasonable for modeling purposes. Evidence from field studies with detailed profiles indicates O_2 depletion to low concentrations (<<1%) and a corresponding reduction in petroleum vapor concentrations (see, for instance, Davis, Patterson, and Trefry 2009).

5.3.2 Model Sensitivity

The BioVapor model can show a large sensitivity to source zone concentration and vertical separation distance in cases where biodegradation is the primary attenuation mechanism (DeVaull 2007; Weaver 2012). For these conditions, parameters relating to subsurface O_2 availability (O_2 concentration, foundation airflow), the biodegradation rate and soil moisture can have a significant influence on model estimates (Weaver 2012). Table 5-1 provides a qualitative evaluation of model sensitivity and uncertainty (and recommended data sources).

At sites where biodegradation is negligible, such as sites with high concentration sources and short vertical separation distances, the sensitivity of the BioVapor model is similar to that for the J&E model, which is applicable for nondegrading chemicals. For these conditions, parameters describing the building enclosure and foundation show a significant effect on model estimates (Weaver and Tillman 2005; Weaver 2012; Picone et al. 2012). These parameters include most significantly the building air exchange rate and the foundation air flow rate.

When using a PVI model such as BioVapor, conduct a sensitivity analysis by varying key input parameters to account for uncertainty and variability in site conditions. The key parameters affecting subsurface fate and transport include the O_2 boundary conditions, the first-order decay rate, the PHC source vapor strength, and the soil moisture content. Input a conservative estimate of the distance from the building foundation to the subsurface PHC source. Appendix I includes a more detailed discussion of parameter estimates and input values.

6.0 VAPOR CONTROL AND SITE MANAGEMENT

Management of petroleum vapors may be required at sites where the results of the site investigation indicate that concentrations of PHCs in indoor air exceed mitigation action levels, or are likely to exceed screening levels in future buildings. PVI can be managed by environmental remediation, institutional controls (ICs), building mitigation, or any combination of these approaches. Traditional remedial technologies applied to the source may be sufficient to mitigate PVI for buildings located close to the source. ICs or building mitigation systems can also provide additional notification or protection from potential exposures while longer-term remedies are being developed and implemented. This chapter explains how to evaluate and select a strategy for mitigating PVI, as well as how to identify metrics for performance and closure strategies.

This chapter focuses on chronic exposures and design of an appropriate response. Some of the technologies discussed may be similar to those for emergency situations where the immediate or short term health and safety of the building occupants is the primary concern. Both short-term and long-term risks should be considered to determine the appropriate response action.

Stakeholders are often concerned about whether proposed approaches adequately address risk. Chapter 7, Community Engagement, provides information and tools for developing an appropriate plan to address these concerns. For further information on site management strategies for vapor intrusion in general, Appendix J provides an updated section for the remedial and vapor control technologies originally identified in *Vapor Intrusion Pathway: A Practical Guideline* (ITRC 2007).

6.1 Vapor Control Strategies for Petroleum Hydrocarbons

Types of vapor control strategies for PHCs include the following:

- environmental remediation
- institutional controls
- mitigation

Environmental remediation reduces or eliminates the exposure threat by removing contaminant mass from an environmental medium. Mitigation prevents or minimizes exposure by truncating the exposure pathway before vapors can enter a building. ICs are administrative and legal controls that help minimize the potential for human exposure and often protect the integrity of the site remedy. Typically, mitigation measures can be implemented quickly to lessen exposure, whereas remediation takes longer to achieve risk reduction. For this reason, mitigation may be coupled with remediation of the contaminant source. Mitigation measures may also allow immediate reduction of risk to human health prior to remedy selection. ICs are usually necessary while remediation is ongoing, and mitigation of the pathway is required.

For PVI, the interim response action may be the final response action, or the interim response may include a technology that can be rapidly implemented but that will not fully or permanently address the problem. Interim action may be needed quickly to protect human health and the environment from an imminent threat while a final remedial solution is being developed. Temporary interim measures can also stabilize the site or portion of a site (such as an operable unit) and prevent further migration or site degradation.

These vapor control strategies can also be used preemptively to mitigate vapors. When one or more lines of evidence indicate the potential for VI, preemptive action may be reasonable, especially for CVI sites (where preemptive mitigation may be less expensive than a lengthy VI evaluation). For PVI, however, biodegradation without any mitigation is likely to reduce the time needed to maintain the vapor control system or the IC. Also consider the future operation, maintenance, and monitoring requirements of any preemptive mitigation strategy.

At larger operating petroleum facilities, including refineries and terminals/depots, combinations of engineering and institutional (access) controls may already be in place and may be sufficient to address potential PVI issues. For example, in some buildings positive pressure can be induced in order to meet NFPA electrical requirements.

6.1.1 Remediation to Reduce or Eliminate Petroleum Vapors

Effective VI remedial actions reduce exposures to vapors by lowering concentrations in the soil and groundwater to levels that no longer serve as a source of unacceptable vapor concentrations. Levels can be established using the approaches described in Chapter 5, Modeling, or using other state approved methodology or requirements.

Remedial technologies, such as soil vapor extraction (SVE), are typically used to reduce contaminant concentrations in site soils and soil gas. In some cases, these technologies can reverse the flow of vapors from migrating towards or into a structure which may potentially preclude indoor air sampling when the radius of influence can be demonstrated. For these situations, however, an IC may be required. Figure 6-1 shows a small-scale SVE system intended to intercept the vapors migrating to a structure. Remedial technologies such as in situ bioremediation or multiphase extraction can also reduce source contaminant concentrations.

Figure 6-1. Small-scale SVE system designed to address the source of vapors and protect the on-site building. The housing contains a small SVE blower that services SVE wells and was not designed to address the entire source of vapors.

Source: Vapor Mitigation Sciences, LLC.

In general, remedies that directly address the source of the vapors or remedies that facilitate the removal or redirection of the vapors are likely to have the greatest potential to reduce or eliminate VI. If implemented before the contaminated vapors have a chance to migrate to receptors, these remedies may also preempt mitigation actions or ICs.

For PVI, three general remedial approaches address volatilization to indoor air:

- A remedial technology is implemented sitewide to address the source of vapors, as well as any vapors migrating into or towards a building.
- A remedial technology is designed and implemented on a smaller scale to address a specific route of entry (such as a preferential pathway) or a specific structure.
- A remedial technology is implemented quickly enough (for instance, source removal through dig and haul) that mitigation is not warranted and no emergency response is required.

Remediation and site-wide remedies are not the focus of this document; however numerous other resources can help in selecting technologies for source control:

- *ITRC Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater*, 2nd edition (ITRC 2005b)
- *Evaluating LNAPL Remedial Technologies for Achieving Project Goals (LNAPL-2)* (ITRC 2009)
- *CLU-IN: Technologies: Remediation* (USEPA 2013g)
- *Institutional Controls* (USEPA 2013k)

- *Road Map to Understanding Innovative Technology Options for Brownfields Investigation and Cleanup*, 4th edition (USEPA 2005a)
- *Engineering and Design: Soil Vapor Extraction and Bioventing* (U.S. Army Corps of Engineers 2002)
- *Engineering and Design: Multi-Phase Extraction* (U.S. Army Corps of Engineers 1999)

General information on how these remediation technologies can be applied at PVI sites is included in Appendix J, Vapor Intrusion Control.

6.1.2 Institutional Controls

ICs are non-engineered instruments, such as administrative and legal controls, that help minimize the potential for human exposure to contamination and protect the integrity of the site remedy. ICs are important because they limit land or resource use and guide human behavior at a site. These controls, however, also present significant drawbacks:

- ICs can be difficult to implement and enforce over time.
- An IC may be difficult to identify and not immediately apparent, especially ICs that establish building type and occupancy or prohibit activities on all or part of the property.
- An IC may limit or prevent future development activities.
- Some states or parties do not have adequate statutory authority to implement ICs.
- ICs that include restrictive covenants may include items such as zoning modifications, excavation prohibitions, and groundwater advisories. ICs may be necessary to adequately protect human health at sites where remedies have not been implemented or are not immediately effective in reducing or eliminating the potential for PVI. ICs may also be necessary to effectively address the VI pathway at undeveloped sites or at sites where land use may change in the future. In most states, ICs can be put in place on either an interim or permanent basis to protect human health while the longer term site-wide remedies are being developed and implemented or to sever the inhalation pathway without any actual remediation occurring.

At undeveloped sites or at sites where an unrestrictive closure has not been obtained, ICs may also be necessary to address the potential for future exposures to occur. ICs at undeveloped sites can include mechanisms to require the preemptive installation of VI controls, such as vapor barriers or subslab depressurization systems, or additional investigations as part of any new construction or site modifications. This approach avoids some of the difficulties associated with attempting to predict the potential for VI prior to building construction (because soil gas concentrations and distributions might change as a result of construction of the building).

This document does not focus on ICs; however, several guidance documents are available that discuss the implementation of effective and reliable ICs. For more information on ICs, see *An Overview of Land Use Control Management Systems* (ITRC 2008) and other resources on the USEPA IC website (USEPA 2013n).

6.1.3 Mitigation Using Building Control Technologies

Building control technologies mitigate potential exposures by reducing or preventing vapors from entering a building—commonly referred to as mitigation. These building control technologies seal the building entry routes, treat the indoor air, or provide an alternate migration route outside the building envelope for vapors. For PVI, this approach may also consist of implementing smaller scale remediation technologies that are designed to have a small area of influence and may not address the full extent of affected soil and groundwater. Though several remedial technologies are available, SVE is one of the most common methods for small-scale applications.

ITRC's guidance *Vapor Intrusion Pathway: A Practical Guideline* (ITRC 2007) describes many of these mitigation technologies. Appendix J, Vapor Intrusion Control, updates and expands the discussion of these mitigation systems. Additional technologies are provided, along with an updated summary listing the advantages and disadvantages of each. Table J-1 provides a summary of the common building control technologies implemented for PVI and the typical range of installed costs.

6.2 Vapor Control Designs

Building control technologies have been available for decades because of the concerns over exposure to radon. The application of this technology to the VI pathway has led to additional innovative approaches that must be evaluated when determining the appropriate design.

6.2.1 Factors for Selecting Vapor Control Technologies

A number of factors may affect selection of the technology employed for the mitigation of petroleum vapors, including the following:

- new versus existing buildings
- building size
- foundation type and condition
- soil conditions
- high water conditions
- presence of sumps and floor and footing drains

For more information on these factors and other details, see Appendix J.2. Some additional factors are unique to PVI sites, including:

- *COCs*. Because PHCs (as well as methane that is produced during biodegradation) can approach combustible concentrations, intrinsically safe blowers, wiring, and monitoring systems should always be evaluated for use. Additionally, petroleum vapors may cause degradation of membranes, pipes, or the solvents used to join pipes, so use care in selecting compatible materials—especially for systems that will be used for a long time.

- *Location of vapor source*. The location of the vapor source plays a key role in the design of a mitigation system. At sites where PVI has been confirmed, the source of the vapors is likely to be near, beneath, and possibly in direct contact with a structure.
- *Influence of O_2 in the subsurface*. Technologies that enhance O_2 levels, such as SSV or aerated floors, may help promote biodegradation in underlying soils (Luo et al. 2013).
- *Common background sources of petroleum compounds*. Because of the prevalence of background sources or levels of PHCs in indoor air, demonstrating mitigation performance through indoor air testing may be even more difficult than VI in general.
- *Sealing the subsurface without providing venting*. For other VI scenarios, often one of the first steps is to seal any subsurface cracks or features. Though this practice is usually appropriate to prevent vapors from entering into a structure (and must be considered), sealing can limit O_2 entering into the subsurface, which can affect the rate at which biodegradation occurs.

6.2.2 Design Factors and Installation of Building Controls

The following design factors and potential limitations should be considered for the installation of vapor controls that are common to the mitigation of all vapors:

- use of intrinsically safe equipment because of the potential presence of explosive levels of vapors and methane that may accumulate
- design approach and the level of detail necessary to complete the design
- need for stepped mitigation or future system modification and optimization
- requirements for discharge permits and emission controls
- presence of other chemical compounds
- preferences of the owner or tenant
- limitations on the design and installation of the controls
- constraints on collecting representative samples
- limitations on the placement of necessary system components, such as piping runs and vents
- constraints related to obtaining access and scheduling time for installation and assessment
- presence of lead-based paint or asbestos
- HVAC issues, including altering building pressures
- reliability and life cycle costs of the system to remain effective over time

More information on these factors related to system design at VI sites is included in Appendix J.

6.3 Operation, Maintenance, and Monitoring

An operation, maintenance, and monitoring (OM&M) plan should be prepared for each mitigation system that has been installed. The OM&M required for a system installed at a PVI site is typically similar to systems installed for other types of VI. Appendix J.5 discusses the various items that relate to the OM&M. Some aspects of OM&M for PVI sites, however, are different from other types of VI sites and should also be considered when developing an OM&M plan:

- *Monitoring parameters*. A mitigation system for PVI may need to monitor for O_2 and CO_2, as well as CH_4 and other potentially explosive gases, especially if the system was not designed to address the presence of explosive conditions.
- *Operating period*. For many sites, especially those that are undergoing remediation, the mechanisms being used to mitigate vapors will not be maintained or need to be operated over extended periods of time. Therefore, the evaluation of the lifetime average of various parts and components similar to those that ASTM (2005) discusses may require a different approach.

6.4 Closure for PVI Buildings and ICs

Remediation of the petroleum sources at most PVI sites will eventually reduce the concentrations of volatile petroleum compounds in soil or groundwater to values that are protective of human health. After appropriate levels are attained, mitigation systems may be shut down. It is typically prudent to collect confirmation samples to verify that the systems are no longer needed. Even without active remediation, most PHC sites are likely to see continued reductions in source concentrations because of naturally occurring biodegradation. This biodegradation will ultimately result in a reduction of PVI as source concentrations are depleted. With acceptable confirmation sampling results, long-term, vapor mitigation systems could be turned off and removed, depending on the preferences of the building owners and obligations of the responsible parties. Likewise, ICs could be updated or removed upon attainment of the remediation goals, as appropriate and as allowed by the local regulatory authority.

Early in the project, regulators and responsible parties for PVI sites should consider how to determine when vapor mitigation is no longer required. Typically, this determination is made by establishing remediation standards for various affected media, such as groundwater and indoor air. The decision to evaluate the shutdown of mitigation systems may be made when remediation goals for groundwater or soil vapor are attained. Tests to evaluate attainment should also be specified in planning documents. Because of the variability of VI and the many factors that affect it, each structure mitigated should be evaluated as part of the shutdown process.

In addition to remediation standards for groundwater, soil gas profiles of O_2, CO_2, and PHCs can generally be used to demonstrate sufficient biodegradation of PHCs, so that mitigation may no longer be necessary. Mitigation systems and remedial actions that have the potential to influence the flow of vapors must be shut down prior to collecting confirmation samples. Confirmation samples should not be collected immediately after system shutdown because of the potential for rebound of subslab vapor concentrations over time. The amount of time required for rebound, if any, depends on the vapor phase retardation factor of the compound, the effective diffusivity of the soil, and the square of the distance from the source (Johnson et al. 1999). For relatively shallow sources, rebound will likely occur within hours or days, while rebound may take years for sources that are several meters deep (Johnson et al. 1999). Considering that PVI is only likely to occur when sources are relatively shallow, testing after a period of about four weeks may be reasonable at most PVI sites. Another approach is to monitor subslab PID and O_2 levels over time and to collect confirmation samples when these values reach an asymptote or are unchanging. Because of the potential for temporal variability and uncertainty regarding rebound time, at least one additional confirmation sample (for instance, during the following heating season in cooler clients) may be warranted.

Some building owners may choose to continue operation of their mitigation systems to provide radon control. The building owner would be responsible for mitigation system O&M if the system continued operation for radon control.

Appendix J provides additional detailed information that should be considered as part of the shut-down process.

7.0 COMMUNITY ENGAGEMENT

Investigations at VI sites can be disconcerting and intrusive into the lives of individual stakeholders, who may have little technical knowledge about the issues confronting them. These stakeholders may have concerns related to VI in general, and PVI specifically, in addition to concerns typical of other types of environmental investigations.

Be Prepared for Questions

Regulators, project managers, and others involved in community engagement should be prepared to address PVI-specific concerns and questions that are likely to arise during any phase of investigation, mitigation, or remediation.

Community outreach and risk communication at PVI sites is, with a few exceptions, similar to outreach efforts for other environmental projects. This chapter discusses those exceptions and provides, in simple terms, some key technical concepts used in PVI projects that may be unfamiliar to nontechnical readers and the general public. In addition, this chapter discusses the elements of CEPs and provides guidance and tools for tailoring community engagement to PVI projects. Appendix K contains example “Frequently Asked Questions” sheets that can be used as is, or may be adapted to specific sites. Finally, this chapter describes stakeholder concerns that may be raised during a PVI project, includes strategies for identifying and addressing concerns, and offers guidance on risk communication for PVI sites.

At the start of a PVI project, regulators and project managers should consult agency outreach guidance or policies from their respective states. The ITRC document *Vapor Intrusion Pathway: A Practical Guideline* (ITRC 2007) provides useful material for issues common to VI. Finally, if USTs are present at the site, be aware that the federal government mandates public notification of affected parties for actions associated with USTs for which a corrective action plan is required under 40 CFR, Chapter 1.1 Part 280.67.

VI associated with PHC generally poses a lower exposure potential than VI at sites contaminated with CVOCs, such as tetrachloroethene and trichloroethene, and a much lower percentage of PHC sites actually have confirmed PVI than do CVI sites (USEPA 2012g). In many cases, the need for community engagement activities may be limited, or even unnecessary, depending upon the severity of the problem or site-specific conditions. However, the potential for PVI to affect property owners and occupants remains an issue for which preparations and procedures should be in place. When needed, outreach and communication with the potentially affected community can be critical for effective implementation of investigation plans and mitigation activities, while preventing adverse publicity.

Environmental regulators in most states overwhelmingly rely on VI guidance, or even general public relations guidance, at PVI sites (see Appendix A). As discussed in Section 7.2.3, several states currently have public outreach requirements and guidance for VI projects. Particularly comprehensive guidance is provided in California’s *Vapor Intrusion Public Participation Advisory*

(CAEPA-DTSC 2012). Existing guidance for outreach related specifically to PVI, however, is currently lacking.

7.1 Stakeholder Concerns

Stakeholder concerns associated with VI investigations have been listed in many publications, including information provided by many state regulatory agencies (USEPA 2002b, USEPA 2012e), Section 3.4 of ITRC's *Vapor Intrusion Issues at Brownfields Sites* (ITRC 2003), Section 1.7 and Appendix A of *Vapor Intrusion Pathway: A Practical Guideline* (ITRC 2007), and public advocacy groups, such as the Center for Public Environmental Oversight (CPEO 2005, CPEO 2011). These resources commonly cite the following factors to keep in mind when conducting VI investigations:

- importance of timely communication with the community
- need for sensitivity in, and training for, communicating with the public
- ability to translate and communicate technical information and public health issues into a format that is easily understood by the general public
- sensitivity to other impacts to public property, including property value, access, and private property rights
- need to interact with local organizations and government agencies that may have widely-varying responsibilities for, and methods of, dealing with VI (from inaction to emergency response levels)

As with any environmental site, stakeholders may have questions and concerns related to human health. At PVI sites in particular, gases such as methane may be generated in the subsurface as a by-product of biodegradation and create an explosion risk. Another concern at PVI projects is the potential for public mistrust of the use of modeling to make management decisions, particularly if no investigation is implemented as a result. Terms such as “uncertainty,” when used in the context of modeling, may be questioned as a means to avoid doing additional work or to minimize cost. Stakeholders may also request explanation of how the model works and the assumptions used in modeling.

Property owners are also usually concerned about devaluation of their properties. Generally, property owners and other stakeholders are concerned that remedial actions will be minimized, or the implementation schedule extended, to reduce costs to the responsible party. At PHC sites, stakeholders may have concerns when monitored natural attenuation (MNA) is implemented as the remedy (MNA relies on natural processes over time to achieve remediation goals or standards, often in controlled or monitored settings). This concern may be elevated when MNA is selected as a result of accepted modeling results or site screening specific to petroleum, especially if the results are not verified through future monitoring or sampling. Owners of properties or structures at risk of PVI may also be concerned with intrusive site investigations or corrective actions, which may disrupt business. The noise, the presence of environmental contractors, and the placement of equipment required for assessment and remediation may be of greater concern to a property owner or occupant than the potential health risks of PVI.

Sites that have PVI issues can be located in areas that have the potential to affect the public (near residences and commercial establishments, for example). For PVI projects, community stakeholders have many concerns, some of them unique. For instance, stakeholders may have questions or concerns arising from a lack of understanding of PHC biodegradation, including why and how a passive approach will address a PVI problem. Stakeholders may also conclude that "exclusion zones" are being established through site screening, in which no direct sampling will be performed and no data provided. The perceived, or actual, lack of data can create uncertainty that may result in future problems for landowners, tenants, and other stakeholders (during future property transactions, for example).

If a contaminated site is located in an area that has environmental justice (EJ) concerns, then regulators and consultants should consult with the federal (USEPA 2013a), state, local, or tribal government agency involved in EJ issues. The USEPA offers financial assistance to the EJ communities through grants and cooperative agreements. Financial assistance is provided to:

- build collaborative partnerships
- identify local environmental and public health issues
- envision solutions
- empower the community through education, training, and outreach

It is critical to identify all stakeholders involved for a PVI project. In addition to property owners (including their leaseholders and tenants) and other community members, stakeholders that should be kept informed of site activities may include:

- local government agencies
- water utilities
- law enforcement
- environmental activists
- local clergy and faith leaders
- neighborhood associations
- county and city governments or tribal councils
- government officials
- health departments and health care providers
- school boards

It is always best to be as inclusive as possible and reach out to all potentially interested parties through various means of communication. Be aware that varying levels of technical understanding exist within the community, and be prepared to communicate at those levels. Outreach may never be 100% successful—despite the investigators' best efforts, some in the community may assert that they were left out of a communications effort or process.

7.2 Community Engagement Plans

The purpose of a community engagement plan (CEP) is to explain the process by which site-related information will be provided to the community in a formal and coordinated manner. In many cases, it is the responsible party that prepares the CEP with approval and oversight from the regulatory body. The plan should be tailored to address risk to the community as a whole and to the individuals whose properties may be adversely affected. At the start of the community engagement process, strive for consensus among responsible parties, regulators, and other authorities on appropriate levels of outreach, and thoroughly document outreach activities. At a PVI project, information that must be conveyed to the community can be especially complex because of the multiple media affected and the transport mechanisms involved. The information provided to stakeholders should be in simplified terms so that community members without specialized knowledge can understand what to expect regarding communication, investigation, risk, mitigation, and remediation. The CEP should also identify sources of technical assistance for concerned citizens and explain how stakeholders can obtain answers to technical questions.

Know Your Agency's Policies

Although a variety of material is readily available on community engagement and risk communication, public agency staff should become familiar with their agency's guidance and policies and work closely with community engagement staff, if available. Existing engagement plans or guidance can be tailored to PVI-specific projects.

Ensuring that the community has essential information and access to technical resources will allow community members to develop the understanding needed to make informed decisions related to their personal risk. The CEP is a living document and is most effective when it is updated or revised as new information on site or community conditions become available.

7.2.1 Elements of a Community Engagement Plan

CEP development is commonly broken down into three components: basic information, the community profile, and the action plan. The basic information section should contain an introductory discussion of the purpose of the CEP, identify stakeholders, identify agency roles and responsibilities, provide a summary of community concerns, and contain background information on the site or event.

Basic Elements of a Community Engagement Plan

Introduction and Schedule

- *explains the purpose of the CEP*
- *lists the agencies with oversight responsibilities*
- *describes how information was obtained for the CEP*
- *briefly summarizes the community concerns*
- *outlines CEP organization*
- *provides the implementation schedule (internal and external)*

Site, Facility, or Event History and Background

An overview of the site, facility, or event that caused the PVI issue including (at a minimum) details on:

- *the location and date of release*
- *material released*
- *volume released*
- *extent and distribution of contaminants*
- *affected media*
- *investigative and corrective actions to date*
- *what the community should expect regarding investigation and mitigation of the PVI issue*

Community Profile and Community Assessment Results

- *The Community Profile is usually completed during a preliminary environmental assessment process provided by the responsible party, with concurrence from the regulatory agency.*
- *The Baseline Community Survey evaluates the potential interest in a project. Surveys should be conducted prior to commencement of a PVI investigation, mitigation, or closure process.*
- *The Community Concerns section summarizes any concerns identified during the Community Profile development or Baseline Community Survey.*

Objectives of the CEP

- *The CEP provides a narrative of the major objectives of the CEP. Objectives typically relate to the specific concerns outlined in the community profile and survey process and may include objectives such as PVI risk explanation.*

Public Involvement Activities

This section describes the specific activities that will be conducted to meet the objectives outlined in the CEP, such as:

- *communication methods and activities (for instance, social media sites, PVI fact sheets, notices, meetings, and access agreements)*
- *timing of the communication activities related to milestones (for example, a planning matrix)*
- *responsibility for implementing these activities*

Appendices

Appendices can be included to provide supporting information or tools to help execute the CEP. Typical appendices may include:

- *project mailing list/contact list*
- *media contacts*
- *public meeting and information repository locations (the mailing list should not be included within the CEPs that are either distributed to the public or placed in the repository)*

Development of the community profile begins with a community assessment, which describes the community affected and the community's needs, concerns, and expectations. For example, the risk communication methods must account for any non-English-speaking residents in the community. Printed material may need to be produced in more than one language. Also, some members of the community may be deaf or blind and require alternate means of communication. During the development of the community profile, the methods of communication that community members want, and the frequency of those communications, should be captured and incorporated in the CEP. A robust community profile, based on the community assessment, should result in an effective assessment of community interest and identify informational needs. In addition, regulators and responsible parties may be able to anticipate possible community concerns and inquiries and respond appropriately.

The action plan portion of the CEP defines community involvement objectives, describes the decision-making process of the PVI project, outlines a comprehensive plan that describes PVI sampling and future remedial actions, and identifies communication methods that will be used to involve the public in all relevant phases of investigation, mitigation, and remediation at the site. Note that at the start of a PVI project, the action plan may not yet have information related to the sampling or mitigation programs. As more information becomes known, however, the action plan portion of the CEP should be updated to include the new information and plans.

The effectiveness of the risk communication should be routinely measured and communication methods improved as needed. If the information being provided is not effectively reaching the community as set forth in the CEP, the root cause of the lapse should be determined and the plans should be adjusted to reflect any improvements. Overall record keeping is an important part of a CEP and may be particularly useful in any contentious issues develop. Methods of communication may be community specific, so methods of measuring effectiveness may vary. Metrics to consider include the number of hits on a website, the number of letters received by the community (registered or return receipt), survey response rates, and the number of people contacted in door-to-door discussions. Response rates for requests for property access are also helpful (Ivens 2013).

Although nomenclature and order of occurrence may vary slightly, the basic elements of a CEP as outlined above are typical of elements that can be found in other guidance documents such as:

- California Department of Toxic Substances Control's (DTSC) *Public Participation Manual* (CAEPA-DTSC 2001)
- California DTSC's *Vapor Intrusion Public Participation Advisory* (CAEPA-DTSC 2012)
- USEPA Community Involvement Plan (CIP) guidance (USEPA Undated), found in the Community Involvement Toolkit
- Appendix H of the Office of Solid Waste and Emergency Response (OSWER) *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater to Soils* (USEPA 2002b)
- USEPA Superfund Community Involvement Toolkit website (USEPA 2013m)
- USEPA *Superfund Community Involvement Handbook* (USEPA 2005b)

Examples of CEPs that follow an USEPA format can be found in the following documents:

- Iron King Mine-Humboldt Smelter Site (USEPA 2009b)
- Harbor Island Area Superfund Sites (USEPA 2009c)
- Hudson River (USEPA 2009a)
- Foster-Wheeler Energy Corporation Church Road TCE Site (USEPA 2010)

7.2.2 Tools for Effective Community Engagement

As discussed in Section 7.2.1, input on communication preferences should be sought from the community. This input allows regulators and other environmental professionals the opportunity to identify the most appropriate community engagement tools. These tools can then be added as an appendix to the CEP as appropriate. This subsection describes many of the community engagement tools that are available and provides a small sample of these tools.

One example of a community engagement tool is the development of a community advisory group. The group nomenclature may vary for each project; however, the purpose is essentially the same. A community advisory group is a small group of residents interested in, or affected by, a project who meet regularly with regulatory agencies and responsible parties to discuss various aspects and concerns with the project. These residents have no decision-making authority, but can prove influential by providing an opportunity for the public to gain an understanding of the complexities of the PVI investigation and by helping to explain risk and provide constructive advice. Members of the group may aid in gaining access to properties for assessment and mitigation from reluctant property owners. Regulatory agency project managers should communicate with property owners to discuss specific concerns and questions. Information on community advisory groups can be found on the USEPA Superfund Community Involvement website (USEPA 2013f).

A second example of a community engagement tool is the fact sheet. Fact sheets can be a useful communication tool and can be easily shared with the community through mailings, door-to-door distribution, websites, information repositories, and community meetings. The subject matter of fact sheets can vary widely but generally covers items such as frequently asked questions (FAQs) about PVI, PVI risk, PVI-specific chemicals and behavior, and investigation techniques. Also consider preparing brief summaries of site background and history, investigation findings, mitigation, and remediation.

Some resources are presented below:

- California DTSC Vapor Intrusion Public Participation Advisory (CAEPA-DTSC 2012)
- USEPA *Vapor Intrusion Fact Sheet* (USEPA 2007b)
- Federal Agency for Toxic Substances & Disease Registry (ATSDR) fact sheets on chemical contaminants, such as benzene, toluene, ethylbenzene, and naphthalene (ASTDR 2013)
- USEPA fact sheet on bioremediation; contains a basic description of the process of bio-degradation (USEPA 2012a)
- New York Department of Health (NYDOH 2004)
- New Jersey Department of Environmental Protection (NJDEP 2008)
- Massachusetts Department of Environmental Protection (MADEP 2013a)
- Wisconsin Department of Health Services (WIDHS 2013)
- Illinois Department of Public Health (ILDOH 2009)
- Delaware Department of Natural Resources and Environmental Control (DNREC 2013)
- New Hampshire Department of Environmental Services (NHDES 2013)

Generally, no distinction is made between contaminants or contaminant sources in most informational materials supplied to the public. Based on the information presented in this document, sample FAQ sheets for PVI sites were developed and are included in Appendix K. The FAQ sheets may be used with or without modification to suit specific project needs.

Table 7-1 lists community engagement tools that can be used based on community input.

Table 7-1. Community engagement tools (CAEPA-DTSC 2012)

Community Engagement Tools	
Fact Sheets • Investigation findings • Site history • Initial investigation • Ongoing investigation • PVI • COCs	Community Meetings • Community advisory groups • Restoration advisory boards
Access Agreement Guidelines Work Notices	Community Surveys Site Diagrams and Maps
Flyers, Posters, or Signage Neighborhood Newsletters	DVDs Informational Inserts

Table 7-1. Community engagement tools (CAEPA-DTSC 2012) (continued)

Community Engagement Tools	
Agency Contact Lists E-mail Notices/Updates	Public Notices in Newspapers Informational Repositories
Websites/Social Media One-on-One or Small Group Meetings • Door-to-door visits • Phone calls	Radio, TV Informational Programs Community Events

7.2.3 State and Federal Related Links

The PVI team's survey of regulatory agencies identified seven states that currently have specific guidance on community outreach for VI sites and scenarios. No states have developed guidance for conducting community engagement, risk communication, public participation, or public notification specific to PVI sites. The following seven state VI guidance documents are recommended as good sources of information for any VI project:

- Massachusetts

  Vapor Intrusion Guidance (MADEP 2011), which contains the documents listed below:
    - Notification to Property Owners
    - Fact sheet, Public Involvement in Site Cleanup (MADEP 2004)
    - Fact sheet, Opportunities for Public Involvement in Preliminary Response Actions

- New Jersey
    - VI Guidance (NJDEP 2013a)
    - Community outreach guidance
    - Templates for public communications (letters) and access

- New York
    - Soil Vapor Intrusion Guidance; see Section 5 on "Community Outreach" (NYSDOH 2006)
    - Appendix G of Soil Vapor Intrusion Guidance; see "Community Outreach Tools – Additional Information" (NYDOH 2006a)

- Illinois
    - Community Relations Fact Sheet, PVI project (ILEPA 2003)
    - Community Relations Fact Sheet, PVI project

- Minnesota
    - Vapor Intrusion Technical Support Document (MPCA 2010)

- California
    - CalDTSC Vapor Intrusion Public Participation Advisory (CAEPA-DTSC 2012)

- Washington
    - Community and Environment, Vapor Intrusion Web Page (WADOH 2013)

In addition, USEPA OUST has published information on community engagement related to leaking underground storage tanks, a common source of petroleum contamination. The guidance includes a PVI scenario (USEPA 2012d).

7.3 Risk Communication

Effective risk communication is an important component of all outreach efforts. To assist in gaining the trust of the public, it is essential to provide clear and understandable descriptions of the issues, including potential risks. If professional communications personnel are available, involve them in the risk communication process. For communicating risks associated with all contaminated sites, not just PVI-related sites, USEPA (1988a) provides the following points:

- Accept and involve the public as a legitimate partner.
- Listen to the audience.
- Be honest, frank, and open.
- Coordinate and collaborate with credible sources.
- Meet the needs of the media.
- Speak clearly and with compassion.
- Plan carefully and evaluate performance.

Those involved in communicating the risk posed by PVI should be familiar with PVI concepts, which are discussed more fully in Section 7.4, PVI Concepts Explained. Effective risk communication clearly presents these concepts to stakeholders. Additionally, it may be helpful to place potential risks posed by PVI in context with potential risks posed by household products and ambient air.

7.3.1 Communicating the Risk

The goals of effective risk communication include the following (Ivens 2010):

1. Establish trust and credibility.
2. Provide information to enable residents and other stakeholders to make decisions regarding VI impacts.
3. Create open and ongoing lines of communication.
4. Secure continued access to buildings for investigation and monitoring.
5. Limit risk of legal action

Avoiding overly technical terms helps to effectively discuss potential risk with the general public. Terms such as “vadose zone,” “probes,” and “10^{-6} excess cancer risk” may not mean much to non-technical people; even the concept of “groundwater” may be unfamiliar to some stakeholders. Other terms like “free product” may actually sound good to the public. Below are some examples of technical terms made simpler (McDaniel 2012).

Table 7-2. Simpler versions of technical terms

Technical term	Simpler term
Plume	Contaminated groundwater or water table
Vadose zone	Soil above the water table
Subslab	Under your house
Free product, LNAPL	Fuel floating on the water table
Saturated zone, aquifer	Groundwater, water table
Probe	Sampling device
Soil permeability	Porous
Vapor intrusion	Movement of vapor into building
Volatile	Easily evaporates
Biodegradation	A natural process where bacteria break down organic compounds (such as petroleum) in the soil as food
Multiple lines of evidence	Using all available information in decision making

Discussion of health risks and mortality, particularly from cancer, are to be expected in community engagement communications at all environmental sites, including PVI sites. The additional lifetime risk of developing cancer refers to the chance a person has, over the course of his or her lifetime (from birth to death), of being diagnosed with cancer because of estimated reasonable worst-case exposure to a site-related COC. The risk management range for a carcinogen is typically between 1 x 10^{-6} (one in 1 million) and 1 x 10^{-4} (one in 10,000) excess lifetime cancer risk (see Figure 7-1). The risk may also be described as “one additional case in 1 million” and “one additional case in 10,000,” respectively. The 1 x 10^{-4} excess lifetime cancer risk is interpreted by the USEPA OSWER as the threshold for which remedial action is warranted (USEPA 1991a). Different state agencies may have different rules and guidance for risk thresholds.

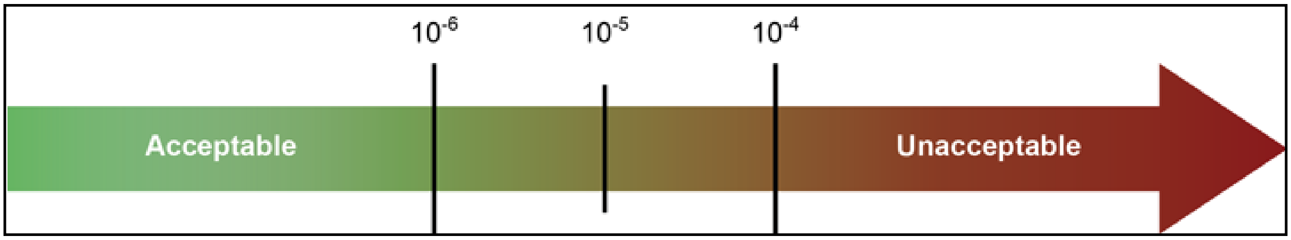


Figure 7-1. Range of acceptable excess lifetime cancer risk.

Source: Adapted from California DTSC Vapor Intrusion Public Participation Advisory (CAEPA-DTSC 2012).

To put a one in 1 million or a one in 10,000 excess lifetime cancer risk into perspective for the public, a useful tool would be to discuss the actual risk posed by the PVI exposure in comparison to other deadly risks that people may encounter in their daily lives. State regulators and consultants should be cautioned, though, that communicating the risk in comparison to other risks may be misinterpreted by the public as a way of explaining their concerns away and not taking them seriously. The following lifetime odds of death are selected from the National Safety Council (2012) injury fact sheet. The one in 1 million and one in 10,000 excess lifetime cancer risk levels are added for reference.

Table 7-3. Excess lifetime cancer risk perspective

Cause of death or injury	Lifetime odds
Heart disease	1 in 6
Motor vehicle accidents Accidental drowning	1 in 98 1 in 1,103
Highest excess cancer risk management threshold Contact with hornets, wasps, and bees	1 in 10,000 1 in 79,842
Earthquakes Lightning	1 in 97,807 1 in 134,906
Lowest excess cancer risk-management threshold	1 in 1,000,000

7.3.2 Communicating Risk Associated with PVI

VI, and PVI specifically, may be perceived as different from other types of environmental contamination in several ways:

- The COCs are common in products that may be stored in homes, schools, day care facilities, or commercial buildings (see Section 7.3.4 and Table 7-4).
- Sampling of buildings may not be needed if certain criteria are met (such as vertical screening distance).
- Sampling of potentially affected indoor air is recommended if screening criteria are not met; this sampling requires obtaining permission for access to assess the hazard.
- Members of the public are generally more familiar with contaminated water or outdoor air; the knowledge that their home may be contaminated may be disconcerting to some.
- Under physical and chemical conditions commonly found in subsurface soil, biodegradation of petroleum contaminants reduces PVI risk.

The risk of PVI into homes and other buildings is low when the PHC-contaminated groundwater or soil is separated from the receptor/building by a sufficient layer of nonsource oxygenated soil. This layer of nonsource soil contains naturally occurring bacteria that can break down the vapors from the petroleum source before the vapors can reach the building. For this reason, it may not be necessary to conduct sampling at a property. As detailed in Chapter 3, states may have different criteria for developing vertical screening distances.

In Section Section 7.4, PVI Concepts Explained, common PVI terms are provided and explained in a way that may make these terms and concepts more understandable to the general public.

7.3.3 Answering Difficult Questions

The following information is adapted from *Two Tools for Responding to Any Difficult Question/Statement on Any Issue from Any Stakeholder in Any Setting*, reprinted by the Navy and Marine Corps Health Center (U.S. Navy 2011). This brief document provides a "Generic Category Tool for Responding to Challenging Questions," which is a table of 12 categories of challenging questions and the appropriate response for each type of question. When communicating with the public on PVI issues, you may encounter many emotions—anger, confusion, fear, or others. To communicate effectively with an emotional person, four approaches are helpful:

- **Empathy**: You must try to think like they are thinking. Remove yourself from your own feelings, and put yourself in their shoes. Using empathy statements is helpful, but they must be relevant. Saying things such as "I live in this community" or "My child also attends that school" shows the public that you empathize with their situation.
- **Conclusion**: In risk communication, the conclusion must be short, simple, and precede the facts that support the conclusion. The conclusion should address the underlying point of the question or statement. Examples of good conclusions include the following:
    - "I don't know, but I'll find out."
    - "We don't plan further cleanup actions."
    - "The vapors do not pose a significant risk."
    - "We've been sharing all the information with you."
- **Facts**: Facts support your conclusions. Usually one, two, or three facts are sufficient. It is crucial that you observe your audience when giving facts to ensure that they are listening. If they are not listening, stop talking about your facts and find out why they are not listening. Ask:
    - "Am I being clear?"
    - "Do you have any questions or concerns?"
- **Future Action**: Future action, if applicable, should have a "when," a timing factor. Whatever your future action is, you should let the stakeholders know that they will continue to be involved and that their continued involvement is important, until their issues have been resolved. Good future action statements are:
    - "I don't know, but I'll call you tomorrow."
    - "I'll be happy to talk to you more after the meeting."
    - "There's more information on this on our website/brochure/fact sheet/Facebook."
    - "We won't know for at least six months, but I'll be glad to call/e-mail once a month on our latest outlook."

7.3.4 VOCs in Commonly Used Products

When discussing risks associated with PVI, the concept of "background" contamination will likely arise. Including a discussion of common sources of indoor air contaminants, especially petroleum compounds, may be helpful. Many household products contain petroleum compounds that can contaminate indoor air. The following list of some common household products that contain petroleum compounds was adapted from two nontechnical websites (Schmidt & Clark 2013, eHow 2013).

One of the tools used to identify products that may serve as background sources in the indoor air environment is the Indoor Air Building Survey and Sampling Form.

Table 7-4. Examples of household products that can contain petroleum compounds

Household Products that Can Contain Petroleum Compounds
Fuel containers (or devices using gasoline, kerosene, fuel oil and products with petroleum distillates, lantern fuel)
Paint thinner, oil-based stains and paint, lacquer thinner Aerosol or liquid insect pest products
Mineral spirits Furniture polishes
Lighter fluid Rubber cement
Glues Lubricants
Blacktop driveway sealer Furniture refinisher
Adhesive remover Liquid paint stripper
Gas treatment Carburetor cleaner
Fuel injector cleaner (aerosol or liquid) Aerosol waxes
Brake cleaners Liquid stainless steel cleaner
Herbicides Styrofoam

It may be helpful to develop a fact sheet to effectively communicate information regarding common household products that contain petroleum COCs. One example of this type of communication is the New York Department of Health *Fact Sheet on VOCs in Commonly Used Products* (NYDOH 2007).

7.3.5 Public Notification of Sampling

Owners and tenants of buildings to be sampled should be notified in advance of sampling activities. While respecting the privacy of property owners and tenants, as appropriate, also notify the surrounding community of pending sampling. Individual letters, fact sheets, and other appropriate materials stating that sampling is planned and explaining how and when the sampling will occur should be mailed to owners, tenants, and the community.

If indoor air sampling is to be conducted for a building, about two weeks prior to sampling, contact each occupant in person to schedule the sampling and to explain the sampling procedures. Also provide written instructions to the occupants. The instructions should state that use of certain consumer products is discouraged prior to, and during, sampling because these products can bias the sampling results.

Then, at the time of sampling, the occupant should again be asked about consumer products. This approach offers at least two opportunities to discuss the use of consumer products with occupants prior to the indoor air sampling. California's Vapor Intrusion Public Participation Advisory (CAEPA-DTSC 2012) provides useful guidance on public outreach in relation to indoor air sampling. This guidance recommends, to the extent feasible, scheduling appointments at the convenience of the building occupants. Therefore, for residences, appointments are often scheduled and sampling initiated in the morning (before work) or evening (after work).

Owners of private property, and tenants and leaseholders in many instances, have the right to deny access to private property. In cases where the public welfare is at stake, access to private property may be gained through other means (such as legal action or a court order). It is often easier to attempt to collect data from adjacent public areas or rights-of-way, if possible and appropriate, rather than engage in protracted legal battles that can have negative consequences in the public domain.

Any data generated from sampling should be provided to individual owners, tenants, and other stakeholders, as appropriate. State regulatory agencies may have specific guidelines or regulations on the transmittal of data to the public. Once any data are submitted to a governmental regulatory agency, it may be considered an open public record that must be provided to any individual requesting that information under public law. Private property data being open to any and all public review may be one reason why property owners, sometimes at the urging of their legal counsel, are reluctant to allow sampling to be conducted on their property.

7.4 PVI Concepts Explained

Previous chapters of this document provide in-depth details of PVI concepts, and serve as a resource for understanding PVI. Some difficult concepts, however, may require additional explanation in a nontechnical format for nontechnical readers. This section focuses on explaining those concepts in simple terms for the benefit of nontechnical stakeholders, managers, and regulators.

7.4.1 Contaminants of Concern and Key Indicator Compounds

See additional information in Appendix E, Common Types of Petroleum Sites.

Throughout the PVI document, the term "contaminants of concern" (COCs) is used to indicate specific compounds or groups of compounds that are common to many types of petroleum products or associated with a specific site. Depending on the types of petroleum products being discussed, these contaminants or contaminant groups are relevant for the following reasons:

- They are the specific compounds sought when investigating contamination.
- They tend to be the more hazardous, toxic, and volatile compounds in petroleum; that is, they are the compounds that may cause acute or chronic health effects upon exposure.

- Certain chemical key indicator compounds are diagnostic of the type of petroleum product released.

These specific COCs are listed by the federal government, and state and federal agencies typically require that samples collected at petroleum sites are analyzed by laboratories for these specific COCs.

COCs in PVI investigations include the following:

- BTEX—short for “benzene, toluene, ethylbenzene and xylenes.” This group of hydrocarbon compounds is a common constituent of gasoline and most other light- to medium-weight PHCs. The common occurrence of BTEX compounds, along with attributes such as toxicity, volatility, solubility, make them primary indicators of gasoline. Benzene is the highest priority of the group because it is a known carcinogen (cancer-causing agent) and has relatively high mobility in the environment.
- Naphthalene(s)—a compound, or group of compounds, commonly occurring in diesel fuel and heating oil and found during PVI investigations.

Finding certain petroleum compounds in certain concentrations or ratios may be important evidence in determining the type of petroleum released, the relative age of the release, and other site characteristics (such as multiple discharges, ongoing discharges, or discharges of multiple types of petroleum). Professionals conducting investigations use these data to attempt to assess the PVI pathway.

7.4.2 Biodegradation

Biodegradation (see Section 2.2) may be defined as the "transformation of a substance into new compounds through biochemical reactions or the actions of microorganisms such as bacteria" (USGS 2013), or “a process by which microbial organisms transform or alter (through metabolic or enzymatic action) the structure of chemicals introduced into the environment" (USEPA 2013l). Most stakeholders, however, require a much simpler explanation, and the process can be simply described as “microbes eating or using the petroleum compounds.”

The key message to stakeholders about PHCs in the environment is that they are biodegraded by naturally occurring soil microbes that live where O_2 is present. As long as O_2 is available, these microbes can usually degrade PHC vapors to nontoxic compounds (such as CO_2 and water) before these vapors can migrate to and enter a building.

7.4.3 Conceptual Site Models

CSMs are simplified versions of complex systems and are “an important tool for organizing information about the current state of knowledge and understanding of the problem” (USEPA 2006b). CSMs created to describe contaminated sites to nontechnical stakeholders are typically represented in a simplified diagram (see Figure 7-2).

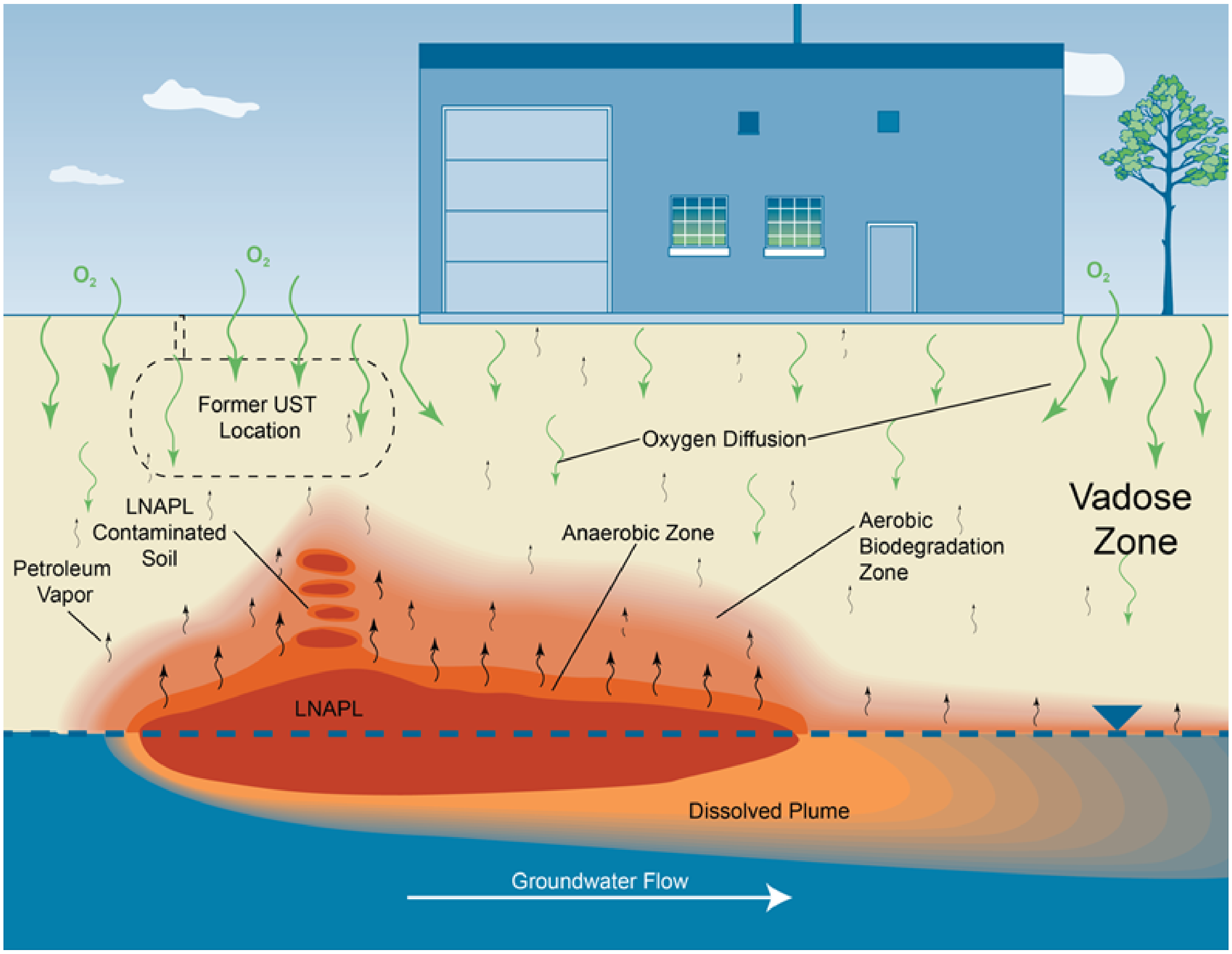


Figure 7-2. Basic CSM.

CSMs commonly break down complex systems into their basis components, and then describe the relationships between these components. Using the figure above, the model depicts the source of contaminants (in this case, a former leaking UST), environmental media (soil, groundwater, air) through which the contaminant travels, and the receptor, in this case a commercial building in which people work. The graphical model typically uses a simple indication, such as arrows, to show how contaminants move from the source, through the environmental media, and toward the receptor.

For additional information about CSMs, see *Petroleum Hydrocarbons and Chlorinated Hydrocarbons Differ in Their Potential for Vapor Intrusion* (USEPA 2012g).

7.4.4 Criteria for Determining the Source-to- Building Vertical Separation Distance

Factors that allow screening criteria to be established at a petroleum release site include:

- contaminant phase (dissolved versus free-phase product)
- distance from the source (distance from contaminated soil or groundwater to the building of concern)
- physical conditions in the subsurface that allow for, or enhance, the ability of existing bacteria to metabolize petroleum into nontoxic compounds

The evidence supporting natural biodegradation of PHCs in soil, soil vapor, and groundwater is included in Chapter 3. Based on this evidence, screening tools that account for biodegradation are gaining wider acceptance among regulators and stakeholders, in addition to the scientific and technical community.

7.4.5 Multiple Lines of Evidence

When evaluating complex relationships between groundwater, soil, soil gas, and air, decisions cannot be made on any single, simple fact, procedure, or data point. Investigators must gather, evaluate, and weigh different types of data and information. Thus, multiple independent sources of information, often termed "lines of evidence," must be evaluated to determine whether PVI is occurring or likely to occur.

In the VI screening process, assessments of all available lines of evidence are recommended (ITRC 2007) before drawing conclusions about the exposure risks. The ITRC guidance recommends collecting multiple lines of evidence to evaluate the completeness of the VI pathway:

> "…it is recommended that all available data (e.g., analytical results, building type, and ventilation rates) be used in making a determination about whether vapor intrusion is occurring and whether there are potential health concerns as a result." (ITRC 2007)

The concept of multiple lines of evidence includes the collection of information from different media (groundwater, soil gas, indoor air, outdoor air) and by different methods (such as modeling, chemical analysis, and spatial associations). If the weight of evidence points to the same scenario, then the reliability of that scenario is supported and uncertainty is reduced.

7.4.6 Site Investigation Process

The site investigation process can be defined for nontechnical audiences as the determination of the level (concentration) and extent (size) of contamination. For PVI, this definition can be further restricted as the level and extent of PHC vapors in the environment. Through the collection and analysis of data, the site investigation process attempts to describe some factors that are important for understanding site conditions, including:

- biodegradation influences
- geologic and hydrogeologic characteristics
- building characteristics
- nature and extent of impacts

- vapor source characteristics
- spatial and temporal variability of vapor concentrations in and beneath structures
- CSM

Chapter 4, Site Investigation, and Appendix G, Investigation Methods and Analysis Toolbox, describe the many technical variables associated with the collection, analysis, and interpretation of data. The appendix is particularly useful to technical professionals interested in understanding the best methods of collecting and analyzing samples and interpreting data in PVI investigations.

Stakeholders should be informed about the scope of the investigations and the results of the samples collected. Stakeholders may be reassured to know that multiple lines of evidence are used for project decisions and that data from more than one source, or obtained by more than one method, are used to determine whether public health is adequately protected or whether no public health threat exists. Communications should stress the variety of environmental media that may be sampled and stress that modeling is just one part of an assessment. Preferential pathways may be of concern, particularly to owners and occupants of structures within the area of investigation. Communications should describe how the unique features of structures (such as utility connections, trenches, or HVAC systems) and the subsurface (such as soil type or moisture) at each site are assessed and may dictate sampling locations and techniques.

7.4.7 Modeling

All models are simplifications of complex systems (see Chapter 5). In the simplest terms, modeling requires the input of certain site information into the model, which then mathematically evaluates that information and produces output describing the site. For PVI modeling, computer models are used to predict the behavior of vapor-phase chemicals, such as benzene, in the environment. Using models can help to predict where PHC vapors might (or might not) occur and, if so, in what quantity.

Models may also be used to predict the maximum extent of PVI. Regulators and other environmental professionals can use the model results to focus PVI investigations where resources are needed most and to provide boundaries outside of which little or no sampling is required. Models are updated as more PVI information becomes available.

7.4.8 Vapor Control and Site Management

Site management at any environmental site may involve off-site parties that have no prior relationship with the responsible party. In the case of PVI sites, the intrusion of contaminated vapors into homes makes the contamination personal and invasive. This aspect of PVI requires careful site management and good community relations.

Managing risk at a PVI site may involve vapor control technologies that physically prevent vapors from entering a structure and posing a health risk to occupants. The vapor mitigation methods can be preventive methods (such as sealing cracks in floor or walls), passive methods (which allow vapors to vent to the atmosphere without entering a building), or active methods (which vacuum vapors away from a building or filter or treat the air within a building).

Stakeholders, specifically residents and occupants of affected buildings, may be inconvenienced by the following:

- installation of vapor mitigation systems (fans, piping, and other building modifications and construction activities)
- generation of noise during system operation
- periodic presence of personnel who conduct sampling or maintenance
- vapor mitigation systems that may affect the operation of HVAC systems
- possible increased electrical costs associated with vapor mitigation systems

Site management at a PVI site includes keeping the community informed while conducting mitigation of affected structures and remediation of contaminated media. Stakeholders want to be reassured that they and their family are not at risk. In case of a mitigation system malfunction, having the contact information of the installer available (for example, labeled on a system component) provides some assurance to these stakeholders.

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APPENDIX A. PVI SURVEY—SUMMARY OF STATE RESPONSES

In the spring of 2012, shortly after the initiation of the ITRC PVI project, the team conducted a state survey to gain a national perspective as to how state environmental agencies address PVI sites. A coordinated response was requested from each state, which could be attributed to the state rather than an individual. The survey was to be completed by the PVI or VI experts within each state in coordination with other people, programs, and agencies involved with PVI. Survey responses were provided by 49 states (all states except South Dakota) and the District of Columbia.

A goal of the PVI Team is to give states (and others) a "PVI Tool Box" so that they can make confident, timely, and quality decisions related to PVI sites. The results of this survey have provided key supporting information for the development of this guidance document. Through this survey, the team gained an understanding of the current state of PVI issues across the country and identified potential regulatory barriers related to PVI solutions.

The following key findings from the survey are arranged to correspond with the chapters presented in this guidance document.

A.1 State Survey Results - Chapter 1. Introduction and Chapter 2. Characteristics of Petroleum Vapor Intrusion

- 49% of the states indicated they have guidance on the evaluation of PVI; 10% of the states indicated they had draft PVI guidance.
- 86% of the states include BTEX compounds as contaminants of concern related to vapor samples for PVI sites, although many will consider other compounds (such as MTBE and naphthalene) or TPH.
- 94% of the states consider distance between source and building as part of a site investigation. Exclusion distances ranged from 5 feet to 100 feet for dissolved PHC contaminants, and 15 feet to 100 feet for LNAPL.
- 78% of the states allow use of a generic residential slab attenuation factor. Factors vary from 0.00015 to 0.1. 38% of the states have a separate attenuation factor for commercial buildings. Factors vary from 0.00006 to 0.1.
- 48% of the states use "clean soil" to define which sites may be excluded from PVI assessment. Clean soil criteria may include VOC or TPH analysis of subsurface soil adjacent to or beneath the building, or measurements of fixed gases (O_2, CO_2, CH_4, and others).

A.2 State Survey Results - Chapter 3. Site Screening Using Vertical Screening Distance

- 70% of the states consider future land use when evaluating a site for VI.
- 58% of the states have confirmed a dissolved-phase PHC source causing VI (in the absence of residual phase LNAPL). Most (66%) of these occurred at off-site residences.

- 94% of the states consider preferential pathways during a VI evaluation. These pathways include storm/sanitary sewers and other utilities (90%), soil/bedrock fractures (70%), soil heterogeneity (68%), elevator shafts (64%), and other features such as basement sumps or cracks in the foundation.
- Aside from the presence of LNAPL or groundwater entering a storm/sanitary sewer or basement sump, 36% of the states reported observing an issue with preferential vapor migration associated with features such as cracks in foundations, utility bedding, and elevator shafts.

A.3 State Survey Results - Chapter 4. Site Investigation

- 42% of the states consider biodegradation as part of a PVI site investigation. Several states indicated that biodegradation will likely be included in future versions of state guidance.
- 80% of the states require either a formal or informal CSM as part of a VI investigation.
- 82% of the states employ a multiple-lines-of-evidence approach for VI investigations, with the majority of states weighing some lines of evidence (chemical data) more than others.

A.4 State Survey Results - Chapter 5. Modeling

- 74% of the states make decisions regarding the PVI pathway based on modeling information, although more than half of these also require additional PVI-specific investigations.
- 76% of the states do not have specific requirements or policies with respect to biodegradation in VI modeling (i.e., acceptable models or input parameters).

A.5 State Survey Results - Chapter 6. Vapor Control and Site Management

- 50% of the states have guidance on VI mitigation. Of these, less than half of the guidance specifically addresses PVI mitigation.
- 42% of the states do not require permitting for PHC mitigation. Other states may require air, building, electrical or fire permitting depending on the technology used. Local permitting requirements may also apply.
- Most (62%) of the states do not require a certified/licensed installer or licensed professional engineer for CVI or PVI mitigation systems.
- 56% of the states require chemical analysis of indoor air samples to monitor mitigation system performance. Other types of measurements (such as differential pressure readings, and chemical analysis of venting stack air) may also be required. 14% of the states do not require performance monitoring.
- 52% of the states require institutional controls for VI mitigation systems, most commonly when a site is to be closed with a mitigation system in place.

A.6 State Survey Results - Chapter 7. Community Engagement

- 50% of the states have guidance on community outreach related to contaminated sites. Of these, less than half specifically address VI.
- 80% of the states' outreach plans do not differentiate between CVI and PVI cases.
- 88% of the states require communication (for instance, sampling results or public meetings) with affected off-site parties.
- 56% of the states have tools for communication with non-English speaking communities.

A.7 State Survey Results - Appendix E. Common Types of Petroleum Sites

- 100% of the states responded that gasoline/diesel USTs ranked important to very important when assessing the PVI pathway. 86% of the states have confirmed a PVI occurrence related to a UST discharge.
- 57% of the states responded that refineries ranked important to very important when assessing the PVI pathway.
- 73% of the states responded that pipelines ranked important to very important when assessing the PVI pathway.
- 69% of the states responded that manufactured gas plants ranked important to very important when assessing the PVI pathway.
- 65% of the states responded that heating oil tanks ranked important to very important when assessing the PVI pathway.
- 88% of the states responded that bulk storage facilities ranked important to very important when assessing the PVI pathway.
- 20% of the states responded that exploration and production ranked important to very important when assessing the PVI pathway.

A.8 State Survey Results - Appendix G. Investigation Methods and Analysis Toolbox

- 62% of the states prefer TO-15 for analysis of PVI compounds.
- 70% of the states required either state or National Environmental Laboratory Accreditation Conference certification for laboratory analysis. Other states indicated that certification requirements are being considered.
- The majority of states require a 24-hour sample duration for residential settings and an 8-hour duration for nonresidential settings.
- 56% of the states do not specify duration for soil gas samples. Of states with specific requirements, most require a flow rate of less than 200 mL/minute.

A.9 Additional Findings for Confirmed PVI Occurrences

- 86% of the states confirmed a PVI occurrence related to a UST discharge.
- 58% of the states confirmed a dissolved-phase PHC source causing vapor intrusion (absence of residual-phase LNAPL).

For the 17 states that confirmed both types of PVI occurrences as noted above, a member of the ITRC PVI Team made phone calls to gain additional information. The following list summarizes the information obtained from those calls.

Alabama

Most PVI incidents from dissolved PHC groundwater plumes are due to direct migration into basements or sumps. A PVI incident occurred, however, from shallow soil contamination that off-gassed PHC vapors into an air conditioner intake for a building. Another PVI incident involved shallow groundwater contaminated with dissolved PHCs at about 2 feet bgs. The PHC vapors entered a cold joint between the building slab and the sidewalk.

Arkansas

A PVI incident occurred in a retail shopping center. Groundwater was at a depth of about 3 feet bgs and contained TPH-GRO concentrations of 50 to 100 mg/L. Vadose zone soils consisted of silty clay. A dual-phase vapor extraction system with horizontal piping was installed to mitigate PVI.

Arizona

Arizona has areas with shallow groundwater (10 to 15 feet bgs) and dry sandy soils or fractured rock vadose zones (low biodegradation potential). These conditions can enhance the potential for PVI from dissolved PHC sources in groundwater.

Colorado

The Colorado staff contacted knew of no PVI incidents with clean soil separating the dissolved PHC groundwater plume from the receptor.

Delaware

PVI incidents involving dissolved PHC groundwater plumes result from contaminated groundwater entering basements directly.

District of Columbia

District of Columbia staff reported a PVI incident from a dissolved PHC groundwater plume involving a dry p-trap in a basement drain.

Idaho

PVI occurred in residences with basements (7 to 8 feet bgs) and shallow groundwater (10 feet bgs) with benzene concentrations in groundwater of 10 to 15 mg/L. The vadose zone soils were sands and gravels.

Iowa

PVI occurred in a residence with a French drain and sump. Shallow groundwater with a benzene concentration of about 600 µg/L went into the French drain and sump.

Kentucky

A PVI incident occurred from a dissolved PHC groundwater plume entering a basement.

Maine

Maine staff reported PVI incidents from dissolved PHC groundwater plumes entering basement sumps. One PVI incident occurred from gasoline LNAPL at 12 feet below the bottom of a basement. The vadose zone soils were sandy.

Minnesota

Most PVI occurrences result from direct contact or preferential pathways connecting the groundwater (contaminated with dissolved PHCs) with a receptor. Most, if not all, occurrences were discovered by someone smelling a PHC odor. One recent PVI occurrence involved a LUST release with LNAPL and a dissolved groundwater plume migrating off site under slab-on-grade apartments. Groundwater was at about 15 feet bgs and the vadose zone soils were medium sands. Extensive pavement and the apartment complex may have prevented sufficient O_2 from entering the vadose zone soils. Petroleum odors were noticed in the apartments, so subslab depressurization systems and soil vapor extraction systems were installed to mitigate PVI.

New Hampshire

New Hampshire staff reported PVI incidents from dissolved PHC groundwater plumes that entered basements directly. PVI has also resulted from broken vent lines at operating gas stations.

New York

Most PVI occurrences result from direct contact of contaminated groundwater with a basement (some through preferential pathways such as subsurface utility lines). Most are discovered by someone smelling a PHC odor. In one case on Long Island. contaminated groundwater was 2 to 3 feet below the bottom of the homes (slab-on-grade). The vadose zone soils were sandy.

Ohio

A PVI incident occurred from a dissolved PHC groundwater plume entering a basement sump of a house.

Oklahoma

Oklahoma reported a PVI incident from a dissolved PHC groundwater plume at about 4 to 5 feet below the floor of the basement in a residential house. PVI occurred when it rained hard and infiltrating stormwater may have forced PHC vapors into the basement.

Rhode Island

A PVI incident occurred in a building with a basement (earthen floor) at a depth of about 10 feet bgs. Shallow groundwater was at about 11 to 15 feet bgs and was contaminated with dissolved compounds from a gasoline LUST.

Vermont

PVI incidents involving dissolved PHC groundwater plumes result from contaminated groundwater entering basements or basement sumps directly.

APPENDIX B. STATE GUIDANCE AND CONTACTS FOR PETROLEUM VAPOR INTRUSION

Alaska

- State Agency: Alaska Department of Environmental Conservation
- State PVI Guidance (whether stand alone or as part of VI guidance): Vapor Intrusion Guidance for Contaminated Sites, October 2012. http://dec.alaska.gov/spar/csp/guidance/Vapor%20Intrusion%20Guidance.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Todd Blessing
  Alaska Department of Environmental Conservation
  907-269-7699
  todd.blessing@alaska.gov

Alabama

- State Agency: Alabama Department of Environmental Management
- State PVI Guidance (whether stand alone or as part of VI guidance): ARBCA: Alabama Risk-Based Corrective Action for Underground Storage Tanks Guidance Manual, Revision 1.0, November 2001. http://www.adem.state.al.us/programs/water/waterforms/ARBCA-corraction.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Dorothy Malaier (UST sites)
  Alabama Department of Environmental Management
  334-270-5613
  dsm@adem.state.al.us

Arizona

- State Agency: Arizona Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:

  Wayne Pudney
  Arizona Department of Environmental Quality
  602-771-4192

  wdp@azdeq.gov
  Deborah (Debi) Goodwin
  Arizona Department of Environmental Quality

602-771-4453
dg1@azdeq.gov

Arkansas

- State Agency: Arkansas Department of Environmental Quality, Regulated Storage Tanks Division State PVI Guidance (whether stand alone or as part of VI guidance): https://www.epa.gov/ust/technical-guide-addressing-petroleum-vapor-intrusion-leaking-underground-storage-tank-sites
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  David T. Frazier, PG
  Arkansas Department of Environmental Quality
  501-682-0982
  frazier@adeq.state.ar.us

California

- State Agency: California State Water Resources Control Board
- State PVI Guidance (whether stand alone or as part of VI guidance): Low-Threat Underground Storage Tank Case Closure Policy. http://www.waterboards.ca.gov/board_decisions/adopted_orders/resolutions/2012/rs2012_0016atta.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

Colorado

- State Agency: Colorado Division of Oil and Public Safety
- State PVI Guidance (whether stand alone or as part of VI guidance): See Remediation Section links with direct reference to ITRC PVI Document at Petroleum Hydrocarbon Vapor Intrusion guidance document at: http://www.coworkforce.gov/petroleumguidance/#Release%20Response/Site%20Characterization/PVI.htm%3FTocPath%3DR_____2
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Michael Kwiecinski
  Colorado Department of Labor, Division of Oil and Public Safety
  303-318-8512
  Mike.Kwiecinski@state.co.us

Connecticut

- State Agency: Connecticut Department of Energy and Environmental Protection
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Carl Gruszczak
  Connecticut Department of Energy and Environmental Protection
  860-424-3948
  carl.gruszczak@ct.gov

Delaware

- State Agency: Delaware Department of Natural Resources and Environmental Control
- State PVI Guidance (whether stand alone or as part of VI guidance):

  - VI policy
    http://www.dnrec.delaware.gov/dwhs/sirb/Pages/SIRB_Laws_Regulations_Guidance_Policies.aspx

  - VI sampling guidance
    http://www.dnrec.delaware.gov/dwhs/sirb/Documents/SIRB_SOP_Soil_Gas_Sampling.pdf

    http://www.dnrec.delaware.gov/dwhs/sirb/Pages/SIRB_Laws_Regulations_Guidance_Policies.aspx

- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:
  Rick Galloway
  DNREC Site Investigation and Restoration Section
  302-395-2600
  Rick.Galloway@state.de.us

  Christopher Brown
  DNREC Tank Management Section
  302-395-2500
  Christopher.Brown@state.de.us

District of Columbia

- State Agency: District Department of Energy and Environment
- State PVI Guidance (whether stand alone or as part of VI guidance): The Risk Based Corrective Action Technical Guidance Manual [for Underground Storage Tank Division] is used to assess risk for indoor inhalation for select compounds (BTEX, EDB, EDC, MTBE, GRO, and DRO). If COCs are not listed in the RBCA Guidance Manual, the District of

Columbia defers to USEPA Region 3 Regional Screening Levels (RSLs). No stand-alone document is available, only the standards listed in the RBCA that were added in the recent past in response to numerous inquiries related to VI. http://ddoe.dc.gov/publication/dc-risk-based-corrective-action-dcrbca-or-risk-based-decision-making-dcrbdm-process

- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Raymond Montero
  District Department of Energy and Environment
  202-535-2294
  raymond.montero@dc.gov

Florida

- State Agency: Florida Department of Environmental Protection
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

Georgia

- State Agency: Georgia Environmental Protection Division
- State PVI Guidance (whether stand alone or as part of VI guidance): PVI guidance under development and will be a part of the state's VI guidance, Evaluating the Vapor Intrusion Pathway at Regulated Sites. https://epd.georgia.gov/vapor-intrusion-technical-guidance
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Undine Johnson
  Georgia Environmental Protection Division
  404-362-2594
  undine.johnson@dnr.state.ga.us

Hawaii

- State Agency: Hawaii Department of Health
- State PVI Guidance (whether stand alone or as part of VI guidance):
  - HDOH 2012. Field Investigation of the Chemistry and Toxicity of TPH in Petroleum Vapors: Implications for Potential Vapor Intrusion Hazards. Hawaii Department of Health, Office of Hazard Evaluation and Emergency Response, http://eha-web.doh.hawaii.gov/eha-cma/documents/4c0ca6c1-0715-4e0d-811b-33debe220e31
  - HDOH 2011. Screening for Environmental Concerns at Sites with Contaminated Soil and Groundwater (Fall 2011 and updates). http://eha-web.doh.hawaii.gov/eha-cma/Leaders/HEER/EALs

  - HDOH 2013, Technical Guidance Manual (refer to Sections 7, 9 and 13): Hawaii Department of Health, Office of Hazard Evaluation and Emergency Response. http://www.hawaiidoh.org/tgm.aspx.
- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:
  Roger Brewer (non-UST sites)
  HDOH/HEER
  808-586-4249
  roger.brewer@doh.hawaii.gov

Idaho

- State Agency: Idaho Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): Appendix G: Evaluation of the Vapor Intrusion Pathway; contained in the Risk Evaluation Manual for Petroleum Releases. http://www.deq.idaho.gov/media/878259-idaho-risk-evaluation-manual-for-petroleum-releases-0812.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Derek Young
  Idaho Department of Environmental Quality
  208-373-0525
  derek.young@deq.idaho.gov

Illinois

- State Agency: Illinois EPA
- State PVI Guidance (whether stand alone or as part of VI guidance): Illinois' Tiered Approach to Corrective Action Objectives rules (35 Illinois Administrative Code 742), and an accompanying Fact Sheet specific to Petroleum Vapor Intrusion Assessment for Leaking UST Program Sites. The rules may be found at http://www.ipcb.state.il.us/documents/dsweb/Get/Document-38408/. The Fact Sheet is available at http://www.epa.illinois.gov/topics/cleanup-programs/taco/vapor-intrusion/petroleum-usts/index.
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Greg Dunn, Manager, Leaking Underground Storage Tank Section

  Illinois EPA
  217/785-2359
  Greg.Dunnn@Illinois.gov

Indiana

- State Agency: Indiana Department of Environmental Management
- State PVI Guidance (whether stand alone or as part of VI guidance): part of VI guidance/Remediation Closure Guide. http://www.in.gov/idem/6683.htm
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Patricia Troth
  Indiana Department of Environmental Management, Office of Land Quality
  317-233-5681
  ptroth@idem.in.gov

Iowa

- State Agency: Iowa Department of Natural Resources
- State PVI Guidance (whether stand alone or as part of VI guidance): Currently, the state has stand-alone guidance: RBCA Tier 1 and Tier 2
  - Tier 1: http://www.iowadnr.gov/portals/idnr/uploads/ust/tier1guide.pdf
  - Tier 2: http://www.iowadnr.gov/portals/idnr/uploads/ust/tier2guide.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Lee Osborn
  Department of Natural Resources
  515-725-8335
  Lee.osborn@dnr.iowa.gov

Kansas

- State Agency: Kansas Department of Health and Environment
- State PVI Guidance (whether stand alone or as part of VI guidance): Kansas Vapor Intrusion Guidance – not specific to PVI. http://www.kdheks.gov/ber/download/Ks_VI_Guidance.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  David Meyer

  Kansas Dept. of Health & Environment
  785-296-8063
  David.Meyer@ks.gov

Kentucky

- State Agency: Kentucky Department of Environmental Protection/Division of Waste Management

- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Nathan Lewis

  Department of Environmental Protection/Division of Waste Management
  502-782-6400

  nathan.lewis@ky.gov

Louisiana

- State Agency: Louisiana Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Kyle Blanchard

  LDEQ

  225-219-3618

Maine

- State Agency: Maine Department of Environmental Protection
- Vapor Intrusion Evaluation Guidance, Supplemental Remediation Guidelines for Petroleum Contaminated Sites in Maine (Updated May 2014) http://www.maine.gov/dep/spills/petroleum/documents/petroremguidelines.pdf
- Guidance for Vapor Intrusion of Chlorinated Solvents and Other Persistent Chemicals (February 5, 2016) http://www.maine.gov/dep/spills/publications/guidance/rags/VI-Persistent-Chems-Guidance-final-020516.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Troy Smith
  Maine Dept. of Environmental Protection
  207-592-0830

  Troy.T.Smith@maine.gov

  Peter Eremita

  Maine Dept. of Environmental Protection

  207-592-0592

  Pete.m.eremita@maine.gov

Maryland

- State Agency: Maryland Department of the Environment
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Drew Miller

Maryland Department of the Environment, Oil Control Program, Remediation Division
410-537-3389
andrew.miller@maryland.gov

Massachusetts

- State Agency: Massachusetts Department of Environmental Protection
- State PVI Guidance (whether stand alone or as part of VI guidance): MassDEP BWSC (Bureau of Waste Site Cleanup) released its Final Vapor Intrusion Guidance on October 14, 2016, http://www.mass.gov/eea/docs/dep/cleanup/vapor-intrusion-guidance-10-14-2016.pdf.
- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:

  Ken Marra
  Massachusetts Department of Environmental Protection
  617-292-5966
  Kendall.Marra@State.ma.us

  Greg Braun
  Massachusetts Department of Environmental Protection
  617-292-5718
  greg.braun@state.ma.us

Michigan

- State Agency: Michigan Department of Environmental Quality, Remediation and Redevelopment Division
- State PVI Guidance (whether stand alone or as part of VI guidance): Attachment B.3 Alternate Approach for Investigating Vapors for Petroleum Hydrocarbons Considering Biodegradation from the May 2013 guidance document, which is titled Guidance Document for the Vapor Intrusion Pathway. http://www.michigan.gov/documents/deq/deq-rrd-VIGuidanceDoc-May2013_422550_7.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Matthew Williams
  Remediation and Redevelopment Division
  Michigan DEQ, RRD
  517-284-5171
  williamsm13@michigan.gov

Minnesota

- State Agency: Minnesota Pollution Control Agency
- State PVI Guidance (whether stand alone or as part of VI guidance): The MPCA Petroleum Remediation Program has two guidance documents related to Petroleum Vapor Intrusion:
    - Vapor Intrusion Assessments Performed During Site Investigations: http://www.pca.state.mn.us/index.php/view-document.html?gid=3018
    - Vapor Intrusion Technical Support Document: http://www.pca.state.mn.us/index.php/view-document.html?gid=14165
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Rose Schmaedeke
  MPCA
  651-757-2490
  rose.tusa@state.mn.us

Mississippi

- State Agency: Mississippi Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Willie McKercher
  Mississippi Department of Environmental Quality
  601-961-5731
  Willie_McKercher@deq.state.ms.us

Missouri

- State Agency: Missouri Department of Natural Resources
- State PVI Guidance (whether stand alone or as part of VI guidance): Risk-Based Corrective Action for Petroleum Storage Tanks, October 17, 2013. http://dnr.mo.gov/env/hwp/tanks/mrbca-pet/mrbca-pet-tanks.htm
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Tim Chibnall
  Missouri Department of Natural Resources, Hazardous Waste Program
  573-522-1833
  tim.chibnall@dnr.mo.gov

Montana

- State Agency: Montana Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): Montana Vapor Intrusion Guide, Montana Department of Environmental Quality, April 22, 2011. http://deq.mt.gov/Land/statesuperfund/viguide
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Jason Seyler
  Montana Department of Environmental Quality
  406-444-6447

  BKingsbury@mt.gov

Nebraska

- State Agency: Nebraska Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): The numbers used by the Department are identified in the following guidance document: Risk-Based Corrective Action (RBCA) At Petroleum Release Sites: Tier 1/Tier 2 Assessments & Reports (Revised May 2009). http://www.deq.state.ne.us/Publica.nsf/6f475f9acdf9ebe8862569050055582c/66fdec793aefc4b286256a93005b8db8!OpenDocument
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  David Chambers

  Nebraska Department of Environmental Quality – Petroleum Remediation Section

  402-471-4258

  david.chambers@nebraska.gov

Nevada

- State Agency: Nevada Division of Environmental Protection, Bureau of Corrective Actions
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Michael Friend
  Nevada Division of Environmental Protection, Bureau of Corrective Actions
  775- 687-9371

  mpfriend@ndep.nv.gov

New Hampshire

- State Agency: New Hampshire Department of Environmental Services
- State PVI Guidance (whether stand alone or as part of VI guidance): Vapor Intrusion Guidance (Petroleum compounds are included in VI document). http://des.nh.gov/organization/divisions/waste/hwrb/documents/vapor_intrusion.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Robin Mongeon, P.E.
  New Hampshire Department of Environmental Services
  603- 271-7378
  Robin.Mongeon@des.nh.gov

New Jersey

- State Agency: New Jersey Department of Environmental Protection
- State PVI Guidance (whether stand alone or as part of VI guidance): NJDEP Vapor Intrusion Technical Guidance, August 2016 (Version 4) http://www.nj.gov/dep/srp/guidance/vaporintrusion/vig_main.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  John Boyer
  New Jersey Dept. of Environmental Protection
  609-984-9751
  john.boyer@dep.nj.gov

New Mexico

- State Agency: New Mexico Environment Department-Petroleum Storage Tank Bureau
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Lorena Goerger
  New Mexico Environment-Petroleum Storage Tank Bureau
  505-476-4385
  lorena.goerger@state.nm.us

New York

- State Agency: New York State Department of Environmental Conservation and New York State Department of Health
- State PVI Guidance (whether stand alone or as part of VI guidance): part of SVI guidance
  - http://www.health.ny.gov/environmental/investigations/soil_gas/svi_guidance/
  - http://www.health.ny.gov/environmental/indoors/air/guidance.htm

- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:
  Kevin Hale (PVI)
  New York State Department of Environmental Conservation
  518-402-9543
  kghale@gw.dec.state.ny.us

  Michael Hughes (PVI)
  New York State Department of Health
  518-402-7800
  michael.hughes@health.ny.gov

  Krista Anders (SVI)
  New York State Department of Health
  518-402-7860
  krista.anders@health.ny.gov

North Carolina

- State Agency: North Carolina Department of Environment and Natural Resources (NCDENR)
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Delonda Alexander (VI)
  NCDENR
  919-707-8365
  delonda.alexander@ncdenr.gov

  Jared Edwards (PVI)
  NCDENR
  919-707-8153
  jared.edwards@ncdenr.gov

North Dakota

No response provided.

Ohio

- State Agency: Ohio Bureau of Underground Storage Tank Regulations (BUSTR)
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Scott Sigler
  Ohio Bureau of Underground Storage Tank Regulations (BUSTR)

614-752-7938
ssigler@com.state.oh.us

Oklahoma

- State Agency: Oklahoma Corporation Commission, Petroleum Storage Tank Division
- State PVI Guidance (whether stand alone or as part of VI guidance): Vapor intrusion guidance for situations related to petroleum fuel releases can be found in our Oklahoma Risk-Based Corrective Action Guidance. This guidance will most likely be upgraded soon after USEPA VI guidance is finalized. http://www.occeweb.com/ps/Forms/Technical%20Forms/Orbca%20Guidance/ORBCA%20Guidance.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Salim Douglah, Technical Manager
  Oklahoma Corporation Commission, Petroleum Storage Tank Division
  405-522-1444

Oregon

- State Agency: Oregon Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): Risk-Based Decision Making at Petroleum Contaminated Sites, and Guidance for Assessing and Remediating Vapor Intrusion in Buildings. http://www.deq.state.or.us/lq/rbdm.htm; http://www.deq.state.or.us/lq/pubs/docs/cu/VaporIntrusionGuidance.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Henning Larsen, R.G.
  Oregon Department of Environmental Quality
  503-229-5527
  Larsen.henning@deq.state.or.us

Pennsylvania

- State Agency: Pennsylvania Department of Environmental Protection
- State PVI Guidance (whether stand alone or as part of VI guidance): Recycling Program Technical Guidance Manual for Vapor Intrusion into Buildings from Groundwater and Soil under Act 2 http://www.dep.pa.gov/Business/Land/LandRecycling/Standards-Guidance-Procedures/Guidance-Technical-Tools/Pages/Vapor-Intrusion.aspx
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Carolyn Fair
  PA Department of Environmental Protection
  717-425-7514

cfair@pa.gov

Puerto Rico

- State Agency: Puerto Rico Environmental Quality Board
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available. Puerto Rico is currently recommending the use of the OSWER Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance) – November 2002
- Vapor Intrusion/Petroleum Vapor Intrusion Contact: no contact provided

Rhode Island

- State Agency: LUST Program/Rhode Island Department of Environmental Management (RIDEM)
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Sofia Kaczor
  LUST Program/RI DEM
  401-222-2792 extension 7121
  sofia.kaczor@dem.ri.gov

South Carolina

- State Agency: South Carolina Department of Health and Environmental Control
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Mihir Mehta, Division Director
  SCDHEC, UST Management Division
  803-898-0623
  mehtam@dhec.sc.gov

South Dakota

- State Agency: South Dakota Department of Environment and Natural Resources
- State PVI Guidance (whether stand alone or as part of VI guidance): Screening Tables
  http://denr.sd.gov/des/gw/LookUpTables/Lookup_Tables.aspx
- Vapor Intrusion/Petroleum Vapor Intrusion Contact: no contact provided

Tennessee

- State Agency: State of Tennessee, Division of Underground Storage Tanks
- State PVI Guidance (whether stand alone or as part of VI guidance): 1) Initial Site Characterization (ISC) Guidelines and ISC Report (part of guidance) 2) Technical Guidance Document-018 (stand alone). http://www.tn.gov/environment/underground-storage-tanks/tanks_release.shtml; http://www.tn.gov/environment/underground-storage-tanks/tanks_guidance.shtml#tgds
- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:

  Geina Skinner
  State of Tennessee, Division of Underground Storage Tanks
  615-532-0981
  geina.skinner@tn.gov

  Ahmet Bulbulkaya
  Department of Environment & Conservation, Division of Remediation
  615-532-0227
  ahmet.bulbulkaya@tn.gov

Texas

- State Agency: Texas Commission on Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Michael Aplin
  Texas Commission on Environmental Quality
  512-239-1792
  mike.aplin@tceq.texas.gov

Utah

- State Agency: Utah Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): No state guidance available. Utah DEQ uses EPA PVI Final Guide 2015.
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  John Menatti, Manager, PST Trust Fund
  Utah DEQ
  801- 536-4159
  jmenatti@utah.gov

Vermont

- State Agency: Vermont Agency of Natural Resources
- State PVI Guidance (whether stand alone or as part of VI guidance): included as part of site investigation guidance; Investigation and Remediation of Contaminated Properties Procedure. http://www.anr.state.vt.us/dec/wastediv/sms/pubs/IROCP.pdf
- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:

  Gerold Noyes (PVI)
  VT Department of Environmental Conservation, Waste Management Division
  802-522-5614
  gerold.noyes@vermont.gov

  Mike Smith (VI)
  VT Department of Environmental Conservation, Waste Management Division
  802-249-5826
  michael.b.smith@vermont.gov

Virginia

- State Agency: Virginia Dept. of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance): Virginia Voluntary Remediation Program Vapor Intrusion Screening Fact Sheet, http://www.deq.virginia.gov/Portals/0/DEQ/Land/RemediationPrograms/VoluntaryRemediationProgram/VI_Fact_Sheet_082508.pdf
- Vapor Intrusion Contact:

  Kyle Newman
  Virginia Dept. of Environmental Quality
  804-698-4452
  kyle.newman@deq.virginia.gov

- Petroleum Vapor Intrusion Contact:

  Randy Chapman
  Virginia Dept. of Environmental Quality
  703-583-3816
  randy.Chapman@deq.virginia.gov

Washington

- State Agency: Washington State Department of Ecology State PVI Guidance (whether stand alone or as part of VI guidance): Guidance for Evaluating Soil Vapor Intrusion in Washington State: Investigation and Remedial Action (10/2009).

https://fortress.wa.gov/ecy/publications/SummaryPages/0909047.html. Updated Process for Initially Assessing the Potential for Petroleum Vapor Intrusion: https://fortress.wa.gov/ecy/publications/SummaryPages/1609046.html

- Vapor Intrusion/Petroleum Vapor Intrusion Contact:
  Mark Gordon
  Washington State Department of Ecology
  360-407-6357

  marg461@ecy.wa.gov

West Virginia

- State Agency: West Virginia Department of Environmental Protection
- State PVI Guidance (whether stand alone or as part of VI guidance): no guidance available
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Lawrence Sirinek
  WVDEP
  304-238-1220
  lawrence.P.Sirinek@wv.gov

Wisconsin

- State Agency: Wisconsin Department of Natural Resources
- State PVI Guidance (whether stand alone or as part of VI guidance): Addressing Vapor Intrusion at Remediation & Redevelopment Sites in Wisconsin, PUB-RR-800, http://dnr.wi.gov/files/PDF/pubs/rr/RR800.pdf. also see VI resource page: http://dnr.wi.gov/topic/Brownfields/Vapor.html
- Vapor Intrusion/Petroleum Vapor Intrusion Contacts:

  Alyssa Sellwood
  Wisconsin Department of Natural Resources
  608-266-3084
  Alyssa.Sellwood@wisconsin.gov

  David Swimm
  Wisconsin Department of Natural Resources
  608-264-8766
  david.Swimm@wisconsin.gov

Wyoming

- State Agency: Wyoming Department of Environmental Quality
- State PVI Guidance (whether stand alone or as part of VI guidance):
  - http://deq.state.wy.us/shwd/HW/index_hw.asp (for Hazardous Waste)
  - http://deq.state.wy.us/volremedi/index.asp?pageid=29 (for Voluntary Remediation Program)
  - http://deq.state.wy.us/shwd/stp/index.asp (for Storage Tank Program)
- Vapor Intrusion/Petroleum Vapor Intrusion Contact:

  Storage Tank Program or Hazardous Waste/Voluntary Remediation Program
  Wyoming Department of Environmental Quality
  307-777-7752

APPENDIX C. CHEMISTRY OF PETROLEUM

This appendix provides information about the composition and chemistry of PHC fuels and their vapors. This information may be used to identify certain petroleum chemicals that pose the greatest potential risks through PVI.

C.1 Aliphatic and Aromatic Compounds

The chemicals that make up PHCs can be divided into two general groups: aliphatic and aromatic compounds. Aliphatic compounds are composed of straight-chained, branched, or cyclic compounds and can be saturated (alkanes) or unsaturated (alkenes, alkynes, and others), whereas aromatic compounds have one or more conjugated, benzene or heterocyclic rings within their structures. "Conjugated" refers to the presence of delocalized (shared) electrons within the chemical structure, such as benzene. Some examples of aliphatic and aromatic compounds are shown in Figure C-1.

In general, aromatic and large aliphatic compounds (C9 and above) are more toxic than smaller aliphatic compounds (under C9); however, smaller aliphatic compounds are more volatile and are, therefore, generally the primary component in vapors if present in the petroleum source. Aromatic compounds are more readily biodegraded than aliphatic compounds; however, a few volatile aromatic compounds, such as benzene and ethylbenzene, and some semivolatile aromatic compounds, such as naphthalene, pose a carcinogenic risk whereas the aliphatic compounds are generally assumed to pose a noncarcinogenic risk. Although many aliphatic and some aromatic compounds may not be carcinogens, they can collectively pose a noncancer hazard if present at high enough concentrations and should be considered during PVI investigations.

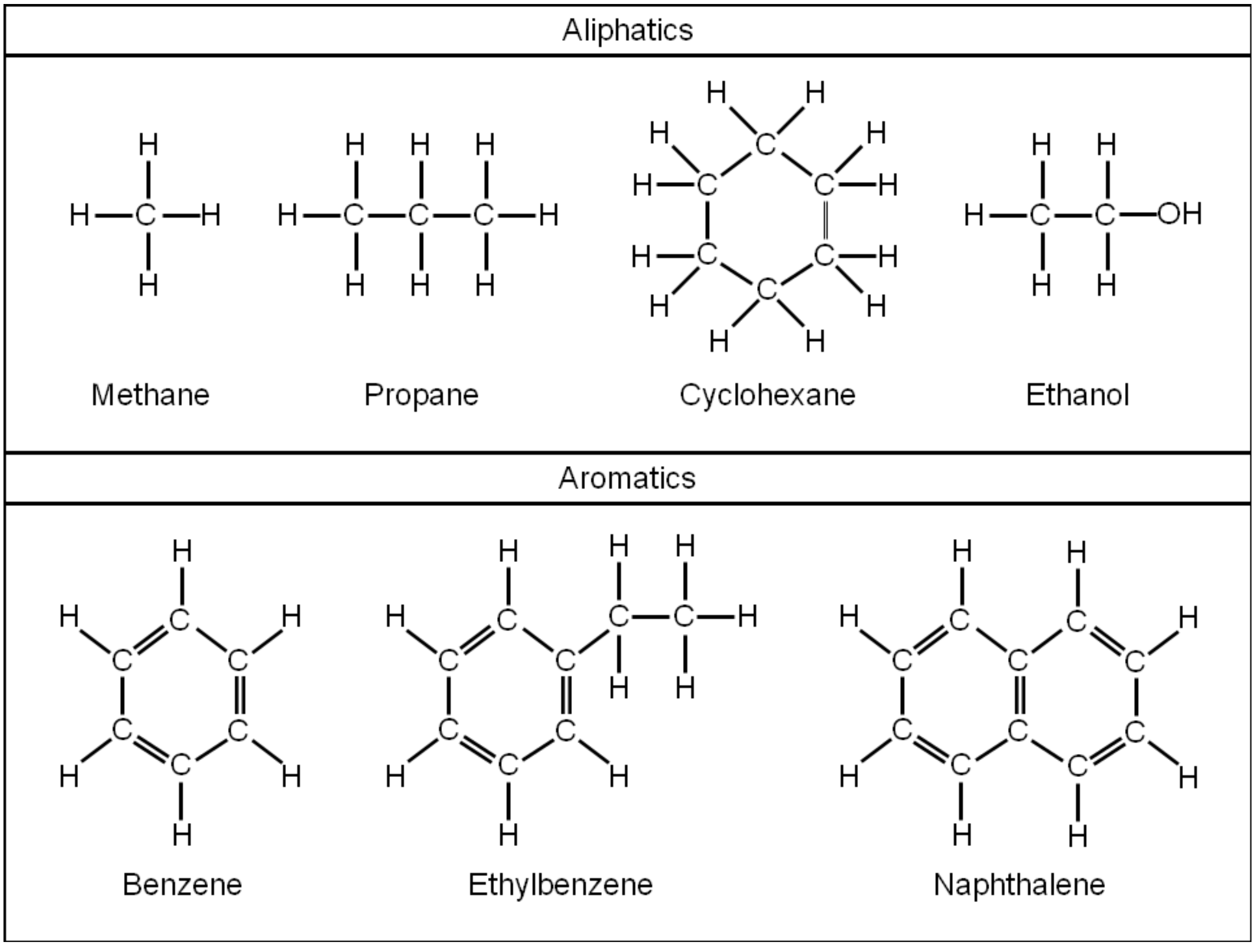


Figure C-1. Examples of aliphatic and aromatic compounds.

Fuels as well as vapors are characterized in terms of individual compounds and carbon range groups of aliphatic and aromatic compounds. Physicochemical parameter values for aliphatic and aromatic carbon ranges as well as BTEX and naphthalene are presented in Table C-1.

Table C-1. Default physicochemical constants for BTEXN and TPH carbon ranges (adapted from Brewer et al. 2013)

Chemical/carbon range[1]	Molecular weight	Vapor pressure (atms)	Solubility in water (mg/L)	Henry's constant (unitless)	Partition coeff, k_c (cm^3/g)	Diffusion coefficient (cm^2/s)	
						Air	Water
Benzene	78	0.1	1,790	0.23	146	0.09	1×10^{-5}
Ethylbenzene	106	0.01	169	0.32	446	0.068	8.5×10^{-6}
Toluene	92	0.04	526	0.27	234	0.078	9.2×10^{-6}
Xylenes, m-	106	0.01	161	0.29	375	0.068	8.4×10^{-6}
Naphthalene	128	1.0×10^{-4}	31	0.018	1,544	0.06	8.4×10^{-6}
C5–C8 Aliphatics	93	0.1	11	54	2,265	0.08	1×10^{-5}

Table C-1. Default physicochemical constants for BTEXN and TPH carbon ranges (adapted from Brewer et al. 2013) (continued)

Chemical/carbon range[1]	Molecular weight	Vapor pressure (atms)	Solubility in water (mg/L)	Henry's constant (unitless)	Partition coeff, k_c (cm^3/g)	Diffusion coefficient (cm^2/s)	
						Air	Water
C9–C12 Aliphatics	149	8.7×10^{-4}	0.07	65	150,000	0.07	1×10^{-5}
C13–C18 Aliphatics	170	1.4×10^{-4}	3.5×10^{-4}	69	680,000	0.07	5.0×10^{-6}
C19–C36 Aliphatics	280	1.1×10^{-6}	1.5×10^{-6}	110	4.0×10^{-8}		
C9–C10 Aromatics	120	2.9×10^{-3}	51	0.33	1,778	0.07	1×10^{-5}
C11–C22 Aromatics	150	3.2×10^{-5}	5.8	0.03	5,000	0.06	1×10^{-5}

[1] Constants for BTEXN from USEPA RSL guidance (USEPA 2014a); vapor pressures from TOXNET (USNLM 2014); carbon range values from Massachusetts DEP (MADEP 2002b) except C13-C18 Aliphatics (based on EC > 12-16) and C19-C36 Aliphatics (based on EC > 16-35 aliphatics) (TPHCWG 1997)

C.2 Petroleum Fuels

"Gasolines", "middle distillates", and "residual fuels", with the middle category including diesel, kerosene, and Stoddard solvent, as defined by the (API 1994), are classifications developed for different mixtures of aliphatic and aromatic compounds.

Gasolines are defined as petroleum mixtures characterized by a predominance of branched alkanes with carbon ranges from C2–C12 and lesser amounts of aromatic compounds (such as BTEX), straight-chain alkanes, cycloalkanes, and alkenes of the same carbon range. Because of the lower molecular weights of these constituents, gasoline has the greatest volatility of the three classes and generally emits the most vapors.

Middle distillates (such as diesel fuel, home heating fuel, kerosene, and jet fuel) are characterized by a wider variety of straight, branched, and cyclic alkanes, as well as PAHs (especially naphthalene and methylnaphthalenes) and heterocyclic compounds with carbon ranges of approximately C5–C9. A small percentage of C8–C25 aliphatic and BTEX compounds are also present in middle distillates. In general, the constituents of middle distillates are less volatile than those of gasolines. Although BTEX compounds are present in middle distillates, their concentrations are several orders of magnitude lower than in gasoline. Naphthalene can also sometimes be considered an aromatic of concern for releases of middle distillates.

Residual fuels (such as fuel oil Nos. 4, 5, and 6, lubricating oils, waste oils, and asphalts) are characterized by complex PAHs and other high-molecular-weight hydrocarbon compounds with carbon ranges that generally fall between C24 and C40. Residual fuels lack a significant amount of volatile compounds and, aside from the potential generation of methane, are generally assumed to pose a minimal VI risk.

Table C-2 summarizes the makeup of past and current gasolines and diesel in terms of commonly targeted, aromatic compounds. Although important in terms of PVI, these compounds constitute a relatively minor proportion of the bulk fuel. The remainder of the fuels is composed of hundreds of nonspecific, hydrocarbon compounds, collectively referred to as TPH. Table C-3 summarizes the typical TPH composition of gasolines and diesel in terms of carbon ranges.

Table C-2. Range of current and past BTEX and naphthalene (BTEXN) concentrations in gasolines and diesel (adapted from Brewer et al. 2013)

Chemical	Gasolines[1]	Diesel[2]
Benzene	0.1–3.6%	0.003–0.1%
Ethylbenzene	0.1–3%	0.007–0.2%
Toluene	1–25%	0.007–0.7%
Xylenes	1–15%	0.02–0.5%
Naphthalene	< 1%	0.01–0.8%

[1] Gasoline ranges (after Potter and Simmons 1998, Kaplan et al. 2007, Weaver et al. 2009)
[2] Diesel #2 (after Potter and Simmons 1998)

Table C-3. Example carbon range makeup of non-BTEXN, TPH component of gasolines and diesel; exact carbon range makeup of individual fuels will vary (adapted from Brewer et al. 2013)

Carbon range	Gasolines [1]	Diesel [1]
C5 to C8 aliphatics	45%	< 1%
C9 to C18 aliphatics	12%	35%
C19+ aliphatics	< 1%	43%
C9 to C12+ aromatics	43%	22%

[1] Indiana Department of Environmental Management (IDEM 2012)

As noted in Table C-3, fuels are dominated by aliphatic compounds, although gasolines can contain a relatively large proportion of C9-C12 aromatic compounds. These aromatic compounds are not significantly volatile and as discussed below play a relatively minor role in PVI. The same is true of the heavier, relatively low-volatility, C9–C18 aliphatic compounds, although in some cases these compounds can make up an important proportion of vapors emitted from middle distillate fuels. Although they constitute a significant proportion of middle distillates and heavy fuels, aliphatic compounds with nineteen or more carbon molecules are not considered volatile and, other than the potential generation of biogenic methane during degradation, do not play a role in PVI.

In addition to gasolines, middle distillates, and residual fuels, other petroleum-related products exhibit potential for PVI, including coal tar, coal tar creosotes, natural gas, and others. Coal tar was created as a by-product of the pyrolysis of coal, coke, or oil in a closed vessel (retort) during production of manufactured gas during the late 1800s to the 1940s (EPRI 1999). Coal tar is a dark reddish brown to black, oily liquid that does not readily mix with water. Coal tar has a strong odor of mothballs or driveway sealer and can be found either as an LNAPL or a DNAPL depending on the formulation process. Coal tar contains a small percentage of VOCs such as BTEX compounds. These compounds are the most soluble in groundwater. Coal tar also contains hundreds of PAHs, which do not readily dissolve in water and are not easily transported in groundwater. With the exception of naphthalene, most of the PAHs also do not readily volatilize. Coal tar creosotes are distilled from coal tar and contain similar compounds with lesser amounts of the heavier compounds (EPRI 1993).

The class of petroleum product released has a significant effect on what COCs could be present and can be used to determine the presence or absence of PVI. The original composition of the product can vary within the classes and can affect the composition of vapors. The amount of BTEX, naphthalene, other aromatics, and aliphatics can differ based on the refinery producing the fuel and the additives in the formulation of the fuels (Table 5-1). For example, in 2011, USEPA restricted the volume of benzene allowed in gasoline, whether refined or imported, to an average of 0.62% volume through exhaust emissions regulations (USEPA 2007a).

Original fuel formulation and composition has likely varied over time and, along with the effects of weathering (noted in Appendix M), can change the composition significantly; therefore, the composition must be evaluated on a site-by-site basis.

C.3 Petroleum Vapors

The chemical makeup of vapors emitted from petroleum fuels is predictable based on the composition of the fuels and the theoretical partitioning of chemicals released to soil and groundwater (USEPA 2002c; Hartman 1998). Compounds with comparatively higher vapor pressures and Henry’s law constants can be expected to dominate vapors relative to their proportions in the parent fuels (see Table C-1). Vapors emitted from fresh gasolines can thus be predicted to be dominated by C5–C8 aliphatics (and C2–C4 aliphatics, if present) based both on the relative abundance of these compounds in the parent fuel and on their volatility in comparison to the other compounds. More recent fuels have a lesser amount of benzene because of the increased restriction in the amount of benzene allowed in the fuel; therefore, lower concentrations of benzene in soil vapors can be expected at more recent releases.

Although less volatile than gasolines, diesel and other middle distillate fuels contain variable amounts of C5–C8 aliphatics and a relatively large component of C9–C18 aliphatics (see Table C-2). Therefore, these compounds should again be expected to dominate vapors emitted from soil and groundwater contaminated with these fuels. The relative proportion of C5–C8 to C9–C12 aliphatics will depend in part on the original composition of the fuel (Hayes et al. 2007). The fraction of BTEX in the vapors will be significantly smaller than for gasolines, given their lower relative abundance. Naphthalene could also be present, depending on its presence in the parent fuel.

The USEPA OUST has compiled an empirical database of soil vapor results for more than fifty, primarily gasoline-contaminated sites in the US, Canada, and Australia (USEPA 2013i). The database provides an overview of the basic chemistry of vapors at gasoline release sites. C5–C8 aliphatics overwhelmingly dominate the TPH fraction in samples that were tested.

The predicted composition of vapors from diesel and other middle distillate fuels is also observed in the field. Mixtures of C5–C12 aliphatics composed the overwhelming majority of vapors at sites contaminated with middle distillate fuels (see Brewer et al. 2013 and HDOH 2012 for more details).

In summary, vapors from PHC-contaminated soil and groundwater are generally dominated by volatile, aliphatic compounds with lesser but potentially important amounts of benzene and other aromatic compounds. A detailed discussion of methods to quantitatively assess the vapor intrusion risk posed by individual compounds or groups of compounds, including TPH aliphatics, is beyond the scope of this document. Brewer et al. (2013) present an approach for the quantitative assessment of TPH in vapor intrusion studies and to compare the risk posed by TPH with that of other COCs.

TPH aliphatics can be the primary COCs when benzene is not present or is depleted. The estimated magnitude of this risk depends in part on the toxicity factors applied to individual TPH carbon ranges. Equally important, vapor intrusion depends on the ability of the vapors to migrate though the vadose zone and enter s structure above levels of potential concern. As summarized in the other sections of this document, field studies indicate that biodegradation of hydrocarbon compounds significantly limits this threat at many if not most sites.

APPENDIX D. PETROLEUM VAPOR INTRUSION CONCEPTUAL SITE MODEL CHECKLIST

PETROLEUM VAPOR INTRUSION CONCEPTUAL SITE MODEL CHECKLIST

The information included in this checklist may be useful for developing the site-specific conceptual migration model and in planning the soil gas sampling. You can use this checklist to compile information for each site.

Site ID/Name: ____

Address/Location: ____

Site Owner/Operator: ____

Released Product(s) & Volume(s): _______________________________________

Release Date: ____

Type of Petroleum Site

(Identification of indicator petroleum hydrocarbon compounds and release sources)

☐ Gasoline and/or diesel UST locations

☐ Commercial and home heating oil locations

☐ Refineries

☐ Bulk storage facilities

☐ Pipelines and transportation

☐ Oil exploration and production sites

☐ Former manufactured gas plants

☐ Creosote (wood treating) facilities

☐ Dry cleaners using petroleum solvents (such as Stoddard solvent)

☐ Other, describe:

(Required for screening evaluation)

Source(s)

☐ Identify affected media

- ○ LNAPL
- ○ Dissolved
- ○ Sorbed
- ○ Vapor

☐ Define magnitude and extent of affected media

☐ Indicators for screening (state-specific)

☐ Indicators/COPCs for investigation (state-specific)

☐ Nonpetroleum VOCs

- ○ Indications of an ongoing release?
- ○ Describe source stability (stable, increasing, decreasing)
- ○ Have petroleum odors been reported or documented in buildings?

Migration

☐ Define lateral separation distance between source and receptor.

☐ Define the thickness of unaffected ("biologically active" or "relatively clean") soil between the source(s) and the building foundation.

☐ Describe biodegradation indicators, including O_2, CO_2, methane, total organic carbon (TOC) content, moisture, temperature, and pH at depths specified.

☐ Describe vadose zone lithology.

Buildings (Receptors)

☐ Identify and denote on site plan existing and potential future buildings.

☐ Identify the occupancy and use of the buildings, for example residential, commercial, or industrial (may need to interview occupants to obtain this information).

☐ Describe the construction of the building including materials (such as wood frame or block), openings (windows, doors), and height (one-story, two-story, multiple-story); identify any elevator shafts present in the building (if applicable).

☐ Describe the foundation construction including:

- ○ Type (basement, crawl space, slab on grade)
- ○ Floor construction (such as concrete or dirt)
- ○ Depth below grade/ground surface
- ○ Describe foundation drainage or penetrations if they exist (French drains, sumps, cracks, or other)

☐ Describe the HVAC system in the building including:

- ○ Furnace/air conditioning type (forced air, radiant)
- ○ Furnace/air conditioning location (basement, crawl space, utility closet, attic, roof)
- ○ Source of return air (inside air, outside air, combination)
- ○ System design considerations relating to indoor air pressure (positive pressure is often the case for commercial buildings).

☐ Describe subslab ventilation systems or moisture barriers present on existing buildings, or identify building and fire code requirements for subslab ventilation systems (such as for methane) or moisture barriers below foundations.

☐ Identify occupancy and use of off-site buildings affected or potentially affect by site sources. Assess the need for public communication plan.

Engineered Preferential Pathways—Utilities, Process Piping, Sumps

☐ Locate and denote on site plan all underground utilities near the soil or groundwater impacts; note utilities that connect affected areas to occupied buildings including depths and entry points.

☐ Locate and denote on site plan all underground process piping near the soil or groundwater impacts.

☐ Locate and denote on site plan building basement dewatering sumps.

Source Area

☐ Identify and denote on site plan the sources and their locations contributing to vapor-phase contaminants related to the subsurface VI pathway (LNAPL, dissolved plume, contaminated soil, soil gas). Estimate mass of LNAPL, dissolved plume size, affected soil volume.

☐ Describe and denote on site plan the presence, distribution, and composition (gasoline and ethanol content, diesel, and fuel oil) of LNAPL at the site.

☐ Identify and denote on site plan any presence of comingled chlorinated hydrocarbon plume.

☐ Identify the vapor-phase contaminants (based on volatility and toxicity) that are to be considered for the subsurface VI pathway (benzene).

☐ Describe the status and results for the delineation of contamination in environmental media, specifically soil and groundwater, between the source area and the potential affected buildings.

☐ Describe the environmental media (soil, groundwater, both) containing contaminants.

☐ Describe the depth to source area (LNAPL, dissolved plume, unsaturated soil, soil gas).

☐ Describe the potential migration characteristics (stable, increasing, decreasing) for the distribution of contaminants.

☐ Describe contaminant transport mechanisms (diffusion in vadose zone or through capillary zone, advective flows, movement through preferential pathways).

☐ Describe remedial actions completed to date.

Geology/Hydrogeology

☐ Describe regional geology (especially important in fractured rock or karst areas).

☐ Review all boring logs, monitoring well construction, and soil sampling data to understand the following: depth of vadose zone, capillary fringe and the phreatic (saturated) zone

- Note any seasonal water table fluctuations and seasonal flow direction changes (hydraulic gradient).
- Note the depth interval between the vapor source and the ground surface.
- Note the presence and thickness of a biologically active layer to support biodegradation.
- Note the presence of any perched aquifers.
- Note where the water table intersect well screen interval or note the presence of submerged screen.

Biological Indicators

☐ Describe biological indicators.

- O_2 concentrations to support aerobic PHC biodegradation, note presence of large building footprint that may limit atmospheric oxygen transport beneath center area of building
- CO_2 concentrations
- Methane concentrations (generation under anaerobic biodegradation of PHC because of high concentrations at plume interior or presence of LNAPL, or because of high-ethanol gasoline), potential for concentrations in explosive range (especially in confined areas), increased O_2 demand because of aerobic biodegradation of methane
- Organic soil (such as peat) with low O_2 that limits potential for aerobic PHC degradation

☐ Describe distinct strata and characteristics (soil type, temperature, moisture content, porosity, bulk density, organic content).

☐ Identify the depth to groundwater.

☐ Describe groundwater characteristics (seasonal fluctuation, temperature, hydraulic gradient: vertical and horizontal; natural versus induced, flow directions).

Site Characteristics & Considerations

☐ Estimate and denote on site plan the lateral extent of and the distance from edge of groundwater plume to building.

☐ Identify groundwater beneficial use (potable or nonpotable).

☐ Identify nearby potential contaminant sources.

☐ Estimate vertical separation distance from vapor source to building foundation and denote on subsurface cross-sections.

☐ Describe the surface cover between the vapor source area and the potentially affected building.

☐ Identify presence of continuous pavement that may result in unimpeded migration of vapor in the subgrade layer to building foundation.

☐ Describe surface water/precipitation infiltration in unpaved areas, serving as a pathway for transport of dissolved O_2 to vadose zone for aerobic PHC degradation.

☐ Describe background contributions and concentrations of volatile contaminants to indoor air (both ambient/outdoor and indoor sources).

☐ Describe data quality for VI assessment (sample collection methods, laboratory detection levels, sufficiency of sample numbers and events, and representative sample locations).

☐ Describe rationale for determination of VI exposure pathways and any exclusion.

APPENDIX E. COMMON TYPES OF PETROLEUM SITES

Petroleum contamination can occur at various types of sites including industrial, commercial, and residential land use settings. Potential PVI issues may be different depending on the unique characteristics (such as nature of release or subsurface lithology) of each site. This appendix summarizes different features that may influence the potential for PVI at some commonly encountered petroleum sites. Nine different types of petroleum sites are used as selected examples in this appendix:

- Section E.1: Gasoline USTs and Diesel USTs
- Section E.2: Commercial/Home Heating Oil Tanks
- Section E.3: Refineries
- Section E.4: Bulk Storage Facilities
- Section E.5: Pipelines and Transportation
- Section E.6: Oil Exploration and Production (E&P) Sites
- Section E.7: Former Manufactured Gas Plants
- Section E.8: Creosote (Wood-treating) Facilities
- Section E.9: Dry Cleaners Using Petroleum Solvents

The site type examples detailed in this appendix are examples of common petroleum site types and may not cover all site type possibilities or all site-specific scenarios. Components of the sites described in this appendix may be applicable to other types of petroleum sites. In addition, the site types listed in this appendix are scenarios focused on risk from the potential VI pathway and not on other general indoor air quality issues (such as odors) that may result from indoor sources.

The following site features are discussed for each site type:

- history and general description
- possible compounds and COCs
- description of potential sources of releases
- description of contaminant migration and typical receptors
- description of potential PVI pathway and site-specific limitations to PVI
- potential for methane generation

The following topics are not addressed in the site descriptions contained in this appendix:

- state or federal regulations or guidance for PVI assessments
- OSHA regulations (may apply but are beyond the scope of this appendix)
- sites with comingled contaminants (sites where releases of chlorinated and non-chlorinated hydrocarbons occur together)
- sites closed prior to regulatory consideration of the PVI pathway
- sites with blended PHC compounds

For sites with blended PHC compounds, the fate and transport of blended PHC compounds containing more than 10% ethanol may differ from fuels that contain less than 10% ethanol. Additionally, methane may be generated during the ethanol biodegradation. For more information on this topic, refer to *Biofuels: Release Prevention, Environmental Behavior, and Remediation* (ITRC 2011).

The following table provides a summary of the characteristics of each type of site discussed in this appendix. Characteristics used to distinguish each type include the presence of specific indicator compounds, the presence of certain carbon-chain ranges, the potential sources of the release, the relative size of the release, preferential pathways potentially associated with the release source, and key assessment factors. Note that the characteristics summarized in the table are characteristics as they relate to the potential for PVI. For example, the indicator compounds listed in the table are compounds that may be important in evaluating the potential for PVI. The group of indicator compounds summarized is not an exhaustive list of possible compounds that may be detected on the particular petroleum site type. Also, note that elevated TPH values may be an indicator that PVI risk is possible and that it may be necessary to conduct further investigation.

Table E-1. Selected common petroleum site types (Part 1 of 3)

Characteristic	Gasoline and diesel USTs	Commercial and home heating oil tanks	Refineries
Common Indicator Compounds	Gasoline: BTEX, naphthalene, methane Diesel: Naphthalene, methane	Naphthalene, benzene	BTEX, naphthalene, methane
Carbon Chain Range(s)	C5–C12 Aliphatics C6–C10 Aromatics	No. 2 Fuel: C8–C21 No. 6 Fuel: C8–C30	Various
Potential Release Sources	USTs, product lines, dispensers, service bays	USTs, ASTs, product lines	Underground or aboveground piping, USTs (former and current), ASTs, loading areas, tank pits (current and former), processing units, historical disposal sites
Relative Size	Small to medium	Small to medium (pending site of tank release)	Large
Potential Preferential Pathways	General utilities, karst/fractured bedrock (location dependent)	Utilities corridor entering building foundation, sumps in basement, cracks in basement floor, karst/fractured bedrock (location dependent)	General utilities, pipeline corridors, karst/fractured bedrock (location dependent)
Key Assessment Factors	Documenting historical and current uses of the site (former UST locations)	Amount of release, distance to the building foundation	Documenting historical and current uses of the site.

Table E-1. Selected common petroleum site types (Part 2 of 3)

Characteristic	Bulk storage facilities	Pipelines/transportation	Oil exploration and production sites
Common Indicator Compounds	**For oil/petroleum/gasoline:**: BTEX, naphthalene, methane	**For oil/petroleum/gasoline:**, BTEX, naphthalene, methane **For natural gas:** methane, butane, propane, benzene	BTEX, methane
Carbon Chain Range(s)	Various but most often **Diesel:** C12–C24 **Gasoline:** C4–C12	Various	Broad range including crude oil and any number of refined products
Potential Release Sources	Underground or aboveground piping, ASTs, oil/water separators, loading areas	Pipeline, pipe joints, valves, flanges, weld points	Wells and well area, pipelines, gathering lines, mud pits, USTs (and associated piping), ASTs (and associated piping), maintenance facilities, oil water separators
Relative Size	Variable	Variable	Large (many acres/hectares), although smaller parts may be carved out for redevelopment
Potential Preferential Pathways	General utilities, pipeline corridors, karst/fractured bedrock (location dependent)	Gravel bed fill, shallow coarser-grained soil, karst/fractured bedrock (location dependent)	Natural oil seeps, incorrectly abandoned wells, faults/structures along which VOCs could migrate, karst/fractured bedrock (location dependent)
Key Assessment Factors	Documenting historical and current uses of the site	Knowing precisely where the pipeline corridor is	Documenting historical and current location of all exploration wells and infrastructure on site and site use

Table E-1. Selected common petroleum site types (Part 3 of 3)

Characteristic	Former manufactured gas plants	Creosote (wood-treating) facilities	Dry cleaners using petroleum solvents
Common Indicator Compounds	BTEX, indane, indene, naphthalene, trimethylbenzenes	Naphthalene, alkyl-naphthalene derivatives, benzene	BTEX
Carbon Chain Range(s)	C6–C10 aromatics C10–C36 polyaromatics	C6–26	C7–C12, C11–C13
Potential Release Sources	Tar holders, oil/water separators, gas holder foundations, purifying boxes, tar wells	Drip pads, product storage areas, unlined pits, lagoons	Outside building (especially windows and doors), storage areas, dry wells, drains
Relative Size	Usually small (min 0.2 acres/0.08 hectares, median 2 acres/0.8 hectares, average 6 acres/2.4 hectares), however some can be larger (max 75 acres/30 hectares)	Medium to large	Small; commonly located in strip malls, but can be stand-alone buildings of less than 0.5 acre (0.2 hectares)
Potential Preferential Pathways	Permeable zones such as gravel layers, storm and sanitary sewers leading off site, karst/fractured bedrock (location dependent)	General utilities, karst/-fractured bedrock (location dependent)	**Subsurface:** utility corridors, improperly abandoned monitoring wells and karst/fractured bedrock features **Building structure:** cracks in floors/walls, utility conduit entrances, floor drains and associated piping, karst/fractured bedrock (location dependent)
Key Assessment Factors	Documenting historical and current uses of the site; source areas including gasholders, retort houses, tar wells, oil/water separators, purifying boxes	Documenting historical and current uses of the site; location of pits	Documenting historical and current uses of the site. Past solvent use

E.1 Gasoline USTs and Diesel USTs

At small-scale facilities, such as gasoline stations, petroleum products are typically stored in USTs. According to information obtained from the USEPA OUST, approximately 587,000 USTs nationwide store petroleum or hazardous substances. Of the 501,000 releases reported since the beginning of the program, more than 413,000 of these releases have been addressed (approximately 82%), leaving a backlog of almost 88,000 releases remaining to be cleaned up (USEPA 2012i).

BTEX and naphthalene are the main indicator compounds that may be of concern for PVI from a petroleum UST release. MTBE, ethanol and other alcohols, fuel oxygenates, and to a lesser extent, certain PAHs are also components associated with releases at USTs. The alcohols and oxygenates, however, typically have high aqueous solubilities and low Henry's law constants, which greatly reduce their potential for PVI.

Potential receptors at this type of site may include those present at the filling station, as well as surrounding residential, commercial, and industrial properties. Potential redevelopment of a site for a different use may change the receptors and should be evaluated.

USTs may be constructed of steel, which can corrode over time and allow the contents of the tank to leak into the environment. UST releases may happen suddenly (such as a UST/piping rupture) or gradually (such as a UST/piping perforation caused by corrosion). The size of a UST release depends on the capacity and content of the UST, as well as the rate and duration of the release. Petroleum products released from the UST system enter into the subsurface and may migrate down through the vadose zone to the water table. Depending on the size of the release, the product may pool as LNAPL at the water table and may also dissolve into groundwater and migrate off site as a contaminant plume.

Vapors are released from the free-phase LNAPL and contaminated groundwater. Vapor migration may also occur through natural and artificial pathways present in the subsurface, including UST piping corridors to buildings. Contaminated groundwater may migrate into a basement, basement sump, or foundation drain and release PHC vapors into indoor air. If sources of gasoline and diesel vapors are present near a receptor, the potential for PVI is increased. Figure E-1 depicts a typical site with a UST release as it pertains to the potential for PVI.

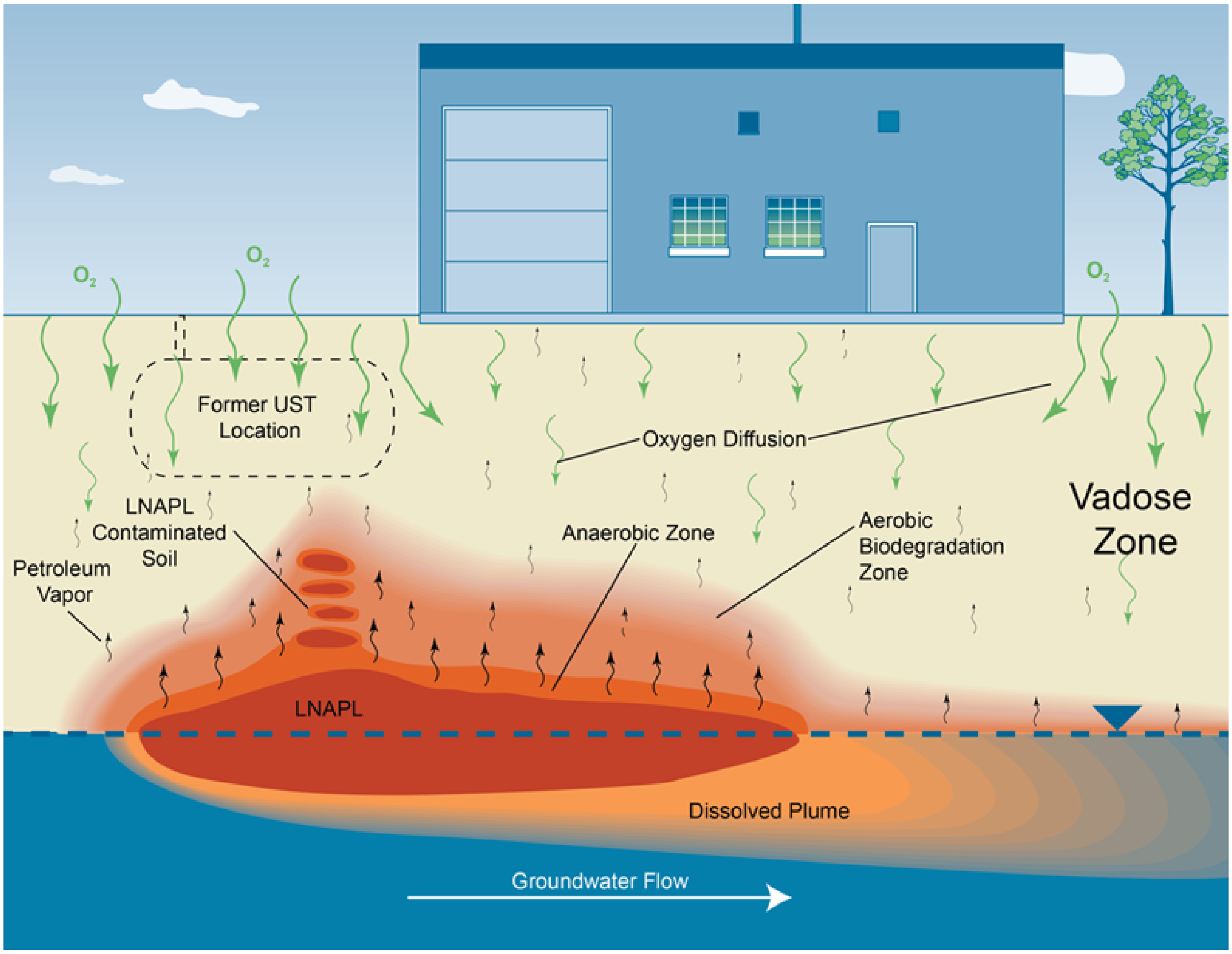


Figure E-1. Petroleum release at a gasoline or diesel UST site.

Additional resources for the evaluation of releases from USTs include guidance documents from IDEM (2012).

E.2 Commercial/Home Heating Oil Tanks

Heating oil is commonly used to heat both residential and commercial buildings in many parts of the United States. Releases from commercial and home heating oil tanks are typically small, but may range in size from less than one acre (approximately 0.4 hectares) to several acres (hectares) of land. A release from a site that currently uses heating oil will most likely contain No. 2 fuel oil. Sites where a historical release is suspected, however, will likely contain No.6 fuel oil, which is a heavier fuel oil.

Heating oil can be stored in either ASTs or USTs located inside or outside of the building. The capacity of these tanks can typically range from 250 gallons (946 liters) to 2,500 gallons (9,463 liters) although some tanks may be larger. Releases may be caused by tank corrosion, filter breakage, leakage from the copper line between the tank and furnace, and tank overfills.

Releases from ASTs located on concrete floors in building basements may be more contained within the basement and present a lower potential for PVI (although the release may migrate through the concrete and affect soil and groundwater, which may lead to the potential for PVI). Note that releases from ASTs that are completely contained within the basement may present an indoor air quality issue and are not covered as part of this guidance. Releases from interior ASTs located on dirt floor basements or basement floors with cracks, as well as releases from exterior ASTs located close to the building structure, may contaminate the groundwater and soil beneath the building, leading to the potential for PVI.

Releases from exterior USTs can have potential for PVI if the UST is located near the building or if the volume of the release is enough to contaminate shallow groundwater beneath the building (see Figure E-2). Vapors originating from a leaking heating oil UST or AST may also enter the building through preferential pathways such as utility conduits, sumps, and drains. BTEX, and to a lesser extent certain PAHs (such as naphthalene), are the primary COCs for PVI from commercial/home heating oil releases. Receptors at residential or commercial fuel oil sites typically include residents of the building structure and workers in commercial or office settings. Potential redevelopment of a site for a different use may change the receptors and may need to be evaluated. Nuisance odors may trigger an investigation to determine whether PHC odors are associated with PVI or an indoor air background source (indoor sources of PHCs are not covered as part of this guidance document).

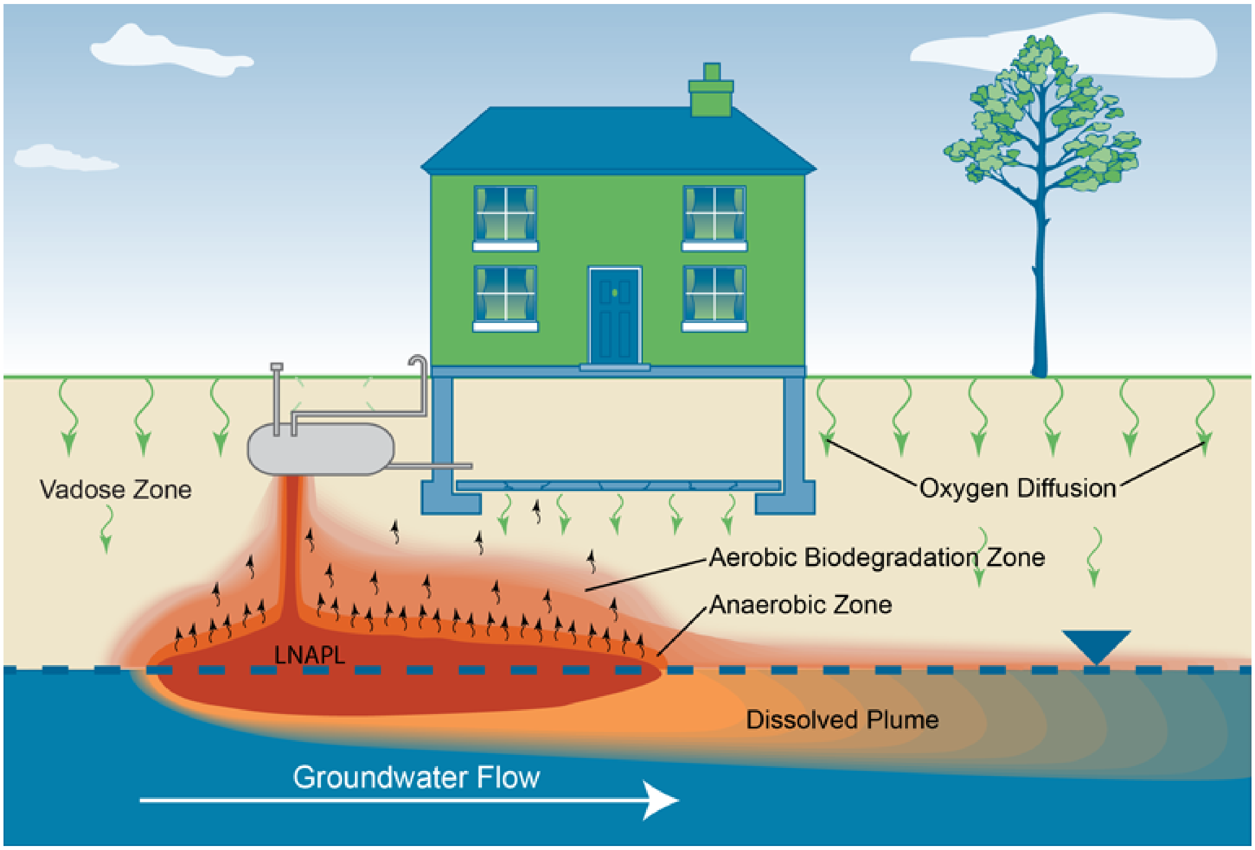


Figure E-2. Release from a home heating oil tank.

E.3 Refineries

Refineries receive large quantities of unrefined crude oil, which is processed into petroleum products used for fuel and other petroleum-based commercial products (see Figure E-3, Release at a refinery). Refineries are typically large facilities (many acres/hectares) constructed near surface water bodies or large groundwater reserves for use in the process for cooling water, and in the case of navigable surface water bodies, for ease of delivery of crude oil for processing and for shipment of refined petroleum. No new refineries have been built in the United States since 1976.

Conveyance piping at refineries occurs both above and below ground. When releases occur at a refinery, they are typically associated with transfer of the petroleum through the conveyance piping and result from failure of valves or connections, or from corrosion of the infrastructure piping. Refineries use various large storage vessels that contain a variety of refined products and can also be sources of a release. Petroleum or petroleum products within refineries include feedstocks, intermediate process streams, and final products from a variety of sources. Major petroleum or petroleum products (API 2002) that may drive potential PVI risk include:

- feedstocks: crude oil, natural gas liquids, recycled oil
- intermediate streams: atmospheric gas oil (light and heavy), naphtha (light and heavy from various units), vacuum gas oil (light and heavy), gas oil (light and heavy), residuum, aromatics (benzene, toluene, xylenes, other aromatics)
- major products: gasoline, jet fuel/kerosene, diesel oil, fuel oil (several grades), asphalt, lubricants, petrochemicals (such as olefins and aromatics), residuum
- other process streams: used solvent or lean oil, slop oil

Large volumes of PHCs are transported and managed at refinery sites, so repeated small spills may create incidental areas with LNAPL-contaminated soils. These LNAPL-contaminated soils can be a source for PHC vapors that is unrelated to LNAPL bodies near the water table. Large pools of LNAPL at the water table are also commonly found at these sites and represent a major source for PVI.

Potential risk drivers at refinery sites are highly variable within a refinery and between refineries as a function of the type of feedstock and end products produced at the refinery. Potential redevelopment of a former refinery site for a different use may require PVI assessment.

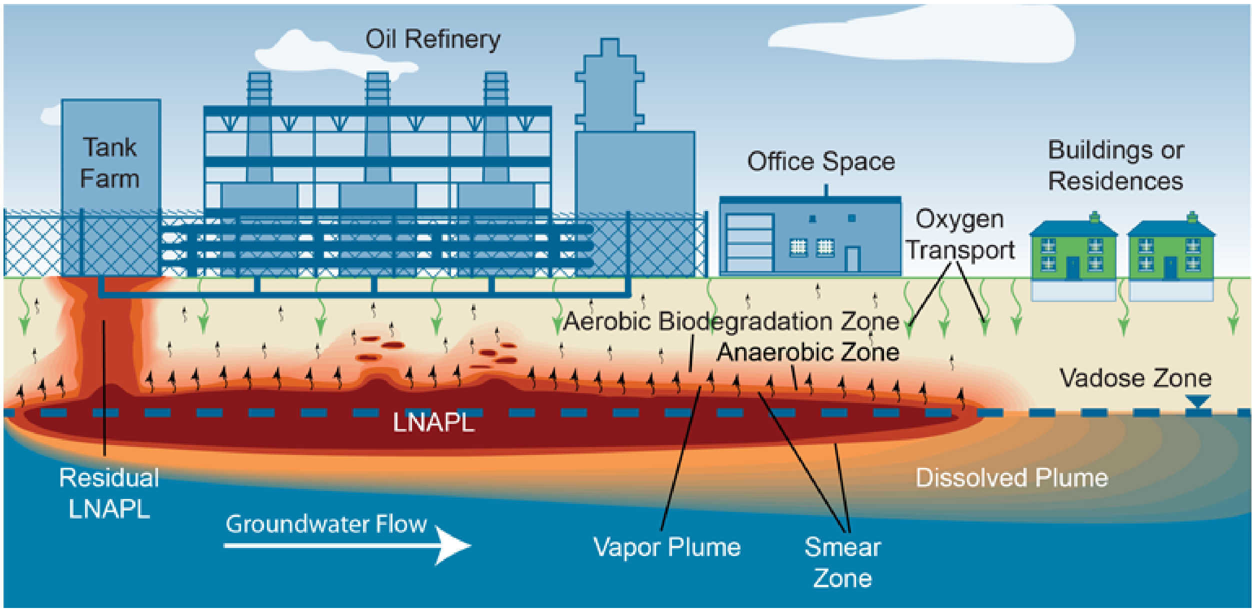


Figure E-3. Release at a refinery.

E.4 Bulk Storage Facilities

A bulk storage facility is one that is used primarily for the storage and transfer of petroleum products. Bulk storage facilities are also referred to as terminals or bulk storage terminals. Bulk storage facilities typically have ASTs with a storage capacity greater than 50,000 barrels (2.2 million gallons/8.3 million liters) and receive petroleum and refined petroleum products by tanker trucks, barges, rail, or pipelines. The types of refined petroleum products transferred at these types of facilities include gasoline, diesel, jet fuel, and heating oil. This transfer is typically through above or underground piping to delivery trucks or rail cars at the loading racks. Figure E-4, Releases at a bulk storage facility, shows typical features at a bulk storage facility.

Petroleum products at bulk storage facilities can be released from surface or subsurface infrastructure. Releases of gasoline (BTEX, naphthalene) present the greatest potential for PVI risk because gasoline contains more volatile components than other petroleum products handled at these sites. Many of the releases are related to the transfer of petroleum from the refinery to the terminal or from the transfer of the stored material to trucks or rail cars. Leaks from the large ASTs are less common than releases associated with the transfer of the petroleum products. Typically, releases from storage tanks will be contained within bermed areas, which act as secondary containment; infiltration from spills will vary depending on subsurface geology and if bermed areas are lined.

The distribution of the released LNAPL depends on the size of the release, location, and the surface and subsurface geology. Surface releases tend to spread following topography. Smaller releases of LNAPL are mainly distributed within the vadose zone; larger releases may migrate to groundwater. Most surface releases are confined to the secondary containment areas at these facilities. Underground releases have the ability to migrate to the water table depending upon the amount of product released and the local geology. Guidance and training on the behavior of LNAPL plumes and their relevance to PVI are available from the ITRC LNAPLs web page (ITRC 2013).

Potential for PVI is minimized when releases are localized and contained within the facility boundaries. The potential for PVI at these sites may be a concern if LNAPL is near an office building or if the property is later redeveloped into another use.

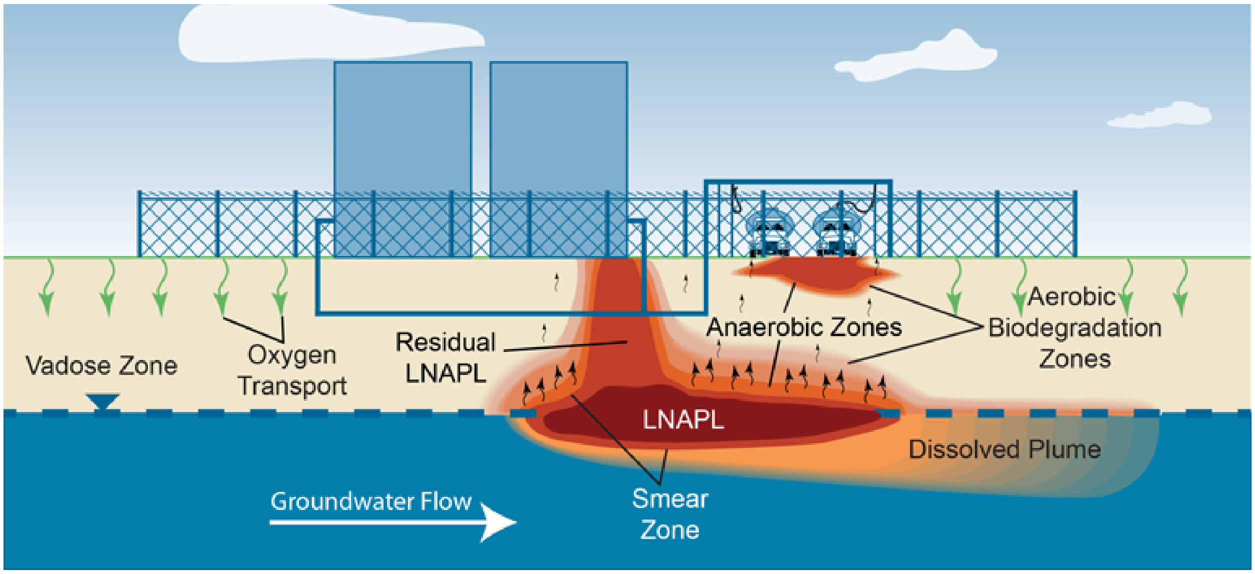


Figure E-4. Releases at a bulk storage facility.

E.5 Pipelines and Transportation

Pipelines constitute a highly specialized transportation system for the movement of crude oil, refined petroleum products, and natural gas. Crude oil, gasoline, jet fuel and many other petroleum products are transported across continents by large distribution networks of underground pipelines (pipelines are usually placed underground to protect them from damage). New pipelines are being built to meet global demand for oil and gas (Hopkin 2007).

Leaks from subsurface pipelines may not be noticed until the product spreads to the surface, so large releases can potentially contaminate deeper soils and groundwater aquifers before the leak is discovered. Pools of dark liquid on the ground surface near the pipeline, discolored or dead vegetation in the area near a pipeline, and PHC odors are some of the indicators of subsurface pipeline leak. Sizes of pipeline spills depend on the length and size of the piping network and duration of the leak or spill. Depending on the size of the pipelines, the volume of product released in a subsurface spill can be substantial.

Leaks are generally the result of corrosion or cracks in the pipeline; leaks may also occur in the flanges, valves, and other accessories of the pipeline. Knowing the location of the pipeline corridor is a key assessment factor for evaluating pipeline leak sites and establishing the nature of a release is an important part of the site characterization process. Age of the pipeline, dimensions, history and products carried in the line, as well as the history of prior leaks or repairs should also be considered. The typical spill migration path for constituents such as LNAPLs is likely linear (along the length of the pipeline) and downward (under the force of gravity). Depending on the properties of contaminants and the subsurface geology, sufficiently large spills can migrate from vadose zone soil layers to the groundwater table.

The BTEX compounds in soil and groundwater are the main COCs for pipeline leaks. For VI, benzene is typically the risk driver for petroleum spills from pipelines. Butane, propane, sulfur, methane, and benzene are the main constituents of natural gas pipelines. For natural gas pipeline spills, methane is of greatest concern as a safety issue, and benzene can also be found at elevated levels. Methane is not a long-term human health risk driver; however, it is flammable, explosive, and can be an asphyxiant.

Utility corridors for pipelines carrying liquid fuel are typically backfilled with coarse material, such as gravel. These permeable fill materials can act as a preferential pathway, aiding in the movement of vapors laterally and upward to the ground surface. PHCs, however, biodegrade relatively well in vadose zone soils when O_2 is present. PVI is most commonly associated with free product or high concentrations of dissolved phase TPH in groundwater near a building foundation (NJDEP 2013a). Buildings that are situated very near or over a leaking pipeline should be investigated for PVI if these conditions are identified. Potential redevelopment of a former pipeline corridor for a different use may require PVI assessment. Figure E-5 illustrates the potential for PVI at pipeline sites.

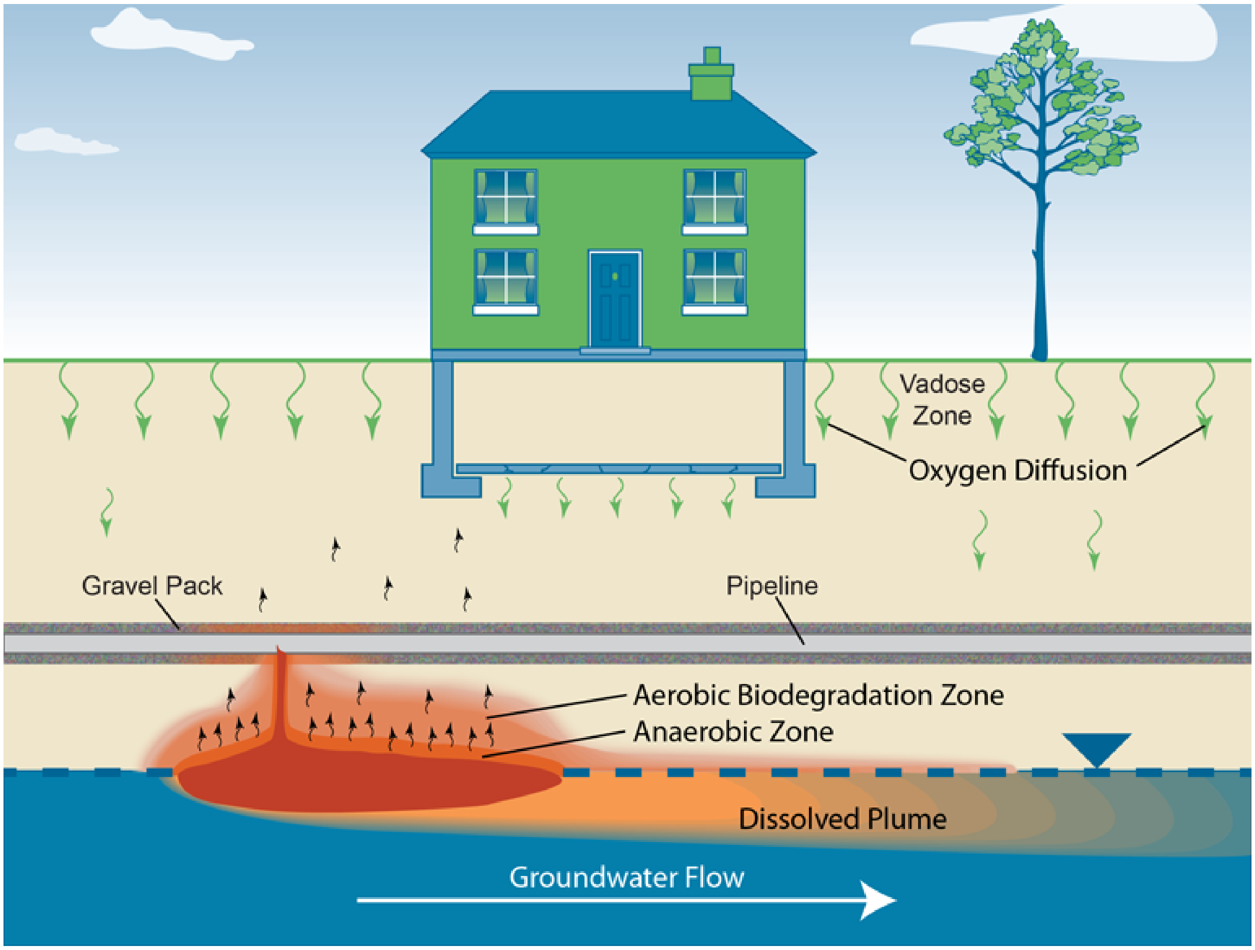


Figure E-5. Release from a pipeline.

E.6 Oil Exploration and Production (E&P) Sites

Oil exploration in the United States has continued for over 150 years. Oil exploration began with settlers and Native Americans finding and using natural oil seeps, and progressed to the large-scale commercial oil drilling and exploration of today.

Oil exploration and production (E&P) sites tend to be relatively large and consist of multiple exploration wells as well as staging, collection, and distribution areas. Parts of an E&P site will operate like the bulk storage facility described in Appendix E.4. Petroleum products at E&P sites range from crude oil to a variety of refined products.

The primary risk drivers are BTEX compounds and, at some sites, chlorinated solvents. Methane is also commonly present and is primarily a safety issue. Evaluation of the PVI pathway at E&P sites applies when these sites are either near existing or proposed commercial or residential development or the E&P sites are being considered for redevelopment. Figure E-6, Exploration and production site, illustrates potential areas to consider when evaluating the PVI pathway. These areas are located where a preferential pathway may exist or where PHC sources may be concentrated. Areas of greater concern regarding the PVI pathway include natural oil seeps, improperly sealed or abandoned wells, and sumps.

Natural oil seeps are commonly associated with shallow oil fields, especially those in seismically active areas such as California. Many of the older oil fields were discovered because of oil seeps, and natural oil seeps should be evaluated and documented at E&P sites. Seeps follow a pathway from a subsurface oil source to the surface and may contain higher levels of PHC vapors. The presence of seeps should be evaluated by searching available records regarding discovery and exploration at the site and by visual inspection of the site for localized or isolated oil pools. Because natural oil seeps are pressure driven, it is not possible to eliminate this source. It may be possible, however, to control vapors by capture and venting or treatment if necessary.

Pits, sumps, and spills are present at E&P sites and are potential source areas for PVI. Older E&P sites (pre-1990s) may not have lined pits and sumps, and thus present the potential for more widespread leakage from these features. These on-site waste and storage facilities can contain a wide range of compounds dominated by PHCs, but may include chlorinated compounds, as well. A detailed description of the large number of waste materials that can be present in E&P sumps and pits is presented in Wascom's study (2007). Pits, sumps, and spills are easily located through visual inspection of the site. Older or abandoned facilities can be located through evaluation of records of past site use, historical aerial photos, and interviews with former workers. Unlike seeps, sources in sumps and pits can be remediated to reduce or eliminate the potential for PVI.

Exploration and production wells are also present at E&P sites and may provide a potential preferential pathway for the migration of PHC vapors. The potential for PVI by these preferential pathways may be greater in older fields, as shown in Figure E-6, where completion methods were not designed to eliminate leakage of reservoir gas to the surface. Many older fields may also contain exploration wells that were abandoned using methods that are not appropriate for eliminating the PVI pathway. Records for the E&P site should be evaluated to locate exploration and production wells that were drilled on the property. Existing wells should be abandoned properly to reduce potential for future leakage. Older wells may need to be evaluated to determine whether they were abandoned properly. It may be necessary to collect soil gas samples around older wells to document whether leakage is currently taking place. Gases that are of particular concern at E&P sites include benzene, the primary risk driver, and methane, the primary safety issue.

Other features that can be present on E&P sites include tanks, transfer pipelines, well pads, maintenance facilities, equipment yards, and roadways. Records, interviews with past workers, and aerial photos can be used to determine whether these features were present and, if so, where they were located. Existing structures may need to be removed to reduce or prevent PVI risk. Potential redevelopment of a former E&P site for a different use may require PVI assessment.

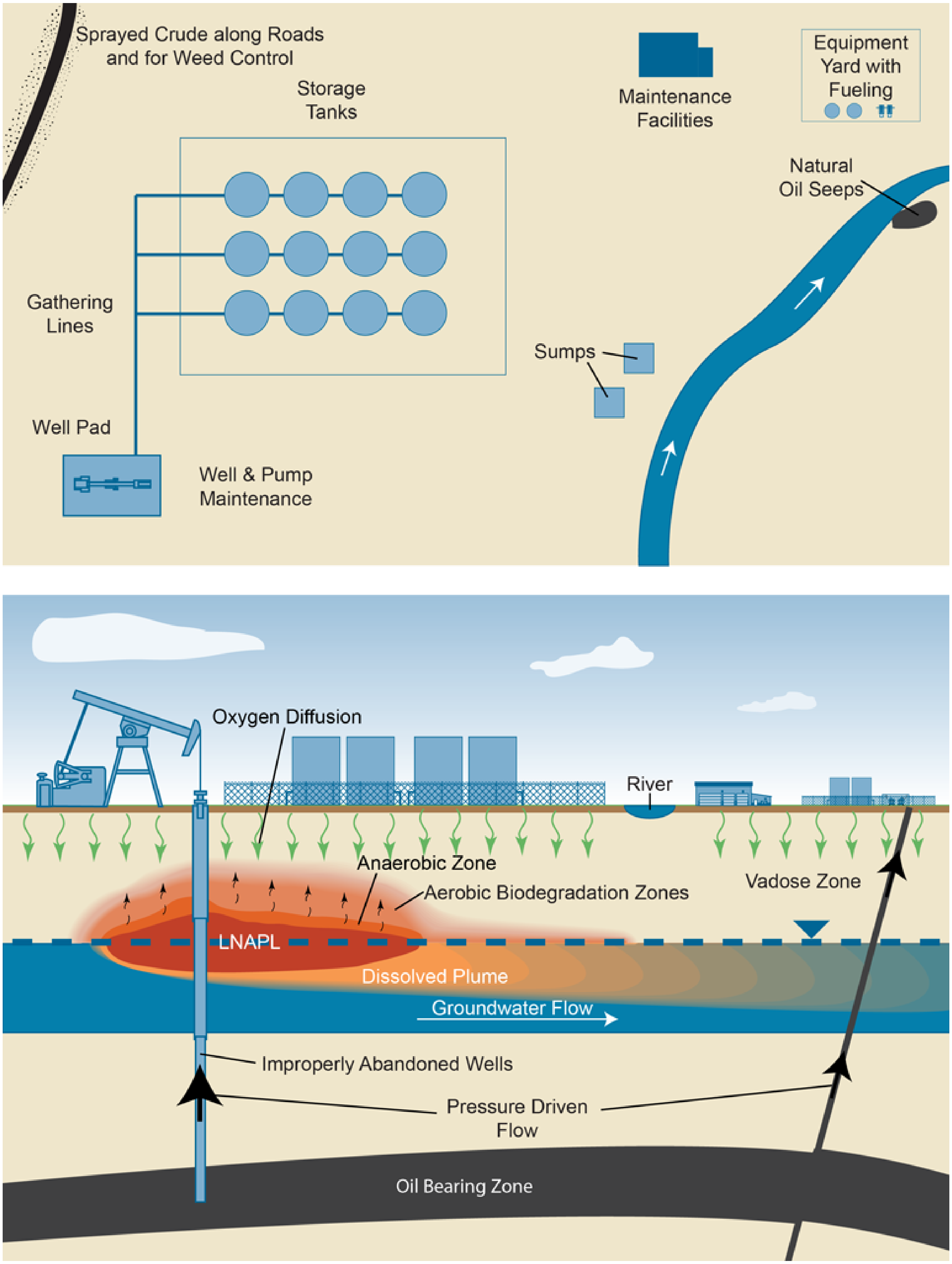


Figure E-6. Exploration and production site.

E.7 Former Manufactured Gas Plants

A manufactured gas plant (MGP) is an industrial facility where gas was produced from coal, oil, and other feedstocks. MGPs operated from the mid-1800s to around the mid-1900s. The process of gasification generated hydrocarbons that are related to and behave in the same manner as PHC compounds. See Appendix C for more information on chemistry. The gas produced was stored and then piped to the surrounding area, where it was used for lighting, cooking, and heating homes and businesses (NYSDEC 2013). MGP sites can range from 0.2 acres (0.08 hectares) to 75 acres (30 hectares) in size, with average and median sizes of 6.1 and 2.0 acres (2.5 and 0.8 hectares) (NYSDEC 2013).

During operation of the MGP, a dense, oily liquid known as coal tar would condense at several stages during gas production, purification, and distribution. Although most of the tar was collected for sale or reuse, recovery was usually incomplete. Most plants had tar/water separators, which sometimes could not fully separate the two liquids. The resulting tar/water emulsion was commonly discharged to a nearby surface water body. Over decades of plant operation, substantial amounts of tar also leaked from storage and processing facilities and contaminated surface soils, subsurface soils, and groundwater. Leakage from underground tanks and piping could contaminate soil and groundwater. Historical information including Sanborn Fire Insurance maps, old photographs, and site drawings may be used to identify former structures and potential source areas. PHCs can generally be found near the gasholders which were used to store gas prior to distribution, or near underground tar wells, tar holders, oil/water separators, purifying boxes, or under "gas oil" storage tanks (kerosene-like oil used in carbureted water gas plants). MGP sites using the coal carbonization process may have separate gas purification areas apart from the retort house.

PHCs present in soil or groundwater generally consist of volatile BTEX compounds and semivolatile PAH compounds. MGP residuals can have a range of densities and may either float on the water table as LNAPL, or sink as DNAPL. DNAPLs and LNAPLs may be found above silt layers in the soil or above confining layers such as tills and clays.

PAHs are typically found near site sources because of their affinity to bind to soil and low solubility in water. Aromatic VOCs may travel farther from sources, as dissolved constituents in the groundwater. Preferential pathways for vapors may include permeable zones such as gravel layers, storm and sanitary sewers leading off site, and karst/fractured bedrock.

Evaluation of the PVI pathway at former MGP sites begins with identification of potential source areas; see Figure E-7, Releases at a former manufactured gas plant. Based on the history of MGP sites, potential receptors may include commercial and industrial workers or residents in homes built over or adjacent to the MGP. Although PHCs may be found in the soil or groundwater at MGP sites, there is a growing body of evidence that the potential for PVI is relatively low at most sites. In one study, BTEX compounds were present the subsurface soils at large MGP sites in New York City and Ithaca, New York. Statistically elevated concentrations of these VOCs were not, observed in the indoor air, however (EPRI 2007). New York State Department of Health also reported preliminary results of an analysis of MGP sites in a VI database. This analysis indicated that levels of MGP-related compounds in indoor and outdoor air at these sites are comparable to concentrations found during background studies (Anders 2012). Another study evaluated data for 10 commercial buildings and 26 single and multiple families overlying or adjacent to three MGP sites and found no unacceptable inhalation risks due to MGP constituents in indoor air. The authors suggested that a number of factors may have prevented soil PVI, including a clean layer of groundwater between the contaminant plume and buildings, as well as natural attenuation through biodegradation of VOCs (DeHate 2011).

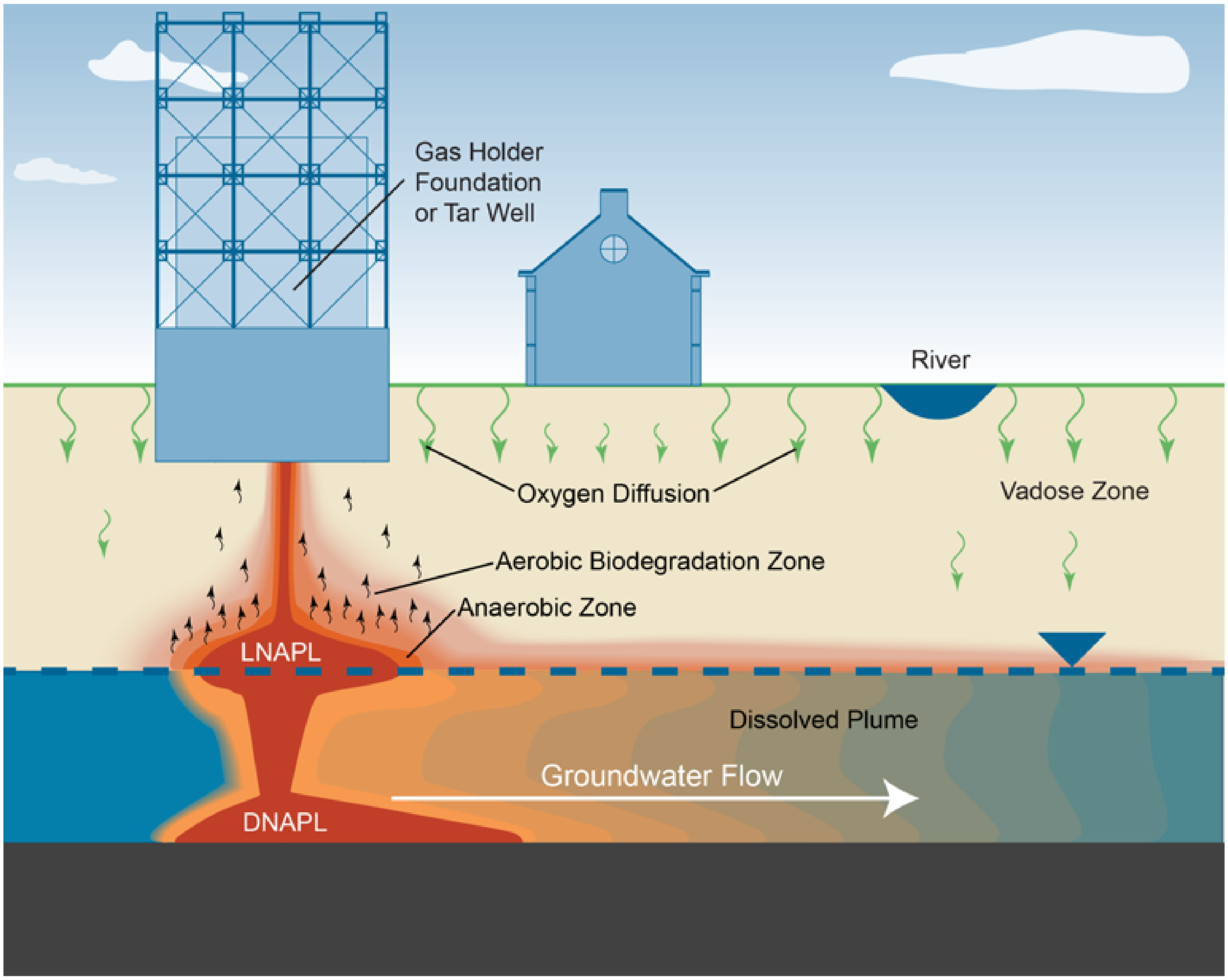


Figure E-7. Release at a former manufactured gas plant.

E.8 Creosote (Wood-treating) Facilities

Creosote (wood-treating) facilities processed coal tar to produce creosote (and other distillation fractions), then treated wood with the creosote. Historically, creosote was refined from coal tar produced at MGPs, but some sources of creosote were refined from pine tar, a by-product of charcoal production. Coal tar creosote was patented in 1836 by Moll, and John Bethell obtained a patent in 1838 for a pressure impregnation process (Freeman et al. 2003). The first factory began treating railroad ties in 1865, and treated railroad ties have since been used across the country. In 2003 alone, U.S. railroad companies installed an estimated 17 million creosote-treated wood ties according to the American Creosote Council website (American Creosote Council 2013). Creosote is also used to treat utility poles, marine pilings, and other wood products for outdoor use.

Wood treating facilities containing creosote and other chemicals have been the subject of numerous Superfund cleanup efforts. USEPA issued a Presumptive Remedy document in 1995 identifying methods to remediate soil and groundwater (USEPA 1995). Areas of potential concern at wood treatment sites include drip pads, product storage areas, processing areas, unlined pits, unlined surface impoundments, and lagoons. Some wood preserving sites contained both coal tar distillation areas for creosote production, as well as separate wood treatment areas. Creosote sites can range from a few acres/hectares to several hundred acres/hectares with volumes of contaminated soil ranging from tens of thousands of cubic meters to hundreds of thousands of cubic meters. Potential receptors include occupants of buildings built on or adjacent to wood treating facilities. Potential redevelopment of former wood treating facilities may require further PVI assessment.

Coal tar creosote is a complex mixture typically composed of approximately 85% PAHs and 2% to 17% phenolic compounds (ASTDR 2002). The PAHs are generally less volatile and less soluble than VOCs. Coal tars and creosotes are slightly heavier than water and tend to sink when released to groundwater or surface water; see Figure E-8, Releases at a creosote (wood treating) facility. After reaching the water table, the soluble components may partition to the dissolved phase, and the lighter compounds may volatilize. Therefore, COCs at creosote sites are primarily naphthalene and its alkyl derivatives. BTEX compounds may be present in leachate and contaminated water. As creosote ages, the more volatile and soluble compounds of the mixture diminish relative to the less volatile and soluble compounds (USEPA 2014b). Diesel fuel may also be present since it was often used as a solvent for creosote.

A study of PVI from a soil source has been conducted at the former Reilly Superfund site in St. Louis Park, MN. The results indicate that the risk from vapor intrusion is within or below the USEPA's acceptable risk range. The Five Year Review for the Cabot/Koppers site in Gainesville, FL suggests that the potential for PVI "…can be evaluated prior to the next Five Year Review as the protocols are finalized" (USEPA 2011a). Study results of the potential for PVI from a soil source at creosote wood-treating facilities were not available during preparation of this document; however, the potential for PVI may be relatively low because the by-products are similar to those at former MGP sites (Appendix E.7).

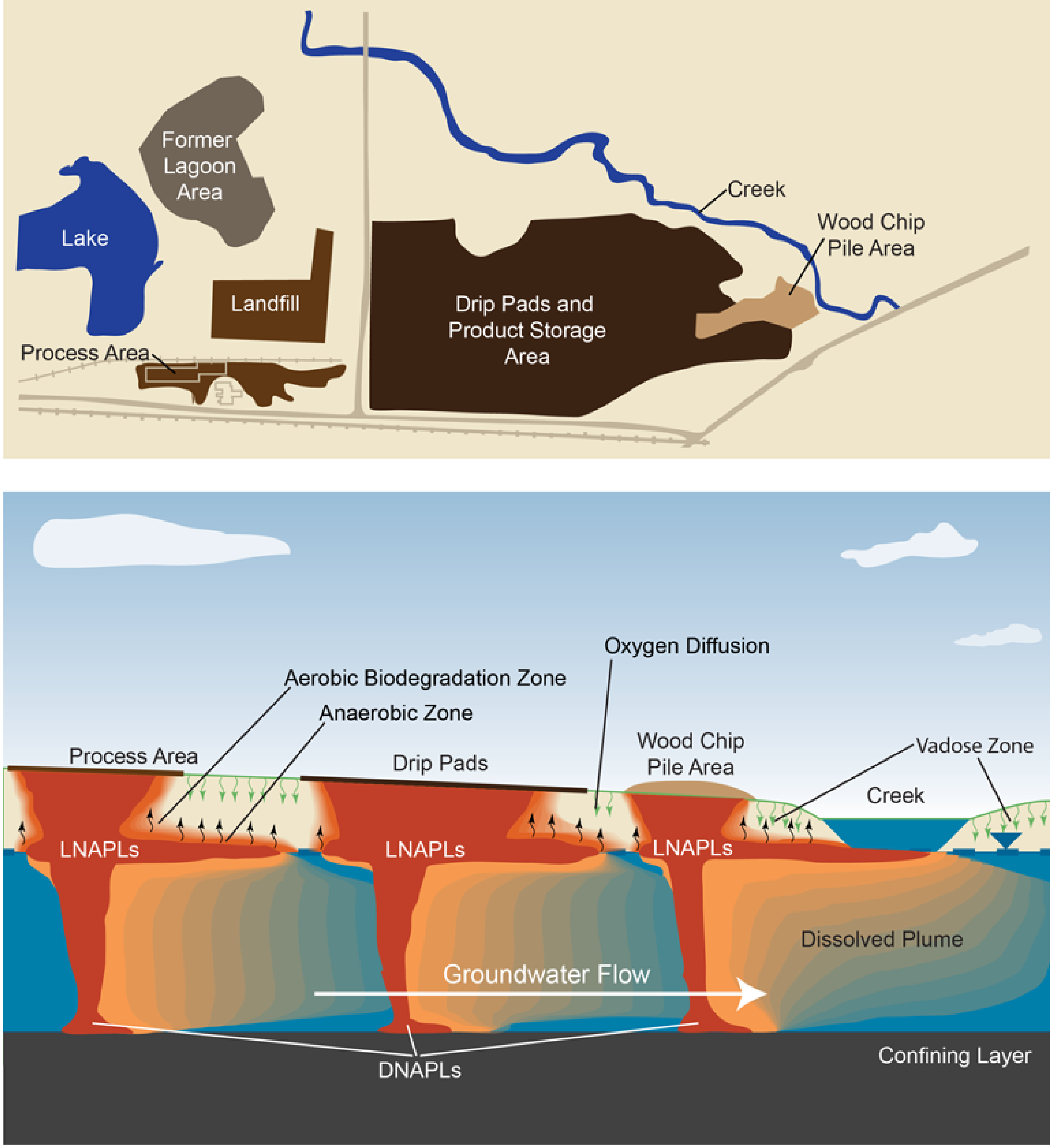


Figure E-8. Release at a creosote (wood treating) facility.

E.9 Dry Cleaners Using Petroleum Solvents

Historically, the most common petroleum product used in the dry cleaning industry was Stoddard solvent, which is a mixture of aliphatic and alicyclic hydrocarbons in the C7–C12 range. Some currently used, high flash solvents are in the C11–C13 range. Currently, it is estimated that fewer than 15% of dry cleaners in the United States use petroleum solvents. The practice is more prevalent in the southern United States, with estimates of 45% to 50% of dry cleaners using these solvents (SCDHEC 2004).

Dry cleaning facilities are commonly located in strip malls, but can also be stand-alone buildings on small lots typically less than 0.5 acre (0.2 hectares). Off-site migration of contaminants in groundwater or as soil gas plumes poses a potential concern for PVI. Potential receptors may include commercial and industrial workers on site or residents in homes adjacent to the dry cleaning facility. Potential redevelopment of a former dry cleaner site for a different use may require PVI assessment. See Figure E-9, Release of petroleum-based solvents from a dry cleaners.

Preferential pathways for PVI include utility corridors, improperly installed/abandoned/damaged monitoring wells, cracks/holes in floor slabs, basement sumps, and naturally occurring subsurface features such as caves, sinkholes, and fractured bedrock.

Releases to the environment generally occur through improper waste disposal and storage practices. Other sources for a potential release can include spills, container rupture, or faulty equipment. Most spills release less than a few of gallons/liters of product; however, poor housekeeping and improper waste disposal practices may release a significantly greater volume of solvent.

Dry cleaning facilities that use petroleum solvents typically pose a lower risk for VI than facilities that use tetrachloroethene, because petroleum solvents degrade under aerobic conditions. Therefore, an important part of the assessment for the potential for PVI at a dry cleaning facility is to assess which solvents have been used at the facility throughout the operational history. It is not uncommon for a facility to have switched from one type of solvent to another. ITRC provides guidance on assessing the potential for VI at a dry cleaner using CVOCs in *Vapor Intrusion Pathway: A Practical Guideline* (ITRC 2007)

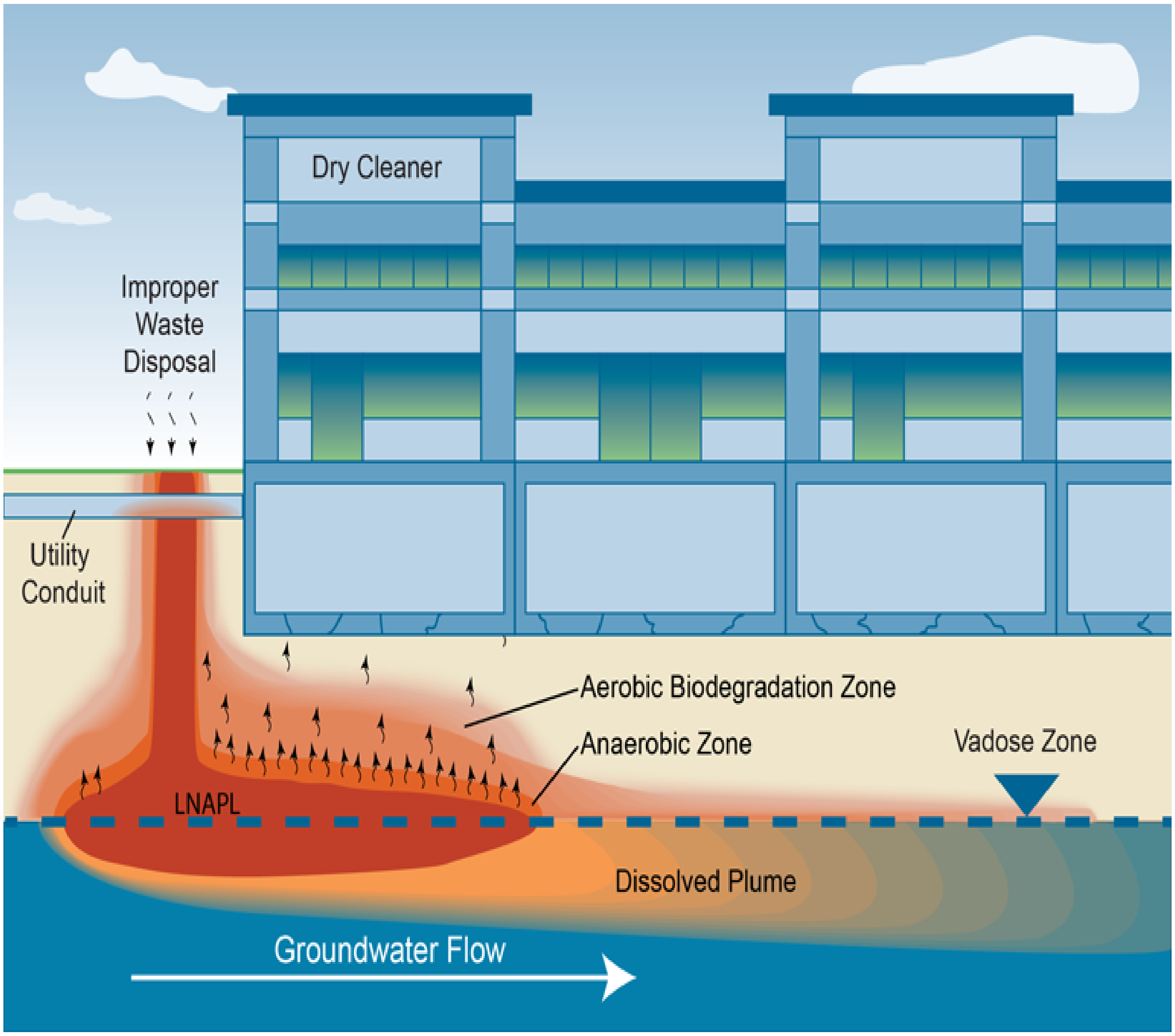


Figure E-9. Release of petroleum-based solvent from a dry cleaners.

APPENDIX F. TECHNICAL INFORMATION TO SUPPORT SITE SCREENING

This appendix provides the technical information used to support the development and application of vertical screening distances for PVI. The information is provided through a Frequently Asked Questions (FAQ) format.

1. What prompted the development of a new screening approach for PVI based on separation distance from the petroleum vapor source?
2. How were the vertical screening distances derived?
3. How were vertical screening distances derived in the empirical studies?
4. What are the key findings of the empirical studies?
5. Are the vertical screening distances determined by empirical studies supported by transport modeling?
6. What if my agency recommends lower soil gas screening levels than those used in the empirical studies?
7. What key data must be collected to support site screening?
8. Why are highly organic, rich soils such as peat a precluding factor for PVI screening?
9. Are O_2 soil gas concentration measurements necessary for PVI screening?
10. Are vertical screening distances used in regulatory guidance?
11. What is the role of groundwater and soil concentration data in PVI screening?
12. How important are TPH soil or groundwater concentration measurements in site screening?
13. How are temporal variations in the water-table elevation and uncertainty in the exact source depth accounted for in PVI screening?
14. What about methane?

F.1 What prompted the development of a new screening approach for PVI based on separation distance from the petroleum vapor source?

New data has prompted the development of a new screening approach for PVI. Numerous site investigations have been undertaken to assess the potential for PVI, yet actual confirmed occurrences are rare (Fitzpatrick and Fitzgerald 2002; Hers et al. 2003; Tillman and Weaver 2005; McHugh et al. 2010). The issue can largely be attributed to conservative screening levels derived using the J&E model (1991) or empirical attenuation factors (AFs) derived primarily from chlorinated hydrocarbon data (USEPA 2012j), neither of which take into account biodegradation in the vadose zone (Tillman and Weaver 2005). The effect of biodegradation in the vadose zone on PVI had not been previously quantified sufficiently to meaningfully incorporate into a regulatory framework to improve site screening.

The use of AFs for PVI screening has recently been brought into question through a number of key modeling studies (Abreu, Ettinger, and McAlary 2009b; API 2009) and empirical studies (Hers et al. 2000c; Davis 2009, 2010; Peargin and Kolhatkar 2011; Wright 2011; USEPA 2013a; and Lahvis et al. 2013a). The studies have shown that:

- Actual AFs of PHC COCs in the vadose zone are generally orders of magnitude less than those predicted by transport modeling assuming no biodegradation.
- AFs for key PVI COCs in the vadose zone can be highly variable, especially across the aerobic biodegradation zone (see Figure 3-1) where AFs can decrease several orders of magnitude over relatively short vertical distances (for example, less than three feet)
- The magnitude of the AF varies depending on whether the PHC vapor source is dissolved or LNAPL, as well as on the vertical separation distance between the source and building foundation.

The noted variability and sharp decrease in AFs at some critical distance above the PHC vapor source limits applicability of AFs for PVI. The behavior of PHC COCs in the vadose zone is more amenable to a PVI screening method based on vertical separation distance or vertical screening distance.

F.2 How were the vertical screening distances derived?

Vertical screening distances for dissolved-phase and LNAPL sources were derived based on collective findings from laboratory, modeling, and most importantly, recent field (empirical) studies conducted by Davis (2009, 2010); Peargin and Kolhatkar (2011); Wright (2011); USEPA (2013a); and Lahvis et al. (2013a). The empirical studies were critical in:

- documenting the significance of biodegradation in the vadose zone
- quantifying the vertical screening distance above a PHC vapor source where concentrations of key COCs biodegrade below levels of concern for PVI

The empirical studies include data for groundwater, soil, and soil gas from hundreds of PHC release sites spanning a range of environmental and site conditions, geographical regions, and a 16-year time period (1995–2011) of data collection. Fuel types included gasoline containing as much as 10% vol/vol ethanol or 15% vol/vol methyl tert-butyl ether (MTBE).

F.3 How were vertical screening distances derived in the empirical studies?

Several empirical studies were undertaken to derive risk-based vertical screening distances for PVI applications from soil gas concentration data. Vertical screening distances were derived specifically for dissolved-phase and LNAPL sources. The empirical studies are described below and summarized in Table F-1:

USEPA (2013)

The USEPA (2013a) study involved a detailed assessment of hundreds of (primarily) UST and non-UST (terminal and refinery and one petrochemical) sites located mainly in North America. The database was originally compiled by Davis (2009) and included a large data set from Maine that was later added by USEPA (2013a). The database spanned a range of environmental site conditions, lithologies, surface covers (e.g., building foundation pavement, open ground) and PHC sources (such as gasoline, diesel, kerosene, and jet fuel) and a broad period of data collection (1995–2011). The composition of the PHC source at sites was largely unknown. Gasoline sources may have contained up to 10% by volume ethanol and up to 15% by volume MTBE. Sites with sources containing greater than 10% vol/vol ethanol were not included in the database analysis. The databases contain general information on concentrations of hydrocarbons (such as benzene, TPH, naphthalene) and fixed gases (such as O_2, CO_2, and CH_4) in soil gas, hydrocarbon concentrations in groundwater and soil, source depth, and surface cover. Virtually all of the soil gas data reported in the database were collected from permanent vapor probes and analyzed using commonly accepted methods (for example, EPA Method TO-15, EPA Method TO-3, Modified EPA 8260, and Massachusetts Air Phase Hydrocarbons for hydrocarbons; ASTM D1946 and EPA Method 3C for fixed gases). The database included 38 sites with subslab vapor samples.

The derivation of screening distances required the differentiation of PHC vapor sources (LNAPL and dissolved-phase) and identification of LNAPL sources in the vadose zone. The effort also included a review of groundwater monitoring data, borehole logs, and field notes. LNAPL was assumed to be present at locations where benzene and TPH (gasoline) concentration in groundwater exceeded 5 mg/L or 30 mg/L, respectively, and where benzene and TPH (gasoline) concentrations in soil exceeded 10 mg/kg or 250 mg/kg, respectively. The latter criterion is not expected to be significant given that it was used to solely identify residual-phase LNAPL in less than 2% cases.

The database was extensively reviewed to ensure that it met strict data QA/QC standards for interpretation and analysis. QA/QC of the data included review of:

- site investigation reports
- groundwater monitoring, soil gas, and borehole log data
- site plans
- sample locations relative to USTs and other potential vadose zone sources
- sample methods and analyses
- data quality testing (such as pneumatic and tracer testing, purging procedures, and sample breakthrough results)
- general relationships between hydrocarbon and fixed gas (O_2, CO_2, and CH_4) concentrations in the vadose zone (for broad consistency with the conceptual model for aerobic and anaerobic hydrocarbon biodegradation)

Site data were also scored based on overall data quality and confidence in the hydrocarbon CSM. Suspect data associated with unacceptable QA/QC tests (for example, tracer tests), sample methods and analyses, or likely presence of LNAPL sources in the vadose zone were flagged and eliminated from further consideration. The USEPA (USEPA 2013a) database is publicly available at: http://www2.epa.gov/sites/production/files/2014-09/documents/pvi_database_report.pdf.

Vertical screening distances were determined as a function of source type (dissolved phase, LNAPL), COC type (benzene, xylenes, hexane, C5–C8 aliphatics, C9–C12 aliphatics, C9–C18 aromatics), site type (UST, non-UST), soil type (fine and coarse-grained), and surface cover (pavement, building foundation, and open ground). The vertical screening distances were determined using two different methods: the clean soil method described by Davis (2010) and a vertical distance method. The clean soil method is based on estimating (interpolating between vapor probes) a thickness of relatively clean biologically active soil (containing O_2) required to biodegrade hydrocarbon vapors to below a specified risk-based COC concentration in soil gas. The vertical distance method is based on estimating the distance of a soil probe above the source where the soil gas concentration is below a specified risk-based concentration. The two methods generally resulted in similar screening distance estimates even though the vertical distance method generally involved less uncertainty. Key findings from USEPA (2013a) are reported in Table F-1.

Lahvis et al. (2013)

Lahvis et al. (2013a) evaluated soil gas data collected only from UST sites. These data were obtained from studies by Wright (2011) and USEPA (2013a). The combined database comprised 728 soil gas (hydrocarbon and fixed gas – O_2, CO_2, and CH_4) samples from 120 UST sites and 332 sampling locations. Screening distances were only derived for benzene.

Lahvis et al. (2013a) used an approach similar to the one used by USEPA (2013a) to discriminate between dissolved-phase and LNAPL sources, identify hydrocarbon sources in the vadose zone, and eliminate poor-quality or suspect data. Approximately one-third of the soil gas samples in the database were collected in relatively high permeability sand, gravel, and fill material; the remaining two-thirds were collected in relatively low permeability silts, silty clay, and clay. Of the soil gas samples, 11% were from subslab locations, and the remaining samples were assumed to be evenly distributed between those located beneath pavement and those located beneath open ground. The dissolved-phase data set consisted of 261 soil gas measurements from 47 sites and 128 sample locations; the LNAPL data set consisted of 467 soil gas measurements from 73 sites and 204 sample locations. Source-receptor separation distances were calculated using the “vertical distance” method described by USEPA (2013a). Key findings from Lahvis et al. (2013a) are also reported in Table F-2.

Davis (2009, 2010)

Davis (2009) analyzed 259 benzene and 210 TPH vapor samples from 53 geographical locations in the U.S. and Canada. The database contained soil gas and co-located, concurrent groundwater data collected at UST and non-UST sites over a 16-year period (from 1995 to 2011) as well as site-specific information on soil type, depth to groundwater, presence of free product, and concentrations of benzene and TPH in both the dissolved phase and the soil vapor phase. Davis (2009) estimated that 5 feet (1.5 m) and up to 30 feet (about 10 m) thicknesses of clean soil (vertical separation distance) were required to biodegrade PHC vapors emanating from dissolved-phase and LNAPL sources, respectively, to below specified soil gas concentrations of concern for vapor intrusion. The screening distances for LNAPL sources were later revised to 8 feet after accounting for residual-phase LNAPL sources above the water table (Davis 2010). A significant portion of data was from published field studies.

Peargin and Kolhatkar (2011)

Peargin and Kolhatkar (2011) found that target 10^{-5} risk-based concentrations of benzene in near-slab soil gas samples (300 µg/m^3) were only exceeded at distances of over 15 feet from relatively high concentration sources (defined by dissolved-phase benzene concentrations, greater than 1,000 µg/L). In addition, benzene concentrations in soil gas were generally over 30 µg/m^3 above inferred dissolved-phase sources. Soil gas data collected from the following locations were excluded from the analysis:

- near locations with shallow vadose zone soil impacts (such as within the footprint of former petroleum USTs, piping, or site excavations or inferred from elevated FID/PID readings from soil borings) more than 30 feet from the nearest groundwater monitoring well
- more than 90 days from the date of groundwater sampling
- from sites with non-gasoline releases and atypical hydrogeologic characteristics (fractured rock aquifers, submerged smear zones, extreme variations in seasonal water tables)
- during and after application of a remediation technology that might have affected the smear zone LNAPL chemistry (such as AS/SVE, MPE, and others)
- from poorly constructed wells or using inappropriate sampling or laboratory analytical methods.

The analysis included an evaluation of 218 pairs of benzene soil vapor and groundwater concentration data from 25 sites (20 in California). The 1000 µg/L benzene concentration used to distinguish dissolved phase source versus. LNAPL source was empirically derived as the most conservative average benzene concentration (about 5th percentile concentration) observed in time series data from 269 wells (83 sites) that at one point in time showed measurable LNAPL thickness in the well.

Wright (2011, 2012)

Wright (2011) included data from 1083 pairs of benzene soil vapor and groundwater concentration data collected from 124 sites in Australia, from both UST and a few non-UST sites (including refineries and terminals). Benzene concentrations biodegraded below a risk-based screening level of 50 µg/m^3 at distances ranging from 5 to 10 feet (1.5 to 3 m) for dissolved-phase hydrocarbon sources (defined by dissolved-phase benzene concentrations greater than 1 mg/L and TPH concentrations greater than 10 mg/L) to around 30 feet (10 m) for some LNAPL and poorly characterized dissolved-phase sources. Subsequent analysis (Wright 2012) found that soil gas screening level concentrations were only exceeded at distances 12 feet (about 4 m) above LNAPL sources. The analysis did not consider subslab soil gas samples.

The calculated screening distances were deemed relevant to all soil types, including fractured rock systems, given that 41% of the soil gas data were collected in such hydrogeologic systems. Among the soil gas samples, 28% were associated with dissolved-phase sources, and the remaining 72% were associated with LNAPL sources. The database underwent extensive QA/QC similar to that in the USEPA study (2013a), including the scoring of site data. The empirical data from this study are used to support regulatory guidance development for Australia CRC for Contamination Assessment and Remediation of the Environment (CRC CARE 2013).

F.4 What are the key findings of the empirical studies?

Key findings of the empirical studies are summarized below. In general, the vertical screening distances and findings reported in the various independent empirical studies involving differing methods and screening levels are all similar (see Table F-1). Findings from two of the more detailed empirical studies (Lahvis et al. 2013a; USEPA 2013a) are summarized in Table F-2. In general, vertical screening distances for dissolved-phase sources range between 0 and 5 feet. Vertical screening distances for LNAPL sources vary slightly depending on site type, ranging from 13 to 15 feet at petroleum UST sites to 18 feet at terminal, refinery, or petrochemical sites. Studies of the empirical data show a 93% confidence in the vertical screening distances for petroleum UST/AST sites and 90% confidence for petroleum industrial sites. There is also more uncertainty with the industrial sites as a result of a relatively small data set of industrial sites (USEPA 2013a). Differences in the vertical screening distances according to site type may relate to the volume of the LNAPL release or extent of the LNAPL plume. Large releases of PHC can result in a large oxygen demand, which reduces biodegradation of the PHC. Petroleum industrial sites, such as terminals, refineries, and petrochemical sites tend to have large infrastructure and may have multiple releases from different locations, which can also exert a high oxygen demand. Given that LNAPL release volumes and plume extents may not always correlate with the site type, a good CSM and professional judgment are needed to select the most appropriate LNAPL vertical screening distance.

Hydrocarbons were also predicted to biodegrade by several orders of magnitude across a relatively narrow (less than 3 feet) region above the PHC vapor source where conditions in the vadose zone transition from anaerobic to aerobic (Abreu, Ettinger, and McAlary 2009b; API 2009); see Figure 3-1. The transition between anaerobic and aerobic biodegradation occurs at O_2 soil gas concentrations in the range of 1% to 4% v/v (DeVaull 2007). The rapid hydrocarbon attenuation is attributed to rates of aerobic PHC biodegradation occurring much faster than rates of physical hydrocarbon transport through the vadose zone by molecular diffusion (Davis, Patterson, and Trefry 2009). Just above the aerobic biodegradation zone, soil gas concentrations of key COCs for PVI (e.g., BTEX, TPH fractions) were found to biodegrade below levels of concern for PVI (Davis 2009, 2010; Davis, Patterson, and Trefry 2009; Peargin and Kolhatkar 2011; Wright 2011; Lahvis et al. 2013a; and USEPA 2013a).

The findings of the studies show that the vertical distance required to biodegrade PHC COCs below levels of concern varies depending on whether the source is LNAPL or a dissolved-phase plume in groundwater. In general, the aerobic biodegradation zone will develop at a higher elevation (or shallower depth) above LNAPL sources because (a) PHC COC concentrations are greater for LNAPL sources than dissolved-phase sources; and (b) LNAPL sources are invariably distributed (by water-table fluctuation induced smearing) above the capillary zone where the vadose zone soils are more conducive to vapor migration (less water saturated); see Figure 3-1. The aerobic biodegradation zone will develop at various distances above LNAPL sources depending on fuel type, composition, and degree of weathering. In general, the aerobic biodegradation zone will develop farthest above LNAPL sources containing large fractions of volatile, aerobically biodegradable hydrocarbons (meaning fresh gasoline rather than diesel or weathered gasoline) and gasoline containing over 10% vol/vol ethanol. High ethanol content fuels have the potential to generate significant concentrations of methane in soil gas (1% to 20%) upon biodegradation in groundwater (Ma et al. 2012). Subsequent oxidation of methane in the vadose zone can reduce the amount of O_2 available for PHC biodegradation and potentially increase the vertical separation distance necessary to biodegrade hydrocarbon COC concentrations in soil gas below levels of concern for PVI. In contrast, the aerobic biodegradation zone tends to develop near dissolved-phase hydrocarbon sources (for example, near the capillary zone) because the hydrocarbon mass flux is more limited than for LNAPL sources. The hydrocarbon mass flux is limited by relatively low source concentrations (compared to LNAPL), relatively slow rates of vapor migration (through the capillary zone), and significant biodegradation in the capillary zone. The relative low hydrocarbon mass flux to the vadose zone (and demand for O_2) is insufficient to drive conditions in the vadose zone extensively anaerobic, even below building foundations and relatively impermeable surface covers (Abreu, Ettinger, and McAlary 2009b; McHugh et al. 2010; Lahvis et al. 2013a; USEPA 2013). PVI cases involving dissolved-phase PHC sources separated vertically from building foundations are also not found reported in the literature (McHugh et al., 2010).

The vertical screening distances are also expected to apply laterally in the absence of hydrogeologic barriers (such as perched water tables or low-permeability soil lenses) or preferential pathways (sewer corridors or fractured rock) that could potentially enhance lateral hydrocarbon vapor migration. It may be challenging or infeasible, however, to accurately delineate the edge of a contaminant plume within the relatively short vertical screening distances (0 to 5 feet) defined in the empirical studies (see Table F-1). Furthermore, the distance between a dissolved-phase plume and building foundation can vary over time with mobile or expanding plumes or changes in groundwater flow direction. Lahvis et al. (2013a) recommend the use of lateral offset (or buffer) distances (for example, 20 feet) to account for uncertainties in dissolved-phase plume delineation and changes in groundwater flow direction. Larger buffer zones may be appropriate in cases where there is more than 20 feet uncertainty in defining the edge of the dissolved-phase plume. In general, lateral offset buffer distance should not be applied at the leading edge of a mobile or expanding dissolved-phase plume where the distance between the plume and building may reduce over time (unless the depth to groundwater exceeds the vertical screening distances for all buildings located within the potential path of the plume.)

Table F-1 Summary of screening distances from empirical soil gas database studies

Reference	Screening distance		
	Dissolved-phase	LNAPL (UST/AST sites)	LNAPL (industrial sites)
Lahvis et al. (2013a)	5 feet (1.5 m) Notes: • Screening distance based on groundwater containing up to 15 mg/L benzene • Screening distance includes an additional 5 feet to account for uncertainty in the depth to groundwater associated with water-table fluctuations	13 feet (4 m)	Not assessed
USEPA (2013a)	0 – 5.4 feet (0–2 m) Note: • Screening distance based on groundwater containing < 5 mg/L benzene or < 30 mg/L TPH; soils containing < 10 mg/kg benzene or < 250 mg/kg TPH_g	13.5 – 15 feet (4–5 m)	18 feet (6 m) Note: • Greater uncertainty exists for industrial sites because of the small number of sites in the database
Davis (2009)	5 feet (1.5 m) Note: Screening distance based on: • groundwater concentrations < 1 mg/L benzene or < 10 mg/L TPH_g • soils containing < 100 mg/kg TPH_g • soil gas containing < 100 ppm-v TPH (PID); O_2: ~ 2 to 4%	8 feet (3 m)	30 feet (10 m)
Peargin and Kolhatkar (2011)	5 feet (1.5 m) Note: • Screening distance based on groundwater concentrations < 1,000 µg/L benzene	15 feet (5 m) Note: • Screening distance based on groundwater concentrations > 1,000 µg/L benzene	Not assessed
Wright (2011)	5–6 feet (1.5–2 m) Note: • Screening distance based on groundwater concentrations < 1 mg/L benzene or < 10 mg/L TPH_g	13 feet (4 m) Note: • Ratio of source depth to building slab size (edge to center) must be > 1.5	Not assessed

Table F-2. Key findings from USEPA (2013a) and Lahvis et al. (2013a)

GENERAL
• Benzene requires the greatest distance to biodegrade below a soil gas concentration of 30 – 50 µg/m³, consistent with risk-based screening levels for subslab soil gas found in regulatory guidance .

Table F-2. Key findings from USEPA (2013a) and Lahvis et al. (2013a) (continued)

- Vertical screening distances derived from soil gas data for benzene are greater than those derived for other PHC COCs, including xylenes, ethylbenzene, hexane, C5–C8 aliphatics, C9 –C12 aliphatics, and C9 –C18 aromatics, and naphthalene.
- Using the vertical screening distance derived for benzene is thus conservative for the PHC COCs studied, whether or not benzene has been detected in the source.

DISSOLVED-PHASE SOURCES

- Dissolved-phase sources pose little risk for PVI unless the source (contaminated groundwater) is near, or in contact with, the building foundation.
- Over 94% of measured benzene concentrations in soil gas are $< 30 – 50\ \mu g/m^3$ at vertical source separation distances as small as 0 feet.

LNAPL SOURCES

- Petroleum UST sites: greater than 93% of measured benzene concentrations in soil gas are $< 30 – 50\ mg/m^3$ at vertical separation distances ranging from 13 to 15 feet
- Refinery, Fuel Terminal, Petrochemical Sites: approximately 90% of measured benzene concentrations in soil gas are $< 50\ \mu g/m^3$ at a vertical source separation distance of 18 feet.
- Greater uncertainty exists in the vertical screening distances estimated for large-scale petroleum industrial sites because the number of sites included in the empirical database was relatively small (n = 13) and vadose zone thicknesses were generally less than 18 feet.

ADDITIONAL FINDINGS

- Vertical screening distances are assumed to be broadly applicable for recent or historical releases of gasoline and diesel fuel.
- Vertical screening distances are not applicable at certain gasoline release sites containing lead scavengers (1,2 dichloroethane, or 1,2 ethylene dichloride, and dibromoethane, or ethylene dibromide – EDB) or > 10% vol/vol ethanol (in the region where ethanol is phase separated) because no soil gas data were available to evaluate screening distances for these PHC COCs.
- Screening distances were not derived for the individual aliphatic hydrocarbons, 2,2,4-trimethylpentane, or cyclohexane because of the lack of available soil gas data and toxicity criteria (USEPA 2013a).
- Vertical screening distances derived for dissolved-phase sources are generally applicable for all PHC sites, including petroleum UST/AST sites and petroleum industrial sites (such as terminals, refineries, pipeline, MGP, and crude oil and condensate sites).
- The effect of surface cover on vertical screening distances was inconclusive.
- The effect of soil type on vertical screening distances was negligible.
- Vertical screening distances are expected to apply laterally in the absence of:
  - preferential pathways that both intercept the source and enter the building
  - mobile or expanding plumes

Note that insufficient data were available to assess screening distances for sites with preferential pathways (such as underground sewers, fractured rock), high organic-rich (for example, peat) soils or excessively dry soils in arid environments, large building foundations (such as those associated with industrial/commercial sites or apartment complexes), high-ethanol content fuel (for example, E85) releases, historical gasoline releases containing lead scavengers (1,2 DCA, EDB, or both). The screening distance method is thus not recommended for application if such environmental or site conditions are encountered. In addition, the screening distance method is generally not recommended at sites with mobile or expanding plumes that are expanding in the direction of current or future buildings. These sites may require additional characterization. It may, however, be possible to ignore this precluding factor if sufficient vertical separation exists between the source and building foundation (that is, the vertical separation distance exceeds the relevant screening distance). For example, further PVI assessment would not be necessary at a UST/AST site with an expanding LNAPL plume provided the vertical separation distance exceeds 15 feet.

F.5 Are the vertical screening distances determined by empirical studies supported by transport modeling?

The model studies of Abreu and Johnson (2005, 2006), DeVaull (2007), Abreu, Ettinger, and McAlary (2009b), API (2009), and Davis, Patterson, and Trefry (2009) generally support the findings from the empirical studies, even though the modeled vapor biodegradation is usually less than the observed. This difference indicates that the models are conservative with respect to the assumptions on hydrocarbon biodegradation and transport. In general, biodegradation in the vadose zone is shown to be relatively rapid at some distance above the hydrocarbon source where conditions in the vadose zone become aerobic. Aerobic biodegradation is predicted to significantly limit hydrocarbon vapor migration above dissolved-phase sources. The presence of building foundations overlying dissolved-phase sources also has little effect on the PHC biodegradation because the mass flux of hydrocarbons is limited by relatively low source concentrations and relatively slow transport through the capillary zone. PHC vapor biodegradation above LNAPL sources is predicted to be more variable and potentially sensitive to limitations on O_2 transport caused by building foundations or other surface features (such as pavement). The effect from building foundation and pavement will vary depending on the hydrocarbon vapor source concentration (related to source type and weathering), source depth (for example, separation distance between the source and building foundation), and biodegradation rate.

The model studies are summarized in more detail as follows:

Abreu and Johnson (2005)

Abreu and Johnson (2005) examined the effects of lateral source separation on the vapor attenuation of nondegrading COCs. For shallow sources of potential concern (for example, vertical separation distances of about 10 feet), the predicted vapor concentration decreased by approximately two orders of magnitude for every 45 feet of lateral offset for a slab-on-grade foundation in sandy soil. The sensitivity of vapor attenuation to lateral offset is expected to increase for degrading compounds (for example,. PHC COCs).

Abreu and Johnson (2006); Abreu, Ettinger, and McAlary (2009); American Petroleum Institute (2009)

Abreu and Johnson (2006) and Abreu, Ettinger, and McAlary (2009b; described in greater detail in API 2009) simulated the behavior of reactive hydrocarbon COCs and, in particular, the effect of aerobic biodegradation rate, source concentration, and source depth, on PHC vapor biodegradation. PHC biodegradation was predicted to increase with decreasing vapor source concentration and increasing vertical separation distance and biodegradation rate. PHC vapors were predicted to biodegrade by over seven orders of magnitude over relatively short vertical distances (for example, 6 feet or 2 m) above low concentration PHC vapor sources, i.e., representative of dissolved-phase sources. For the low concentration vapor sources, residential-sized building foundations had little effect on O_2 availability and PHC biodegradation. The PHC biodegradation predicted above LNAPL sources was more variable. The model predicted that approximately 23 feet was required to fully biodegrade benzene vapors emanating from unweathered, high concentration (200 mg/L) vapor sources assumed representative of fresh gasoline. Building foundations had little effect on hydrocarbon biodegradation for these scenarios.

In these studies, hydrocarbon (benzene) was assumed to aerobically biodegrade at rates ($\lambda = 0.18$ to 0.79 hr^{-1}) which is consistent with mean values published from literature studies (DeVaull, 2007). At these rates, PHC vapors were predicted to biodegrade by roughly two orders of magnitude for each additional meter increase in the vertical separation distance provided conditions in the vadose zone were aerobic. Note that while the aerobic biodegradation rates may seem high, the models assume that biodegradation can occur when the chemical is in the dissolved phase (in soil pore water) and when O_2 concentrations in soil gas exceed 1% vol/vol (i.e., in the aerobic portion of the vadose zone). In addition, the models do not account for limitations on vapor diffusion associated with transport through the capillary zone which can be significant (McCarthy and Johnson1993); see Chapter 1. In lower permeability soils, such as silty clay (API 2009), PHC biodegradation was greater using a similar range of source concentrations and degradation rates and for sources displaced laterally from building foundations (as previously noted in Abreu and Johnson 2005). The models indicate that dissolved-phase PHC sources displaced laterally from the edge of a building foundation by more than a few meters are expected to pose little risk for PVI.

DeVaull (2007)

The work of DeVaull (2007) further supports the findings of Abreu and Johnson (2006). Again, the attenuation factor is shown to be highly sensitive to the vertical separation distance between the source and building foundation. For example, the vapor attenuation factor was shown to decrease by more than nine orders of magnitude when the vertical separation distance was increased approximately three-fold.

Davis, Patterson, and Trefry (2009)

Davis, Patterson, and Trefry (2009) developed a simple biodegradation model that couples hydrocarbon transport and O_2 availability in the vadose zone. The model was used to explain observed behavior of hydrocarbon and O_2 in the vadose zone at seven field sites in Australia with varying surface cover (such as open ground or under a building). Hydrocarbon biodegradation rates were shown to be essentially instantaneous compared to rates of physical transport associated with gas-phase diffusion and advection. Total hydrocarbon vapor concentrations were not observed above detection limits (200 µg/L or 200,000 $\mu g/m^3$) unless O_2 concentrations in soil gas were less than 5% v/v. Biodegradation rates determined by model calibration were generally an order of magnitude higher for aliphatic hydrocarbons than for BTEX. This finding is consistent with the mean biodegradation rates for hydrocarbons published in DeVaull (2007).

F.6 What if my agency recommends lower soil gas screening levels than those used in the empirical studies?

Some regulatory agencies may apply soil gas screening levels less than those in the empirical studies to derive the vertical screening distances. For example, the soil gas screening levels for benzene found in some regulatory guidance (see Eklund et al. 2012) may be an order of magnitude less (3.1 µg/m³) than the value (30 µg/m³) used by Lahvis et al. (2013a) in the derivation of vertical screening distances. A lower screening level will result in a longer vertical screening distance because more vertical source separation is necessary to biodegrade PHC COCs below a lower soil gas screening level.

As shown in Table F-3, lower soil gas screening levels are not likely to significantly increase the vertical screening distance. This result is consistent with the findings of DeVaull (2007) and Abreu, Ettinger, and McAlary (2009b). Vertical screening distances for dissolved-phase sources increase from approximately 0 to 7 feet for benzene soil gas screening levels decreasing from 100 to 1 µg/m³, respectively (see Table F-3). This variability is consistent with the range of vertical screening distances (0–5.4 feet) derived for dissolved-phase sources using independent methods (USEPA, 2013a). Vertical screening distances for LNAPL sources increase from approximately 13.2 to 16.6 feet for benzene soil gas screening levels decreasing from 100 to 1 µg/m³, respectively. Again, this variability is consistent with the range of vertical screening distances (13–15 feet) derived for LNAPL sources using independent methods (Lahvis et al. 2013a; USEPA 2013a). Vertical screening distances for COCs other than benzene would be expected to increase similarly for equivalent differences in soil gas screening levels.

Table F-3. Vertical screening distances for LNAPL and dissolved-phase benzene at various soil gas screening levels

Benzene soil gas screening level (µg/m³)	LNAPL screening distance (feet)	Dissolved-phase screening distance (feet)
100 <	13.2	0.3
50 <	13.6	0.91
30 <	14.0	1.5
20 <	14.3	2.0
10 <	14.8	3.0
5 <	15.4	4.1
1 <	16.6	6.7

The following discussion explains the technical justification for the values in Table F-3. Direct application of the methods used by Lahvis et al. (2013a) and USEPA (2013a) to calculate soil gas screening distances for benzene soil gas screening levels < 30 µg/m³ is problematic because of the influence of background sources and because of a significant fraction of nondetect soil gas concentration data at these low concentration levels. Hydrocarbon biodegradation can, however, be assumed to be aerobic at these hydrocarbon concentrations and be approximated with distance using the following exponential decay expression (DeVaull 2007):

where (c_1, c_2) are soil gas concentrations at distances (x_1, x_2), and L_R is a diffusive reaction length.

For LNAPL sources this relation is applied to the 95% upper bound level of the benzene soil gas concentration versus distance values for data reported in Table 1. Benzene soil gas concentration values greater than 10,000 mg/m^3 are excluded from the analysis as they are very likely to be in an anaerobic soil zone. The resulting best-fit linear regression is shown in Figure F-1, along with the 95% upper bound on the best-fit regression estimate, following the methods presented in Bendat and Piersol (2010). The statistics of the data fit are included in Table F-2. The mean best-fit estimate can be defined as:

The 95% upper bound on the mean best-fit regression estimate, for which parameters are defined in Table F-2, is given by

The 95% upper bound ($\alpha = 0.05$) on the best fit regression depends on the number of data points, N, included in the regression. As a conservative minimum, the value $N = 6$ is applied. For higher values of N, the 95% upper bound will be closer to the mean best-fit estimate.

The empirical L_R parameter found in this evaluation is 0.52 feet, which is consistent with the values and ranges presented in extensive evaluation of aerobic benzene biodegradation in soils (DeVaull 2011). Note that the lower level soil gas concentrations, including all values below the 75% level on the distribution, are within the range of background indoor air.

For a dissolved-phase benzene source in groundwater, the trend in the 95% upper bound distance values in Table 1 of Lahvis et al. (2013a) are similarly evaluated to define a mean best-fit trend and a 95% upper bound on the mean best-fit trend. The result is shown in Figure F-2. The value of L_R found for this data set is 1.0 feet, which is greater than for the L_R value defined from LNAPL data, but within the expected range.

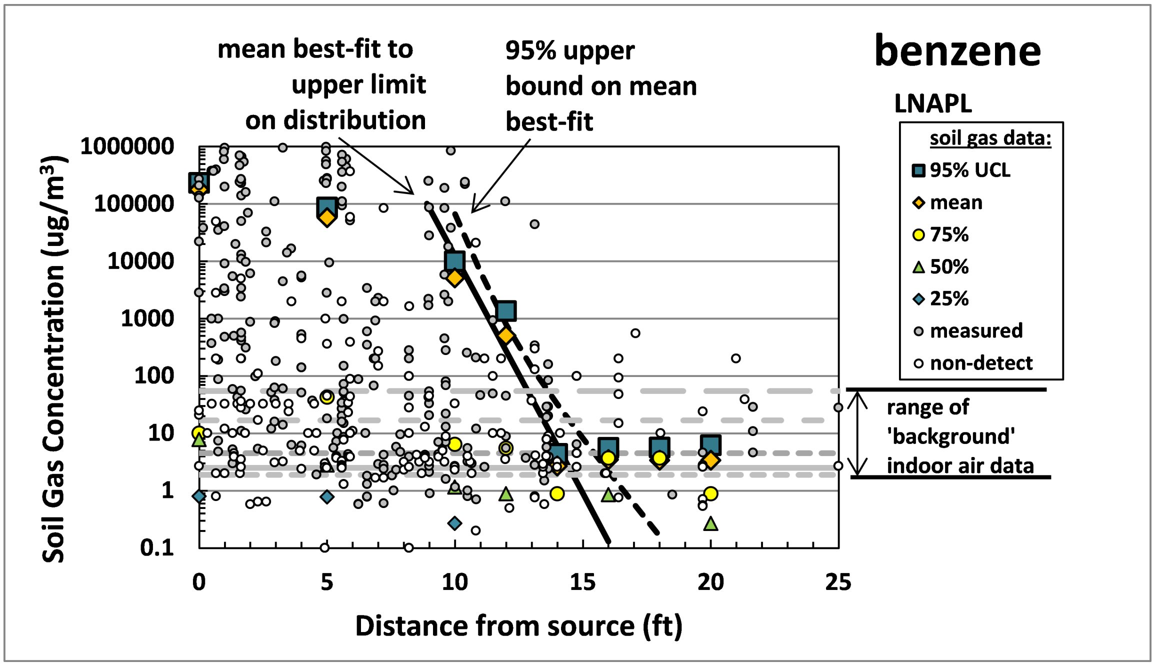


Figure F-1. Vertical screening distance values for an LNAPL source estimates based on soil gas data analysis from Lahvis et al. (2013a). A mean best-fit to the distribution and an upper bound on the mean best-fit are shown. The overlap of lower-level soil gas data with background concentrations (Dawson and McAlary 2009) is also shown.

Note that the soil gas concentrations are significantly lower than for the LNAPL source data, and that a larger proportion of the data falls within the range of background indoor air. Additional statistics of the data fit are included in Table F-4.

Note that, in Figure F-2, a significant fraction of benzene soil gas concentrations collected at sites affected by high levels of subsurface PHC are at and below the range of expected background air concentrations. Soil gas concentrations lower than ambient background are an indication of benzene biodegradation losses from both benzene vapors originating from subsurface sources and from background air concentrations at the surface.

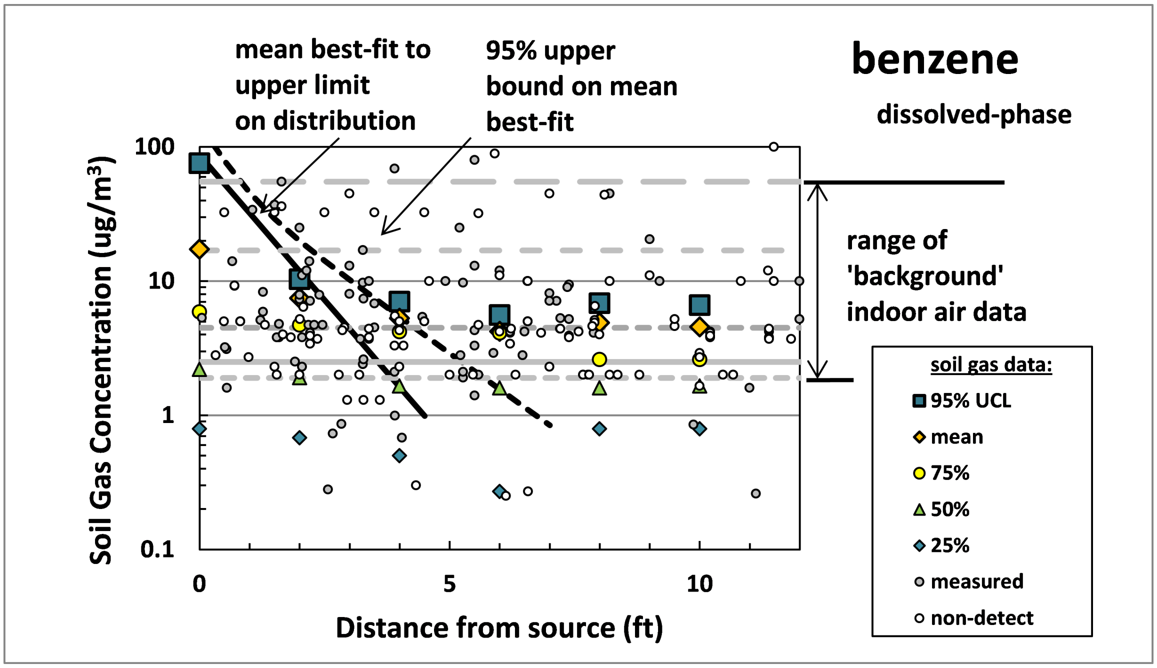


Figure F-2. Vertical screening distance values for a dissolved phase groundwater vapor source based on soil gas data analysis from Lahvis et al. (2013a). A mean best-fit to the distribution and an upper bound on the mean best-fit are shown. The overlap of lower-level soil gas data with background concentrations (Dawson and McAlary, 2009) is also shown.

Table F-4. Statistics for the LNAPL and dissolved-phase linear regression data fit

Parameter	LNAPL	Dissolved phase
Single-sided confidence interval (α)	0.05	0.05
Student t statistic (t_{N-2} α)	2.45	2.45
Mean slope m = (– 1 / L_R) (1/feet)	-1.91	-1.00
Intercept ln [c_0] ln(μg/m³)	28.5	4.47
Standard error in m	0.265	0.248
Coefficient of determination, r²	0.928	0.941
Standard error for the estimate of ln[c] $s_{y\|x}$	1.06	0.351
(Minimum) number of data pairs, N	6	6
Average distance (feet)	12	1
Sample variance in distance s_x (feet²)	3.2	1

F.7 What key data must be collected to support site screening?

Characterization of the PHC vapor source (determining whether it is present as dissolved-phase or LNAPL) is a critical piece of information needed to apply the screening-distance method. The identification of source type can be difficult, however, especially if LNAPL is not readily apparent in a nearby groundwater monitoring well (see Chapter 2). For this reason, soil sampling and field screening of soil cores using a photoionization detector (PID) or flame ionization detector are recommended during the initial stages of a site investigation. The soil sampling and field screening should focus in the immediate proximity of the known or expected PHC release (near UST systems or an AST), along perching or low-permeability soil layers, or just above the water table as a result of water-table induced smearing. Soil samples alone may not be sufficient as a standalone criterion for LNAPL identification, however (see Table 3-1). In general, LNAPL sources located above the water table will tend to biodegrade fairly rapidly provided the PHC release has been stopped.

F.8 Why are highly organic, rich soils such as peat a precluding factor for PVI screening?

High-organic rich soils, such as peat, are prone to oxidation via natural respiration which can compete with PHC for available O_2. For this reason, organic-rich soils are included as a precluding factor for site screening if located between the PHC vapor source and building foundation.

F.9 Are O_2 soil gas concentration measurements necessary for PVI screening?

Although O_2 soil gas concentrations over 2 to 4% vol/vol can be used to document aerobic biodegradation conditions in the vadose zone, these and other soil gas data are not necessary for the application of the PVI screening distance method provided any primary and secondary LNAPL sources in the vadose zone have been properly identified (see Table 3-1 and Section 3.1.3). O_2 soil gas concentration measurements were not directly used in the derivation of vertical screening distances.

F.10 Are vertical screening distances used in regulatory guidance?

The use of screening distances in regulatory site screening is not new. USEPA, for example, proposed a screening distance of 100 feet (applied both laterally and vertically) for all COCs, including hydrocarbon and chlorinated compounds (USEPA 2002b). The screening distance was based on professional judgment given that vapor intrusion had not been documented at any residences located more than 100 feet laterally from the interpolated edge of a chlorinated hydrocarbon plume. A 100-foot screening distance was subsequently adopted by many states for use at PVI sites.

More recently, some states have recommended shorter screening distances for PHC (Connecticut DEP 2003; Pennsylvania DEP 2004; New Hampshire DES 2006; Wisconsin DNR 2010); California State Water Resources Control Board 2012); Indiana DEM 2012; Michigan DEQ 2012; New Jersey DEP 2013a) and other organizations (Atlantic PIRI 2006; ASTM 2010b). These distances range from 5 feet (NJ DEP 2013a; California State Water Resources Control Board, 2012) to 30 feet for dissolved-phase sources and from 30 to 100 feet for LNAPL sources. In the New Jersey guidance and California policy, the shorter screening distances can only be applied if O_2 concentrations in soil gas exceed 2% vol/vol (for New Jersey) to and 5% vol/vol (for California). Note that the referenced regulatory guidance and policy documents referenced here were published developed prior to the empirical studies.

F.11 What is the role of groundwater and soil concentration data in PVI screening?

Hydrocarbon soil and groundwater concentration measurements are critical to identifying LNAPL sources in soil or groundwater (see Table 3-1), and as such are important site data to support PVI screening. Such measurements, however, are not good predictors of hydrocarbon concentrations in soil gas (vapor that could potentially migrate to indoor air). In particular, Golder Associates (2008), Lahvis et al. (2013a), and USEPA (2013a) have shown:

1. Concentrations of benzene and certain TPH fractions in soil and groundwater are poorly correlated with paired hydrocarbon (benzene and TPH fractions) concentrations in soil gas.
2. Predicted concentrations of benzene and certain TPH fractions in soil gas based on equilibrium partitioning from soil and groundwater measurements are often orders of magnitude higher than actual measured soil gas concentrations.

Soil concentration data were also not used significantly in the derivation of screening distances. Soil concentration data were used by USEPA (2013a) to identify residual-phase LNAPL sources in < 2% (21 of 1332) cases and were not used by Lahvis et al. (2013a).

F.12 How important are TPH soil or groundwater concentration measurements in site screening?

Based on reviews of the PVI database, maximum vertical screening distances derived for other individual, indicator compounds (and discussed in Chapter 3) are also considered to be adequate for noncompound-specific TPH fractions such as C5–C8 aliphatics, C9–C12 aliphatics, C9–C18 aromatics (Hers and Truesdale 2012; USEPA 2013a). TPH concentrations in soil and groundwater may, however, be useful in helping identify LNAPL sources or determining the type of LNAPL present (see Chapter 3, Table 3-1).

A number of states, including Hawaii, incorporate a risk-based evaluation of TPH, either by policy or guidance, into their approach for assessing PVI. This approach often requires the collective assessment of nonspecific, TPH-related compounds in targeted carbon ranges (such as C5–8 and C9–C12 aliphatics) in addition to individually targeted compounds. Local regulatory agencies can provide specific requirements related to PVI that apply to sites in their jurisdiction.

F.13 How are temporal variations in the water-table elevation and uncertainty in the exact source depth accounted for in PVI screening?

For dissolved-phase sources, the vertical separation distance is determined from the base of the current or future anticipated building foundation to the shallowest water-table elevation. Although the shallowest water-table elevation cannot be known with exact certainty, some ambiguity is accounted for (including the capillary zone) in the recommended 5 feet vertical screening distance for dissolved-phase PHC sources. The empirical studies by Lahvis et al. (2013a) and USEPA (2013a) showed that benzene concentrations in soil gas were more than 30–50 $\mu g/m^3$ in approximately 95% of cases even directly above (within 1 to 2 feet) the water table (dissolved-phase sources posed little risk for PVI unless in contact with a building foundation). These findings were based on the vertical-distance method.

For LNAPL sources, the vertical separation distance is determined from the base of the current or future anticipated building foundation to the top (or shallowest elevation) of the residual-phase source (or LNAPL smear zone). The depth to the LNAPL source should be determined during borehole development (i.e., monitoring well installation) using soil sampling and field screening (see Table 3-1). The maximum estimated or anticipated water-table elevation can be used as a rough indicator of the top of an LNAPL source at sites where soil and field screening data are not readily available. In addition, the vertical screening distances recommended for LNAPL sources should account for some uncertainty in the depth to the LNAPL source given that this information was not reported in the soil gas databases evaluated by Lahvis et al. (2013a) and USEPA (2013a).

F.14 What about methane?

Methane can be generated through anaerobic biodegradation of PHCs in soil and groundwater and occurs mainly at non-UST (industrial) sites with large gasoline and diesel LNAPL sources (USEPA 2013a). Methane generation has also been shown to be significant for gasoline releases containing more than 10% vol/vol ethanol (Ma et al. 2012), although currently there are no empirical data from hydrocarbon sites to document this. Methane is a concern for PVI because it can create potential explosive (safety and acute risk) conditions in confined space conditions (see Chapter 2). Methane can also increase the potential for PVI by enhancing bulk gas flow (advection) of PHCs and reducing oxygen availability for aerobic PHC biodegradation between the petroleum source and building foundation (see Chapter 2). No published cases, however, have been identified in which methane has generated a PVI issue at a UST site (USEPA, 2013a).

The empirical soil-gas database study conducted by the USEPA (2013a) found methane elevated above the lower explosive limit (> 5% vol/vol) in soil gas at 5 of 27 sites with LNAPL sources, three of which were retail (UST), and two nonretail (refinery). Methane soil-gas concentrations were less than 1% at the remaining 22 sites. Methane concentrations in soil gas were generally below 5% within approximately 10 feet of the PHC source. This distance is less than the vertical screening distance of 15 feet recommended for LNAPL sources. Methane was also not shown to enhance the potential for benzene migration to indoor air. Lastly, methane concentrations in soil gas greater than 1% vol/vol were only observed at sites with LNAPL sources (USEPA 2013a) and thus could serve as a potential LNAPL indicator.

APPENDIX G. INVESTIGATION METHODS AND ANALYSIS TOOLBOX

This section describes various sampling and analysis methods available for vapor intrusion investigations. This information will help you select the techniques that will best meet the data objectives. Specifically this appendix will help with the following tasks:

- selecting the sampling technique
- understanding the importance of sample collection processes to ensure quality data
- choosing sampling locations
- selecting the best analytical method for the required analysis
- developing a list of appropriate questions for your lab
- discussing the applicable field instruments with site counterparts

The investigative toolbox in this guidance is an updated version of the toolbox located in Appendix D in the ITRC guidance document entitled *Vapor Intrusion Pathway: A Practical Guideline* (ITRC 2007). This updated toolbox contains sampling and analysis issues and procedures specific to VI sites, with new sections for sites where PHCs are the COCs. PHCs, unlike CVOCs (with the exception of vinyl chloride), readily degrade in the presence of O_2 during migration through the vadose zone, which lowers the potential risk by VI. Hence, sampling locations and some procedures can differ from those used at sites with chlorinated hydrocarbon contamination. As an example, indoor air and subslab data, commonly collected for assessing the VI pathway for chlorinated compounds, are often not the preferred approach for PHCs since indoor and ambient sources of PHCs are so common.

In many cases, the methods and tools described in this section are applicable to both petroleum and nonpetroleum vapor investigations. Each section explains how to use the tools and when they are appropriate. References are provided for additional information regarding each of the tools.

A summary of the various quantitative options used to evaluate the VI pathway is provided in a matrix in Table G-5, Matrix of recommendations for various quantitative options to evaluate VI. In addition, Table G-6 provides the advantages and disadvantages of various investigative strategies.

Methods Described in Appendix G

The methods presented in this appendix are not arranged in a particular order of preference. Analytical methods and related issues are discussed after the sampling methods.

G.1 Important Considerations in VI Investigations

Vapors and VI are an unfamiliar territory for many practitioners in this field (regulators, stakeholders, consultants, subcontractors). Practitioners commonly make errors with soil vapor programs and soil vapor data in three general areas: units, screening or target levels, and project goals/objectives.

G.1.1 Unit Errors

A common error is assuming that ppbv is equivalent to µg/L or that ppmv is equivalent to mg/L. The units are not equivalent, and the conversion depends primarily upon the molecular weight of the compound. Converting between units (for example, µg/L to $\mu g/m^3$, percent to ppmv) is also a common source of error. Prior to scoping a field program and conducting field work, performing the following tasks will help to prevent unit errors:

- Instruct the laboratory as to the units and detection levels in which it should report the data.
- Locate an easy-to-use unit conversion spreadsheet available at many web sites, such as NJDEP's VI guidance, Table 6-1, p. 89 (2013a).

Most laboratories report air data in $\mu g/m^3$ and ppbv. Example conversion calculations for benzene (molecular weight = 78) at 20°C (68°F) are:

$$\text{ppbv} = \mu g/m^3 \text{ x } (24.0/78)$$

$$\mu/m^3 = \text{ppbv x } (78/24.0)$$

Note that 24.0 is a standard conversion factor based on the ideal gas law at 20°C and 1 atm.

G.1.2 Required Screening or Target Levels

In order to determine what concentrations are of concern and what analytical methods are required, screening levels must be known. Screening levels vary from state to state and, in some cases, within the state itself. Screening levels are also different for different types of receptors, such as primarily residential versus commercial or industrial buildings.

Screening levels can be obtained from three primary sources:

- tables prepared by the oversight agency
- default attenuation factors allowed by the oversight agency
- predictive models allowed by the agency (some states have their own predictive models)

Generally, the screening levels in agency tables are the most conservative (lowest) while the screening levels from the predictive models are the least conservative (highest). Some states only allow their tabulated screening values to be used, with no adjustment for a specific site. If you are unfamiliar with determining screening levels, then seek assistance in determining them. Refer to Appendix H in the ITRC VI guidance (ITRC 2007) for a discussion of how to determine screening levels.

Note that for PVOCs, generic screening levels for groundwater and soil gas tend to be overly protective (conservative) because these levels rarely account for biodegradation in the vadose zone.

G.1.3 Project Goals and Data Quality Objectives

Defining the objectives and goals of a study should always be part of planning a project. Planning tools, such as the USEPA's DQO process, can be used to help ensure that data of the right quality, type, and amount are collected. Clearly defining project objectives and goals also helps in selecting the appropriate sampling methods and locations. Data quality is defined within the discussion for each specific tool because quality requirements may differ according to the tool chosen.

Project goals and objectives are typically addressed during preparation of the work plan. Any planning process that follows the scientific method may be used; however, the USEPA's seven-step DQO process (USEPA 2006b) specifically addresses many of the issues that commonly arise during environmental investigations.

The USEPA's DQO process includes the following seven steps:

1. State the problem that necessitated the study and define the overall objectives of the study.
2. List specific questions that need to be addressed in order to meet the study objectives.
3. Identify what types of samples, data, and other information are needed.
4. Define study boundaries (spatial and temporal), including the lateral and vertical extent of the contamination in all media, as well as multiple exposure areas that may be at the site.
5. Develop "if, then" decisions that will be made based on results of the investigation.
6. Specify tolerable errors in the decisions to be made, as well as the measurement quality objectives for analytical data.
7. Optimize the sampling design. Consider your options for before heading to the field.

Specifying analytical data quality is covered under measurement quality objectives outlined in Step 6 of the DQO process and may include the following:

- Identify COCs and screening levels.
- Choose sampling and analytical methods with appropriate reporting limits.
- Complete presampling building survey (interior sampling).
- Establish appropriate sampling conditions, number of samples, and duration of sampling.
- Identify and collect quality control samples (field blanks, duplicates).

G.2 Groundwater

Recent studies have shown that for PHCs, shallow groundwater concentration data do not correlate well with soil gas concentrations and thus are not a good predictor of the PVI risk (Lahvis et al. 2013). This poor correlation is most likely due to biodegradation in the vadose zone. In general, groundwater data overpredicts risk because groundwater screening values are usually developed without considering biodegradation in the vadose zone.

G.2.1 Use of Preexisting Groundwater Data

In many situations, shallow groundwater data that are already available prior to initiation of a VI investigation are sufficient to use as part of a VI investigation, especially if groundwater contamination has been delineated and the plume has reached steady-state conditions (no longer expanding). In deciding whether existing data are sufficient, consider the site-specific CSM. Groundwater data should be obtained from wells screened across the water table at the time of sampling. In addition, the sampling method used, the construction of existing wells sampled (such as screen length and placement across water table), depth of groundwater, the type of contaminants present, and heterogeneity of the vadose zone and shallow saturated zone media will likely be the most important factors in determining whether existing data are sufficient for VI assessment.

Data from potable or nonpotable wells may or may not be appropriate for use in a PVI investigation depending on how they are constructed and screened. In most situations, it is likely that few drinking water wells are screened/open across the water table. Therefore, the presence of volatiles in private or public drinking water wells could be considered a possible basis for further investigation, but in most situations the data should not be used to evaluate the potential for PVI.

G.2.2 Interpolation of Nearby Data

If groundwater data immediately upgradient (and closest to the contamination source) from the structure are not available, surrounding data points can be used to construct contaminant isoconcentration maps. Complex geologic settings or the anticipated presence of steep concentration gradients warrant a denser sampling grid. When developing groundwater contours, consider the rate and direction of groundwater flow and the time since chemicals were released in order to compare the expected length of the plume to measured concentration data.

G.2.3 Obtaining New Groundwater Data to Evaluate the VI Pathway

The USEPA (2002b) and various state agencies (NJDEP 2013a) provide specific guidance and procedures for the installation of groundwater monitoring wells and the acquisition of high-quality groundwater VOC sample data. Some of the recommendations (CAEPA-DTSC 2011) for collecting groundwater data suitable for VI assessment are:

- *Proper screen intervals*. Contaminants at the top of the water table, rather than deeper contamination, are responsible for causing potential VI problems. Therefore, monitoring wells used to make VI evaluations should be screened across the air-water interface.
- *Proper screen lengths*. Monitoring wells with excessively long well screens, regardless of screen placement, should not be used to make VI evaluations. When sampling long well screens, clean water entering the well screen at depth may dilute the contaminated groundwater near the top of the screen, biasing the sampling results and the associated risk determination. Hence, short screen lengths are preferred for monitoring wells that will be used to make VI evaluations. Ideally, the thickness of the water column in the well should be 10 feet

or less. For new water table wells installed as part of a VI investigation, a 5 to 10 foot screen is generally recommended unless this conflicts with other site investigation objectives.

- *Proper well installation*. Monitoring wells should be designed and installed to yield representative samples of groundwater conditions. Monitoring wells should have proper filter packs, slot sizes, and annular seals. Direct push sampling methods and alternate/temporary groundwater sampling techniques are often well suited for VI investigations, especially if attempting to determine the depth of the interface between a shallow clean water lens and an underlying plume or for determining vertical gradients. Repeated sampling over time at the same locations may be necessary for some sites to determine whether shallow groundwater quality has changed because of water table elevation fluctuations or other factors. If bedrock wells are installed as part of a VI investigation, open hole intervals should generally be 10 feet or less and should target the shallowest water-bearing zone. In highly weathered/fractured bedrock formations, shallow groundwater flow and contaminant migration can exhibit patterns more typical of unconsolidated formations. In those situations, local heterogeneity of the bedrock may not have as much influence on whether volatiles in groundwater can off-gas into the vadose zone and diffuse up to structures at the surface. Therefore, construction of monitoring wells in such settings can be part of a VI investigation.
- *Proper well development*. Monitoring wells should be developed to create an effective filter pack around the well screen, rectify damage to the formation caused by drilling, optimize hydraulic communication between the formation and well screen, and assist in the restoration of natural water quality of the aquifer near the well in order to obtain samples representative of current groundwater conditions.
- *Proper well purging*. Prior to sampling, monitoring wells should be purged to remove stagnant casing water from the well that is not representative of aquifer conditions, or where allowed by the oversight agency, no-purge sampling methods may be employed. Wells can be purged by removing the traditional three casing volumes prior to sampling, or the well can be purged with low-flow techniques as described below. Wells should not be purged dry because this method will drain the filter pack and introduce the potential for volatilization losses during recovery. If adequate purging cannot be conducted without excessive drawdown because of low permeability, consider using no-purge sampling methods or passive diffusive samplers, which do not require purging.
- *Proper well sampling*. Sampling methods that minimize the loss of VOCs during sample collection and handling are preferred, such as using bladder pumps or submersible pumps. Other methods, such as using bailers, may cause unacceptable volatilization of chemicals if not properly implemented, as described in the USEPA Technology Verification Program (USEPA 2013c). Passive diffusion samplers may also be useful.

G.2.4 Groundwater Sampling Locations

Groundwater samples should be collected as close, horizontally and vertically, to the structures as possible because concentrations are not always uniform within a plume because of heterogeneities in source areas and in the subsurface media. Changes in surface cover that significantly affect the amount of infiltration upgradient from structures should be considered in choosing sampling locations. For example, if there is an area of groundwater recharge (such as a stormwater retention pond or a transition from a mostly paved surface to a vegetated area) located between the upgradient edge of a plume and a structure, a sampling location downgradient of the recharge area will be representative of any fresh water lens that may be present.

G.2.5 Perched Water Tables and Vertical Profiles of the Groundwater

If a perched water table exists above the regional water table, it may be appropriate to collect samples from both the perched zone and regional shallow aquifer. Perched saturated zones that are laterally contiguous under or near structures, exist year round, and are below nearby building foundations should be sampled if they are of sufficient thickness to provide a sample. In the above scenario, sampling of the regional water table may not be vital to investigating the VI pathway.

In some situations, vertical profiles of shallow groundwater contamination may yield a more precise evaluation of the current and potential future risk of VI.

G.2.6 Ongoing Groundwater Monitoring

After an initial VI investigation has been completed, long-term groundwater monitoring to reevaluate the VI pathway may be appropriate in some situations. Groundwater monitoring may be appropriate where groundwater concentrations exceeding screening levels are close to, but not currently within, the applicable distance criterion to a potential receptor.

G.2.7 Groundwater Sampling Methods

Table G-1, prepared by the NJDEP (2005), gives a summary of some alternative groundwater sampling methods that may have application to VI investigations. No-purge sampling methods may also be allowed by the local regulatory agency. Sampling guidance for VI investigations may differ from other investigatory purposes because of the objective to determine shallow groundwater quality.

Table G-1 Groundwater sampling methods for vapor intrusion investigations

Methods	Example guidance documents	Advantages or disadvantages
Direct push and alternate groundwater sampling methods	NJDEP Field Sampling Procedures Manual (NJDEP 2005), Section 6.9.2.1	• Can do vertical profiling • Can do discrete interval sampling at defined depth intervals • Rapid sampling at multiple locations • More difficult to repeat sampling in same locations • Some methods limited to unconsolidated formations

Table G-1 Groundwater sampling methods for vapor intrusion investigations (continued)

Methods	Example guidance documents	Advantages or disadvantages
Passive samplers	• NJDEP Field Sampling Procedures Manual (NJDEP 2005) • USGS User's Guide for Polyethylene-Based PDBS to Obtain VOC Concentrations in Wells, Part 1 (USGS 2001) • ITRC Technical and Regulatory Guidance for Using PDBS to Monitor VOC in Groundwater (ITRC 2004) • ITRC Protocol for Use of Five Passive Samplers to Sample for a Variety of Contaminants in Groundwater (ITRC 2005a)	• Can use existing wells for ongoing monitoring May not be adequate where: • VOCs highly soluble in water (such as MTBE) occur • in-well vertical flow occurs • permeability is very low
Low-flow purging and sampling	NJDEP Field Sampling Procedures Manual (NJDEP 2005), Section 6.9.2.2 and 6.9.2.3	• May generally target interval closer to the water table in some settings • Discrete interval sample not obtained
Volume-averaged purge and sample collection	NJDEP Field Sampling Procedures Manual (NJDEP 2005), Section 6.9.2.4	Not recommended to generate new groundwater data specifically for VI investigations because of the potential for vertical averaging

G.2.8 Passive Samplers for Groundwater

Passive samplers are available in several varieties, as described in the ITRC documents listed in the table above. Passive diffusive bag samplers (PDBS) currently may be the most common tool for sampling VOCs. PDBS should be deployed just below the water level in a well for a minimum of two weeks to equilibrate with the well water. Significant water table fluctuations during that period will affect the appropriate depth intervals for the samplers. If the water level drops below the uppermost sampler, then transfer of volatiles from the sampler water into less contaminated well air space occurs. If the upper sampler is exposed to the air space, the upper sampler should be resuspended two feet below the current water level and retrieved after an additional two-week equilibration period. In any event, the depth to water in the well should be measured when the PDBS are installed and removed, and the position of the samplers relative to the water level should be clearly described in the report presenting the PDBS data. PDBS are not applicable to all compounds (for example, SVOCs and soluble compounds such as acetone, styrene, MTBE, and 4-methyl-2-pentanone), so the target analytes must be confirmed. Other passive samplers can be used for detecting and reporting these compounds. More information is available in the ITRC document *Protocol for Use of Five Passive Samplers to Sample for a Variety of Contaminants in Groundwater* (ITRC 2005a).

G.2.9 Low-Flow Purging and Sampling

If evaluating the VI pathway is the only sampling objective, use two modifications to the typical low-flow purging and sampling:

- Set the pump intake level as close to the water table as possible without significant risk that the water level will drop and expose the pump intake. For wells in formations with average or high permeability, about 1.5 to 2 feet below the static water level should be an adequate intake location.
- The purging objective is to flush two volumes of groundwater through the sampling array (such as tubing and pump). While measuring water quality indicator parameters is preferred (but not necessary), drawdown should be measured and should not be excessive.

G.3 Soil

G.3.1 Soil Data for VI Assessment

Soil data are not typically used for evaluating the VI pathway because of the uncertainty associated with using partitioning equations and the potential loss of VOCs during sample collection In order to perform VI risk calculations using soil data, contaminant concentrations in soil must be converted to soil gas concentrations using assumptions about the partitioning of the contaminant into the gas phase. In the case of PHCs, calculated soil gas values from soil data often overestimate actual soil gas concentrations (Golder Associates 2007).

When it is not possible to collect soil gas samples at a site because of low permeability or saturated conditions, or soil data are the only data available, the VI pathway can be evaluated with soil data, especially for PHC sites.

When sampling soil for VOCs, the soil samples should be collected using procedures specifically designed to minimize volatilization losses, such as SW-846 Method 5035A (USEPA 2002a) and augmented USEPA Method 5035A (CAEPA-DTSC 2004). More details on the interpretation of soil data and phase partitioning calculations can be found in the CAEPA DTSC Vapor Intrusion Guidance (CAEPA-DTSC 2011). Existing soil data should be used as part of the lines-of-evidence approach. In general, soil matrix data are not recommended as a stand-alone screening tool for a VI investigation.

G.3.2 Soil Physical Properties

Site-specific soil properties such as bulk density, grain density, total porosity, moisture content, and fraction organic carbon can be measured from soil samples and the results used to replace default input parameters when models are used. Air permeability of the vadose zone can be determined from either in situ measurements or laboratory measurements. In situ measurements test a larger portion of the subsurface than a laboratory measurement of a small core sample and are the preferred method. In situ measurements of air permeability can be conducted in the shallow vadose zone, the area of the vadose zone subject to advection by building-driven depressurization, or to assess the presence of low-permeability layers in the vadose zone, which may act as partial vapor barriers.

G.3.3 Soil Headspace Methods to Determine Clean versus Dirty Soils at Petroleum sites

Some agencies are considering allowing soil headspace concentrations to be used as criteria for defining sufficient thickness of nonsource (clean) soil for screening out sites for VI investigations. Factors to consider in order to obtain consistent headspace readings include:

- the use of a consistent methodology
- the effect of container materials on sample integrity
- awareness of variations in PID response at high humidity
- the effect of soil type on COC concentrations in the headspace

A number of state agencies have established their own methodology; see, for instance, Massachusetts' guidance (MADEP 1994). This method uses the original jar method rather than plastic baggies.

Headspace concentrations are affected by the size of the container, amount of sample, the size of the available headspace, temperature, development time, hold time, and analysis time. In addition, the permeability of the container and any contamination from the container should also be considered. There is evidence that some baggies are not impervious to PHC vapor migration, which would lead to artificially low results—reported to be as much as a factor of two.

The issue of variable PID response at high humidity was documented in a study reported by Maine DEP (MEDEP 2009a). This study discussed the applicability of soil headspace in various scenarios. This study also reported variations in PID response by brand. PHC response over a wide range of humidity varied from unit to unit by up to a factor of four. Note that calibration on 100 ppm isobutylene does not correct for these issues (because it is a dry gas mixture) and so fails to compensate for moisture that is always present in soil samples used for headspace analysis.

G.4 Sampling of Crawl Spaces

Many crawl spaces are designed with vents and may allow for outdoor air exchange, so the concentration in the crawl space may be inversely proportional to the ventilation rate, which is not usually controlled. This situation can affect the sampling results, as well as the VI migration pathway analysis.

There are several options for sampling air from the crawl space. Crawl spaces can be sampled by collecting soil gas samples (active or passive), air samples (with canisters or adsorbents), or soil gas samples with flux chambers (identified as a supplemental data tool later in this appendix).

Typically, crawl space samples are collected following protocols similar to indoor air samples. For crawl spaces with limited access, a sampling tube is typically inserted horizontally through the crawl-space sidewall access ports or vertically through the overlying floor. As with soil gas or indoor air samples, enough measurements should be collected to obtain a representative value for the crawl space. Some crawl spaces, especially in colder environments, are sealed for portions of the year. For these situations, seasonal sampling is recommended.

G.5 Measurement of Indoor Air (Interior)

Indoor air samples are normally collected after other environmental samples (for example, groundwater or soil gas) indicate the need to conduct an internal building-specific assessment. The analyte list should minimally focus on compounds identified in subsurface samples at concentrations above screening levels, their possible breakdown products, and potential compounds that may be useful as marker compounds. Since some state agencies require full parameter analysis, confirm the parameter list with the appropriate regulators.

The temporal variability depends on the duration of the sample. For residential settings, air samples are typically collected over a 24-hour period. Air samples for commercial and industrial settings are normally collected over 8 hours to correspond to an average work day. For commercial receptors with work days longer than 8 hours, multiple samples over the course of the work day might be appropriate. Shorter (grab samples) and longer (greater than 7-day) sampling periods may be used depending upon the site DQOs. The sample duration should be evaluated and agreed upon during the work plan preparation. In addition, confirm the appropriate ventilation conditions with the regulatory agency. Some states require that sampling only be performed in areas where windows and doors have not been opened, or air-handling systems used, for several hours.

Short term temporal variability in subsurface VI occurs in response to changes in weather conditions (such as temperature, wind, or barometric pressure) and the variability in indoor air samples generally decreases as the duration of the sample increases, because the influences tend to average out over longer intervals. Published information on temporal variability in indoor air quality shows concentrations with a range of a factor of 2 to 5 for 24-hour samples (Kuehster, Folkes, and Wannamaker 2004; McAlary et al. 2002). Long-term integrated average samples (up to several days) are technically feasible using a slower flow rate (this is the USEPA recommended approach for radon monitoring). Indoor air sampling during unusual weather conditions should generally be avoided.

Specific situations may warrant collecting indoor air samples before collecting subsurface data because of an immediate need. Examples of such situations may include, but are not limited to, the following:

- in response to a spill event, when there is a need to qualitatively or quantitatively characterize whether the indoor air has been affected
- if high readings are obtained in a building when screening with field equipment (such as a PID, an organic vapor analyzer, or an explosimeter)
- if significant odors are present and the source is unknown
- if groundwater beneath the building is contaminated, the building is prone to groundwater intrusion or flooding (for example, sump-pit overflows), and subsurface soil gas sampling is not feasible
- if the regulatory agency requires indoor air sampling
- if LNAPL is present directly below the building

This section provides general guidance for the collection and analysis of indoor air, and also identifies several key issues and considerations when using this assessment approach.

G.5.1 Presampling Building Surveys

Assessing the VI pathway using indoor air analysis may be complicated by the effects of background contaminant sources (especially for PHCs, because many common consumer products contain PHCs).

Time and attention to detail during the presampling phase of the investigation are advantageous to later stages of the investigation. Many tools are available for the building survey. One of the tools used to identify background sources in the indoor air environment is the Indoor Air Building Survey and Sampling Form. This survey form allows the investigator to document information on the building, the occupants, and potential sources of indoor air contamination. The questionnaire was originally developed by NJDEP in 1997 and has since been revised for this guidance document using several similar survey forms prepared by New Hampshire Department of Environmental Services, New York State Department of Health, Vermont Department of Health, and Massachusetts Department of Environmental Protection.

Although survey forms and questionnaires are commonly used, these tools may not identify important indoor sources. These sources may be missed for a variety of reasons including, but not limited to (1) storage conditions preventing thorough visual inspections; (2) building occupants being unaware of chemicals present in consumer products; and (3) building occupants being unaware of specific products or storage locations. Handheld field screening instruments can be useful for evaluating these types of VOC sources that are unrelated to VI. Instrument sensitivity, however, is an important consideration when selecting tools for the investigation. Field-portable gas chromatograph (GC) with mass spectrometer (MS) instruments have also been used successfully to distinguish between indoor VOC sources and VI (Gorder and Dettenmaier 2011).

As part of the presampling site visit, typical entry points should also be evaluated for each building that is to be sampled. Utility corridors can act as contaminant migration pathways, allowing VOCs to travel long distances. Any foundation penetrations such as water, sewer, gas, electric and telecommunication lines, and sumps should be screened during the presampling site visit.

For commercial/industrial facilities, it is important to understand and document: (1) the use of the building spaces (offices, warehouses, laboratories); (2) the chemicals that may be associated with building industrial activities as well as building operations and maintenance; and (3) the location of spaces where chemicals may be stored or used. Keep a photographic record, as appropriate. Prior to sampling, remove all identified sources from the building and attached garage (if present) to the extent possible. Document which sources were removed and which could not be removed.

As part of the building survey, it is important to identify potential outdoor sources of COCs, especially when conducting a PVI assessment. Ambient air concentrations for PHCs often exceed regulatory screening levels. This survey should include nearby roads and adjacent land uses (such as dry cleaners, service stations, and industrial operations).

G.5.2 Sample Collection Methods

Time-integrated sampling is typically used when conducting indoor air exposure assessments associated with VI investigations. A time-integrated sample represents a sample taken at a known sampling rate over a fixed period of time. Two methods are commonly used: collection of samples in an evacuated canister and collection of samples on adsorbent media.

G.5.2.1 Collection of Samples in an Evacuated Canister

The sampling canister is a passivated or specially-lined inert container (such as a Summa or Silco canister) that is sent to the field under vacuum and is certified clean and leak free. The canister fills with air at a fixed flow rate over a preset period of time with use of a flow controller that is calibrated and set in the laboratory. The newest hardware allows for collection periods of up to seven days.

Canister Retrieval

For time-integrated samples, the canister must be retrieved with some residual vacuum remaining (not filled to 0 psig) or the collection period cannot be determined.

Initial and final vacuums are recorded for each canister. Canisters with dedicated vacuum gauges facilitate this effort and are strongly recommended. Verify that the initial vacuum in the canister is between 30" Hg and 25" Hg (given that the accuracy of the field gauges is +/-5" Hg) and record the reading. An alternative method would be to use an independent gauge to check all canisters before and after sampling. If the vacuum is less than 25" Hg (21" Hg), then do not use the canister. To ensure the canisters are filling at the proper rate, they should be rechecked after deployment. During a 24-hour sampling period, verify the vacuum somewhere between one and four hours after the start of sample collection. Replace any canister that exhibits no decrease in vacuum or an excessive vacuum decrease. At the end of sample collection, record the canister vacuum. The canister must be retrieved prior to being completely filled (with some residual vacuum remaining) or the collection period cannot be determined. Verify with the laboratory how much sample volume, which can be equated to inches of Hg, is necessary to achieve the project required detection limits. Consider having extra Summa canisters and regulators available on site in case of malfunction or a field decision to collect additional samples.

Figure G-1a. Stainless steel canisters.

Source: H&P Analytical.

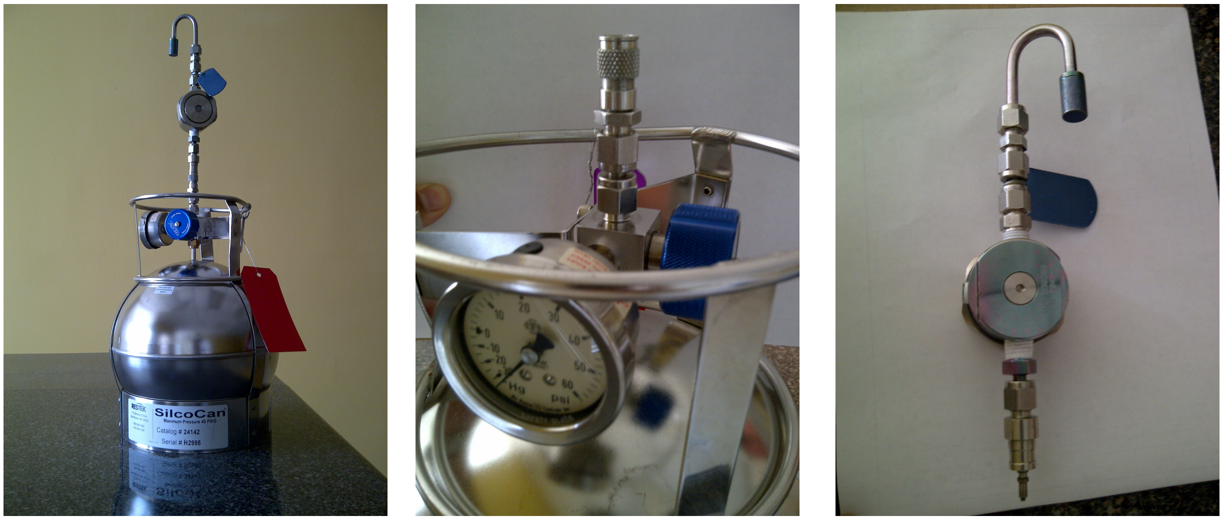


Figure G-1b. Sampling canister sampling assembly.

Source: Mississippi Department of Environmental Quality.

The main advantages of canister sample collection are the capability to analyze multiple samples from the same canister and the ease of deployment and retrieval. Canister methods are most commonly used in North America.

Play video: Canister Cleaning and Certification Process

G.5.2.2 Collection of Samples on Adsorbents

Sample collection on an absorbent is an option for VOCs and a requirement for SVOCs and can be done actively or passively. Active sampling requires drawing air at a calibrated flow rate through a tube containing adsorbent media over a specified time period. The flow rate and sampling volume used are determined based on the adsorbent used, the COCs, and the amount (mass) of adsorbent contained in the tube. The samples are taken to the laboratory for thermal or chemical desorption and subsequent analysis. Reporting limits are based upon the analytical instrument's lower reporting limit and the amount of air that is passed through the tube. Air volumes must provide adequate detection limits and sampling volumes of COCs must be within the specifications of the sorbent for each COC (safe sampling volumes). It is important to use a sorbent that is certified clean and that can be reliably used for the collection and analysis of the COCs. The sample pump flow rate should be verified and documented both at the start and finish of sample collection using a calibrated flowmeter.

A previous disadvantage of adsorbent sampling was that typically only one analysis was possible from a tube. With current analytical instruments, multiple runs can be achieved from the same tube. Other complications of sorbent sampling are potential compound breakthrough and sorbent contamination from passive adsorption of VOCs. If there is any concern for compound breakthrough, two tubes can be collected in series to demonstrate that no breakthrough occurred.

Passive Collectors

Passive collectors enable longer collection periods of days to weeks.

Passive sampling of indoor air is similar to active sampling methods in which vapor constituents are collected onto adsorbents, but the collection of constituents is based on the diffusion of the compound onto the adsorbent and does not rely on pumps. As an advantage, the passive sampler is simply hung in the indoor air space to be sampled and left for a predetermined period of time. After the exposure period, the sampler is sealed in an air tight container until analysis of the media. Exposure times must be determined based on estimated sample concentrations so that the sampler does not reach a state of equilibrium (or saturation) with the environment, which would result in a low bias. This potential bias, however, is only a concern if high concentrations are expected or an inadequate amount of adsorbent is used (USEPA 2012h).

The following video includes a demonstration of passive sampling for indoor air.

Play video: Passive Sampling for VOCs in Indoor Air.

G.5.3 Sample Locations and Frequency

A typical single-family residential dwelling (approximately 1,500 square feet) should have one indoor air sample collected from the first floor and one from the basement or crawl space (if present). Significantly larger buildings may require additional samples, especially if there are separate air spaces or separate air handling units. Multifamily residential units and commercial or retail buildings require a more careful review of the building features. Subsurface structures may be present that would facilitate VI and thus degrade indoor air quality in one portion of the building and not another (such as partial crawl spaces, sumps, and elevators). Any sampling approach should take into account the different exposure scenarios (such as day care or medical facilities) that exist within the building and any sensitive populations that may be exposed to the contaminated vapors. Multiple indoor air sample locations are necessary for multifamily residential units and commercial or retail buildings.

Additional sampling considerations include:

- Samples should be collected in the breathing zone, approximately 3 to 5 feet off the ground, in high-use areas.
- In structures with basements, both the occupied living areas and basement areas are typically sampled.
- For multistory residential buildings, consider collecting samples on the bottom floor and higher floors if elevators or utility chases exist between the lower and upper floors.
- If indoor air samples are being collected as a stand-alone determination of the VI pathway, a second confirmation sample is typically necessary due to seasonal variations. One of the two sampling events should take place during the months between November and March, since these are generally worst-case conditions for VI.

G.6 Ambient (Outdoor) Air Sampling

When conducting indoor air sampling as part of a VI study, outdoor ambient air samples should be collected concurrently. Ambient air samples are collected to characterize site-specific outdoor air background conditions. Ambient air could possibly contain numerous VOCs, especially in highly populated or industrialized areas. The outdoor ambient air levels of some VOCs can often exceed indoor air risk-based screening levels.

Outdoor air samples should be collected from a representative location, preferably upwind and away from wind obstructions such as trees and buildings. The intake should be at about 3 to 5 feet off the ground (at the approximate midpoint of the ground story level of the building) and about 5 to15 feet away from the building.

Representative samples should be placed to minimize bias toward obvious sources of VOCs (such as automobiles, lawnmowers, oil storage tanks, gasoline stations, and industrial facilities). Outdoor air samples should be collected and analyzed by the same method as indoor air samples.

For determining ambient air concentrations, some agencies recommend that ambient sampling begin at least one hour, and preferably two hours, before indoor air monitoring begins and continue until at least thirty minutes before indoor monitoring is complete. This practice is recommended because most buildings have an hourly air exchange rate in the range of 0.25–1.0 and thus air entering the building in the period before indoor sampling remains in the building for a long time.

G.7 Supplemental Tools and Data Useful for VI Investigations

G.7.1 Emission Flux Chamber Method

Flux chambers are enclosures that are placed directly on the surface (ground or floor) for a period of time, and the resulting contaminant concentration in the enclosure is measured. In theory, an effective room concentration can be calculated from the measured flux by assuming the measured flux is constant over time and over the floor area of the room, and also assuming a room ventilation rate. The calculated room concentration can be compared directly to indoor air target values for the VOC of interest. This method offers advantages in some cases because it yields the actual flux of the contaminant out of the ground, which eliminates some of the assumptions required when using other types of subsurface data. Regulatory agencies have long used this method at hazardous waste sites, and it is widely used for measuring trace emissions from natural soils; however, its application to VI assessments is relatively limited.

The testing is typically conducted in one of two modes: static or dynamic. In dynamic systems, a sweep gas is introduced into the chamber to maintain a concentration gradient across the emitting surface. The effluent air from the chamber is collected using canisters and analyzed for COCs. The method is best suited for situations where large fluxes are anticipated. In static systems, a chamber is emplaced, and the contaminant concentration buildup is measured over time. This method is best suited for situations where lower fluxes are anticipated.

Flux chambers are not well suited for structures with covered floor surfaces, such as single family residences, because the primary entry points of soil gas into the structure (cracks, holes, and sumps) are often concealed by floor coverings, walls, or stairs. For structures, the method has broader application to larger industrial and commercial buildings with slab-on-grade construction, where the slab is mostly uncovered. A building survey using a real-time analyzer or on-site GC can be used to attempt to identify the primary locations of VI.

Flux chambers are best-suited for situations where measurement from bare soils is desired, such as:

- homes with dirt basements or crawl spaces
- mobile homes above unfinished slabs or soil
- evaluation of future use scenarios at sites without existing buildings (although the effect of a future building is not known)
- demonstration of biodegradation for areas with shallow-soil gas contamination (less than 5 feet bgs)

Flux chambers can also be used as a qualitative tool to locate surface fluxes of VOC contamination and entry points into structures.

Regardless of the method used, enough chamber measurements should be collected to obtain a representative value under the footprint of the building (analogous to placing enough borings on a typical site) and to ensure samples are located near edges where the slab meets the footing, over any zones with cracks or conduits, and over the center of the contamination if known. In all cases, chambers should be deployed for long enough periods to enable temporal variations to be assessed, similar to indoor air measurements (8 to 24 hours depending upon the conditions; 24 hours if large temperature differences exist between day and night (see County of San Diego Site Assessment Manual).

More details on the flux chamber method can be found in studies by Kienbusch (1986), Eklund (1992), and Hartman (2003).

G.7.2 Determination of Slab-Specific Attenuation Factor Using Tracers

Measurement of a conservative tracer inside the structure and in the subslab soil gas can allow a site-specific attenuation factor to be calculated. The calculated attenuation factor can then be used to estimate the indoor air concentration of other COCs by multiplying the measured subslab soil gas concentration by the attenuation factor for the tracer (or "marker compound"). This method assumes that all subslab vapor phase contaminants are entering the building at equal rates, a relatively safe assumption for most situations. Naturally occurring radon is the most commonly used conservative tracer. Other potential tracers include breakdown products such as 1,1- dichloroethene or cis-1,2-dichloroethene, which are generally not found in consumer products, building materials, or outdoor air. Complications to this technique include the presence of indoor sources of the tracer (if any) and any temporal variations. For colder climates, measurement during the cold and warm seasons may be prudent. If subslab samples are being collected, however,concurrent collection of radon or another tracer data may prove useful and is generally not expensive. Determination of radon concentration using adsorbents is possible for indoor air samples, but not for soil gas samples including subslab samples. Soil gas methods exist for the collection of subslab radon concentration measurements (USEPA 2006a), but analysis of the samples may not be readily available from most commercial laboratories.

G.7.3 Determination of Room Ventilation Rate Using Tracers

The indoor air concentration is inversely proportional to the room ventilation rate: a two-fold increase in ventilation rate decreases the indoor air concentration by two-fold. The default ventilation rates used by the USEPA and many other agencies are conservative: room exchange rates of once every 1 to 4 hours for residences and once every hour for commercial buildings. For some structures, typically commercial buildings, the actual ventilation rate can be determined from the HVAC system or building design specifications, keeping in mind that the air exchange rate should be calculated from the make-up volume, not the total air handling volume. For other structures, typically residences, this information is not readily available so the ventilation rate must be either the default value or it must be measured.

ASTM Method E 741 describes techniques for measuring ventilation rates using gaseous tracers such as helium or sulfur hexafluoride. Typically, a pulse input of tracer gas in applied and the decay in concentration versus time is measured. The inverse of the air exchange rate is the slope of a plot of natural logarithm of the normalized concentration ($C_{t=n}$ / $C_{t=0}$) versus time. If a subsurface tracer gas is used, this gas can serve as the pulse input. Alternatively, a tracer gas can be released at a constant rate and the concentration measured once steady-state conditions are reached (typically after three or four air exchanges).

These techniques are quick and relatively inexpensive. For colder climates, measurement during the cold and warm seasons may be prudent if the ventilation rate during the more conservative case (cold season) suggests unacceptable indoor air concentrations.

G.7.4 Differential Pressure Measurements

Models and look-up values used by the USEPA and many state regulatory agencies are based on assumed advective flow into the structure due to a pressure gradient of 4 Pa. This assumption can be checked in the field (using a digital micromanometer attached to a subslab soil gas probe) to provide another line of evidence to evaluate VI . It is often advisable to use a unit with data-logging capabilities because pressure differentials can change on short time scales (hourly) and assess the response to wind speed and barometric pressure changes if these data are collected.

Measurement of the pressure gradient between the structure and outdoors can assist in interpreting measured indoor concentrations of contaminants. A correlation between indoor air concentration and relative pressure can provide information on the contaminant source. For example, if a building is overpressured relative to the subsurface, then measured indoor concentrations might be more likely attributed to aboveground sources. Under these conditions, VOCs originating from above ground can also be present in subslab samples (McHugh, De Blanc, and Pokluda 2006). Conversely, if the building is underpressured relative to the subsurface, then measured indoor concentrations might be more likely attributed to subsurface sources. Commercial buildings with large HVAC systems, and perhaps residences with AC units, may fall into the former category. Many structures in cold environments, especially residences, fall into the latter category when the heaters are running. This information is usually used as a secondary line of evidence in support of indoor air quality data or other lines of evidence. Often, differential pressure measurements indicate a reversing pressure gradient that supports advective flow through the foundation in both directions, from the subsurface into the structure and from the structure into the subsurface (McHugh, De Blanc, and Pokluda 2006; McHugh and McAlary 2009).

G.7.5 Real-Time and Continuous Analyzers

As with any type of site investigation, it is difficult to reach conclusions with any degree of confidence with only a handful of data points. VI data sets consisting of only one soil gas or indoor air analysis per structure may be difficult to interpret, but cost and access limitations often preclude multiple analyses. Real-time analyzers can be used to collect multiple, less expensive data that can be used to locate problem structures, vapor migration routes into structures, and VOC sources inside the structures, as well as provide the functionality to collect samples at varying depths below ground surface. Continuous analyzers that collect data automatically over a period of time can sort out background scatter and determine temporal variations both indoors and below ground. Larger data sets allow trends in the results to be recognized and correlated to other variables such as pressure differentials, wind speed, and HVAC systems. Larger data sets also allow forensic approaches to be applied.

A variety of real-time analyzers exist, including handheld logging instruments (PID, FID, thermal conductivity, IR analyzers, Z-nose, and ppb RAE), automated gas chromatographs, portable mass spectrometers, and the USEPA's own trace atmospheric gas analyzer. The applicability of many of these units is limited by their sensitivity or cost. Continuous monitoring for CH_4, CO_2, O_2, and some VOCs, along with other environmental parameters, is currently possible. As an example, real time data for these multiple parameters can provide assurance that enough O_2 is present for ongoing bioremediation of PHCs over changing environmental conditions. Temperature, barometric pressure, and changes in groundwater depth can be tracked simultaneously with concentration, so the effect of these external factors can be assessed in real time at those sites where the CSM indicates conditions may favor variable soil vapor concentrations.

G.7.6 Forensic Data Collection and Analysis

Forensic approaches attempt to determine the source of any detected VOCs through a detailed study of the nature of contamination, with a focus on lines of evidence to potential sources. Traditional environmental site assessments focus on the nature and extent of contamination as determined by common methodologies which were developed to provide data for regulatory purposes.

The environmental forensics approaches are more sophisticated analytical techniques, which have the ability to produce chemical fingerprints that are source specific. Potential fingerprinting strategies include:

- using compound ratios (such as benzene/TPHv) and comparing them in the soil gas and indoor air results
- using chemical fingerprinting to distinguish between different types of PHCs (such as diesel, gasoline, and jet fuels), with comprehensive analysis of the samples to include total chromatographic patterns
- using isotope ratios (such as carbon, hydrogen, and oxygen) in the source determination of methane and other light hydrocarbon gases and sometimes for other petroleum products

Forensic approaches have been used to determine whether the source of subslab contaminants were from the overlying structure or from the vadose zone (McHugh, De Blanc, and Pokluda 2006). Environmental forensics is a developing approach that will likely be increasingly important in regulatory enforcement actions and cost-recovery litigation.

G.7.7 Meteorological Data

A variety of weather conditions can influence soil gas or indoor air concentrations. For soil gas, the importance of these variables is greater the closer the samples are to the surface and is unlikely to be important at depths greater than 3 to 5 feet below the surface or the structure foundation. Indoor air may be more susceptible to weather conditions, therefore collection of meteorological data can be helpful to assessing the VI risk. Examples of meteorological effects include the following:

- *Rainfall events*. Precipitation can affect VI rates and possible soil gas concentrations. Percolation of water through the soil can displace soil gas and lead to a short-term spike in VI. The increased soil moisture after a rainfall can reduce vapor transport through the soil due to reduced effective porosity and permeability. Measurements made during or immediately after a significant rain event (greater than an inch) may not be representative of long-term average conditions. For other sites, however, frequent rainfall is common, and testing soon after a rainfall event is both representative and inevitable.
- *High wind speed*. High wind speed can create pressure differentials around a structure, causing an advective flow in the shallow soil gas around and beneath a structure. This condion can lead to an inflow of air into the vadose zone on the windward side of a building, an outflow of soil gas on the leeward side, and overpressurization of the area under the building compared to the building itself. Such a flow pattern can lead to higher O_2 concentrations at deeper depths on one side of a building versus the other, which is relevant at sites with PHC contamination. Recent studies by API have suggested that horizontal flow of the soil gas under slab-on-grade foundations can be rapid in areas with sandy soils, which is also likely coupled to wind speed. Sampling should occur during nominal wind conditions for the site, not during unusually windy conditions or during extreme storm events.
- *Frozen ground or permafrost*. The inflow of air into the vadose zone or soil gas out of the vadose zone may be restricted if the ground surface is frozen and snow-covered. This cover can create a change in the subsurface conditions, such as O_2 concentrations, thus the presence of frozen ground or permafrost should be noted where applicable. An additional sampling event when conditions are not frozen may be appropriate.
- *Major storm events*. Changes in barometric pressure can create movement in the near-surface vadose zone, a process known as barometric pumping. For most normal climatic conditions, the effect of barometric pressure on soil gas concentrations will be minimal; however this effect may be significant near or during major storm events or for sites with very deep vadose zones, especially if the geologic materials are fractured (Parker 2003).

G.7.8 Pneumatic Testing

In some cases, geologic layers can form partial or complete barriers to upward vapor transport toward overlying buildings. Particular causes of these barriers include laterally-continuous, fine-grained soil layers that retain sufficient moisture to be saturated or nearly saturated. It may be possible to identify the presence of such geologic barriers using pneumatic testing, analogous to a groundwater pumping test, in which one well is used for extraction and other wells are used for monitoring the vacuum response. If the extraction well is screened below the fine-grained layer, and the monitoring probe is screened above the fine-grained layer, then the pneumatic test can be analyzed to assess whether and to what extent there is pneumatic connection between the intervals. Alternatively, a test can be conducted using two wells screened in the geologic layer below the fine-grained unit. The vacuum versus time data collected at the monitoring well are analyzed using the Hantush-Jacob (1955) leaky- aquifer solution to calculate the vertical leakage (or absence thereof) through the fine-grained “confining” layer (Thrupp, Gallinatti, and Johnson 1996). Note that this evaluation is for VI due to off-gassing from the saturated zone. These pneumatic tests provide information within the subsurface region that is stressed during the test, which can span hundreds of feet, but knowledge of the geology is important prior to inferring conditions farther from the test location.

G.7.9 Manipulating Pressure Differentials

One possible method for distinguishing subsurface VI from background sources is to collect indoor air samples with and without manipulating the pressure differential from the subsurface to indoor air (McHugh et al. 2012). This method can be accomplished by pressurizing the building or depressuring the region beneath the floor slab. In both cases, if the applied pressure differential is sufficient to prevent subsurface VI, then the concentrations of chemicals intruding from the subsurface are reduced and the concentrations of chemicals from background sources are largely unaffected. Folkes (2000) reported measured indoor air concentrations for several CVOCs before and after the operation of a subsurface depressurization system to mitigate subsurface VI.

Building pressure control can be used with on-site GC/MS analysis to distinguish between indoor sources of VOCs and VI (Gorder and Dettenmaier 2011; Beckley et al. 2014) and to address temporal variability (McHugh et al. 2012). On-site GC/MS analysis can be used to characterize the building under normal operating conditions. The building pressure can then be manipulated and indoor VOC concentrations re-measured through on-site analysis. The pattern of VOC concentration changes under different pressure conditions is then used to determine whether the building is susceptible to VI or not. For example, if VOCs are below screening levels during normal operating conditions, and remain below screening levels during induced negative pressure (condition which supports the flow of soil gas into the building), then the investigator would have more confidence that VI is not a concern in the building.

G.8 Soil Gas Sampling Strategies

The initial criteria to apply when determining where to collect soil gas samples for VI assessments are the location of the contamination source relative to the building, the depth of the contamination source, and the type and construction of the building. The following sections recommend locations for collecting soil gas samples, both laterally and vertically, for some typical situations. Additional suggestions are available from API (2005), NJDEP (2013a), and ASTM (2006, 2009).

Selection of Sampling Locations at Sites with USTs

Though local regulatory guidance will influence the design of soil vapor surveys, the recommended approach is to make a technically defensible evaluation of the vapor pathway at either the structures of concern or at the locations with the highest contaminant concentrations at the site. If a commercial structure is on site, then collection of samples near or under the structure may be all that is necessary, even if contamination exists elsewhere on the site. At many service station sites, the contamination is typically at or near the USTs ,which can be located far from the on-site building. In such cases, if the use of the site will not change for the foreseeable future, sampling at the tank pit may not be necessary since there are no receptors over or immediately adjacent to the contamination. In contrast, if the purpose is to achieve closure of the entire site for potential redevelopment, then sampling at the highest contaminated zones is likely necessary to ensure COC concentrations that are protective for a different future use.

G.8.1 Sample Density

When subsurface contamination is encountered near buildings, soil gas samples are typically collected to assess the contaminant distribution in sufficient detail to identify buildings that may have unacceptable levels of VI. Characterization should continue until concentrations of VOCs meeting acceptable risk-based levels are encountered in the subsurface both laterally and vertically between the source and potential receptors. The exact number and spacing of samples (sample density) varies on a site-specific basis. A soil gas sample should be taken for every existing or future building for smaller sites (for example, houses surrounding a dry cleaner or a gas station). At larger sites (such as a groundwater plume under a large neighborhood), enough samples should be collected to give sufficient spatial coverage of the area over and near the contamination. For sites where current and future land use will be restricted by a land use covenant, the soil gas sampling density can be modified as a function of the size of the current and future buildings pursuant to the covenant.

When sampling near or under individual structures, collect enough samples to obtain a representative value of the soil gas concentration (analogous to placing enough borings on a typical site to characterize the extent and degree of contamination). If statistical averaging methods are being used to process the data, a minimum number of locations might be required depending on the statistical method used.

G.8.2 Selection of Lateral (Spatial) Soil Gas Sampling Locations

Exterior soil vapor samples (samples not under structures) are typically collected in portions of the site where:

- contamination exists and no building is present
- at locations between the contaminated area and an on-site building
- around the perimeter of an on-site building

If the extent of the contamination is not known, and future development is anticipated, then sampling points for assessing the VI pathway are located to give representative coverage of the entire site so that no contamination zones subject to vapor migration are missed. If the extent of the contamination is known, then sampling points are located over the contamination zone. If the property use is not changing, and on-site buildings are not threatened, then it might be appropriate to only locate points at the property borders to ensure that no vapors are migrating off site. When structures exist, collect samples on the side of the structure closest to the source. Collect samples in any known subsurface migration routes, such as sewers or utility lines, that extend towards the contamination. Prior to collection, evaluate the COC list to identify the compounds present on the site. If concentrations exceeding screening levels are detected, the next step may include additional sampling of the soil gas, or it may be appropriate to proceed to interior sampling (subslab or indoor air).

Using Exterior Soil Vapor Data

Some state agencies may not allow the use of exterior soil vapor data to evaluate the risk to an existing structure, preferring subslab soil gas data. Confer with the appropriate local agency for their specific policy and requirements.

G.8.3 Selection of Vertical Soil Gas Sampling Locations Exterior to the Building

Vertical profiles of soil gas concentrations can be useful for the following:

- determining the source of the contamination if not previously known
- determining the degradation of contaminants in the soil gas in the vadose zone due to biodegradation or other processes

G.8.3.1 Near Existing Buildings

Sample locations ultimately depend on the CSM and on the location of the contaminant source to the buildings, both spatially and vertically. For PVI investigations, if all receptors on site and near the site are slab-on-grade construction, then samples may only need to be collected at shallower depths (upper 5 feet). In addition, it is often advisable that at least one additional sample be collected at a shallower depth in the event the results from the 5-foot depth exceed allowable concentrations. This sample demonstrates whether biodegradation decreases the concentrations above 5 feet. If on-site analysis exists, the decision to collect a shallower sample can be made based upon the 5-foot data. If on-site analysis does not exist, it may be prudent to collect an additional sample at 2.5 to 3 feet bgs. This sample is labeled on the chain-of-custody, and to be held pending analysis of the 5-foot sample. If the concentration in the 5-foot sample is below allowable levels, then the shallower sample need not be analyzed.

Some agencies may hesitate to accept soil vapor data at depths shallower than 5 feet bgs on the basis that a sample collected less than 5 feet bgs might be diluted by ambient outdoor air or compromised by atmospheric effects. A number of studies have documented that small variations (less than a factor of two) in soil vapor values collected from depths as shallow as 2 to 4 feet bgs demonstrate that atmospheric effects on shallow soil vapor data are minimal under typical climatic conditions. If sampling at shallower depths, then more care must be taken to avoid any chance of drawing air in from the surface. Some type of leak detection method should be used for these shallower depths.

If structures with basements or subterranean parking garages exist on site or near the site, and the contamination source is below the structure, then samples at or just below the depth of the foundation should be collected. If the contamination source is lateral to the structure, then a vertical profile of the soil vapor is recommended to assess the potential intrusion through the foundation floor and also through the foundation walls. Sampling depths should be selected to give coverage from the top to the bottom of the walls. Vertical sampling locations can also depend on the depth to groundwater and will change if the water table fluctuates.

G.8.3.2 For Locating the Zone of Biodegradation

At some sites, it is desired to document the depth of the reaction zone where conditions change from aerobic to anaerobic in order to determine the thickness of the aerobic vadose zone separating the contamination source from the building. This determination can be made by conducting a vertical profile of soil gas concentrations using field tools to screen for the presence of VOCs, O_2, CH_4, and CO_2, which are indicator compounds of aerobic and anaerobic conditions (see Figure G-2). In general, the depth of the anaerobic vadose zone closely corresponds to the depth of contaminated soil. PHC concentrations are relatively low in the aerobic zone (where O_2 is present), but can be quite high in the underlying anaerobic (O_2-absent) zone. The thickness of the zone in which conditions change from anaerobic to aerobic conditions is typically less than 2 feet (Davis, Patterson, and Trefry 2009).

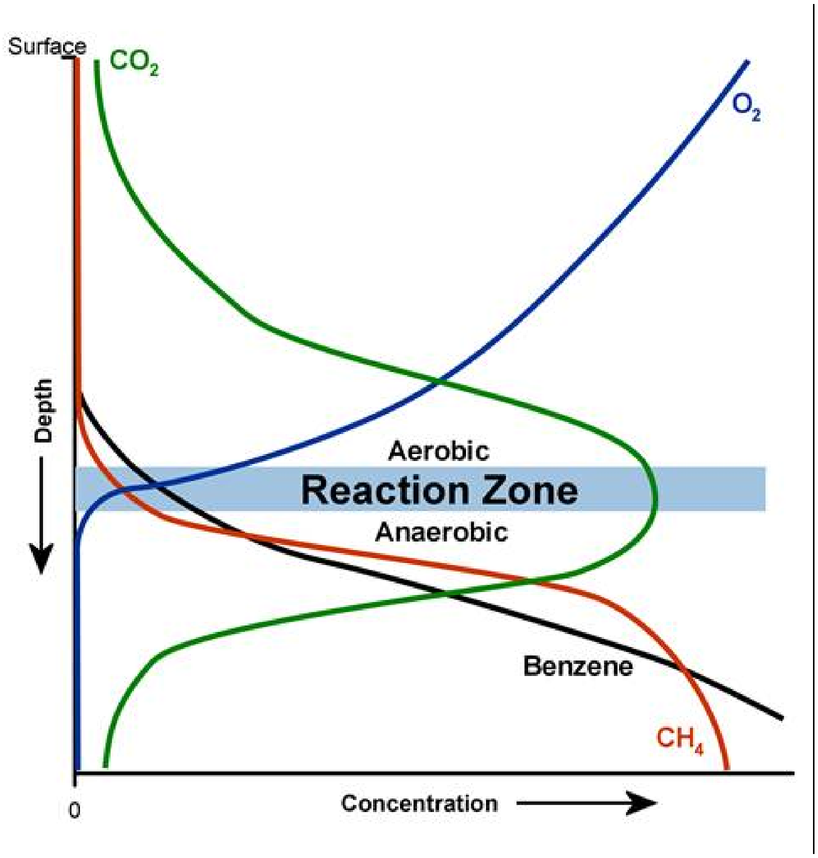


Figure G-2. Depth versus concentration plot of O_2 and PHC concentrations.

Source: G. T. Ririe and R.E. Sweeney.

> ***Note:*** *PIDs do not respond to all PHCs. FIDs respond to all PHCs and also to methane.*

Ideally, the deepest soil vapor sample point is located near the top of the contaminated soil or near the contaminated groundwater. The depth to the top of the contamination might be known from preexisting site assessment data, but it is advisable to confirm this depth in the field before installing vapor sample points. This confirmation is easily done by screening the soil vapor with a portable PID or FID or by screening the soil vapor for O_2 using a portable meter. Additional soil vapor sample points are then installed from the top of the contaminated zone upward in the vadose zone. Typically, three or four sampling depths are all that are necessary to locate and document the biodegradation zone. Procedures for constructing soil vapor sampling points are discussed in the following sections.

G.8.4 Subslab Soil Vapor Sample Locations

Agency Requirements

Check to see if the oversight agency specifies the number and locations of subslab samples.

Some agencies require subslab soil vapor samples in lieu of exterior soil vapor samples when assessing the VI risk to actual structures. For small structures, single family homes, or small convenience stores, one subslab sample may be enough. A majority of current state VI guidelines, however, require more than one subslab sample (Eklund et al. 2012). If contamination uniformly underlies the structure, such as a VOC groundwater plume, the subslab sample is typically located towards the center of the structure, away from the foundation edges. If the contamination is located laterally away from the structure, such as in a tank pit or in a dispenser island, the subslab sample is typically located towards the side of the structure facing the contamination. In practice, especially in residences, the location of the subslab samples is determined more by access and floor coverings than by the location of the contamination.

G.8.5 Near-Foundation (Exterior) versus Subslab Sampling (Interior)

Subslab sampling is intrusive and may not be possible due to access limitations or disturbances to the occupants. For chlorinated compounds, subslab sampling is typically preferred over shallow, near-slab sampling because shallow exterior soil gas samples have been shown to not match subslab samples. The situation is different, however, for PHCs.

Comparisons between near-slab soil gas profiles and subslab soil gas profiles for PHCs are reported in two USEPA modeling studies: the conceptual model scenarios report (USEPA 2012h) and the building size modeling report for PVI (USEPA 2013d). The USEPA (2012b) assumed that building foundations, basements, and slabs were impermeable and thus O_2 transport was not simulated through the foundation, basement, or slab into the subsurface beneath the building. Later USEPA simulations (2013d), however, allowed for oxygen transport using reasonably-expected O_2 permeability values for concrete. When O_2 transport is accounted for, the differences in soil gas profiles are less pronounced between subslab samples and near-slab samples very close to the building basement and slab. The ramifications from these findings (USEPA 2013d) are that near-slab soil gas samples can be substituted for subslab samples in situations where dissolved contamination is present within 6 feet of (but not in contact with) a building basement floor, foundation, or crawl space surface, and where LNAPL is present within 15 feet of (but not in contact with) a building basement floor, foundation, or crawl space surface. For dissolved sources, this practice applies for buildings of any size, and for LNAPL sources it applies to buildings with the shortest side being no longer than 66 feet (USEPA 2013d).

G.8.6 Variations in Soil Gas Values Due to Temporal Effects

A number of recent studies on the temporal variation of soil vapor concentrations due to common meteorological parameters at both chlorinated sites (Johnson and Deeb 2014; USEPA 2010b;

USEPA 2007d) and at PHC sites (Luo et al. 2009; Hers et al. 2014). The results of these studies show that variations in soil vapor COC concentrations at depths as shallow as 2 to 4 feet due to temperature changes, barometric pressure, and wind speeds are typically less than a factor of two. Seasonal variations in cold climates were less than 30% (Hers et al. 2014, in press). Concentration variations are greater the closer the samples are to the surface. For shallower sampling depths (less than 2 feet bgs), larger variations can be expected in areas of greater temperature variation and during heavy periods of precipitation. Based on these studies, shallow soil vapor concentrations are unlikely to show variations greater than a factor of two, unless extreme weather conditions have occurred or the water table has changed (up or down).

Subslab concentrations of CVOCs also do not show much temporal variation. A study in progress by the USEPA from January 2011 to February 2013 showed subslab concentrations to vary by less than a factor of two underneath a house in Indianapolis (USEPA 2012h). For PHC, the study by Hers et al. (2014) showed temporal variations of less than 50% over a period 15 months.

Canadian Cold-Weather Temporal Study

Data from a site in Saskatchewan collected over a 12-month period showed PHC soil gas concentration variations of less than 30% (Hers et al. 2014).

Larger variations may be expected in areas of greater temperature variation and during heavy periods of precipitation as described below:

- *Temperature*. Effects on soil gas concentrations due to actual changes in the vadose zone temperature have been shown to be minimal. Hers et al. (2014) observed only a 20% to 30% annual variation in a cold environment with frozen ground and permafrost. In colder climates, worst-case scenarios are most likely in the winter due to frozen ground or permafrost.
- *Precipitation*. Infiltration from rainfall can potentially affect soil gas concentrations by displacing the soil gas, dissolving VOCs, and by creating a “cap” above the soil gas. In many settings, infiltration from large storms only penetrates into the uppermost vadose zone. In general, soil gas samples collected at depths greater than about 3 to 5 feet bgs or under foundations or areas with surface cover are unlikely to be significantly affected, unless there is a change in the water table. Soil gas samples collected closer to the surface (less than 3 feet) and with no surface cover may be affected. If the moisture has penetrated to the sampling zone, then collecting soil gas samples becomes difficult. If high vacuum readings are encountered when collecting a sample, or drops of moisture are evident in the sampling system or sample, then measured values should be considered as minimum values.

Temporal variations in soil gas concentrations appear to be minor compared to the conservatism built into risk-based screening levels (factor of 10 or more). Thus, it may not be necessary to repeat soil gas sampling if the measured values are some factor below soil gas screening levels, unless a major change in conditions occurs at the site (such as elevated water table or a significant seasonal change in rainfall). As an example, Australian guidance has defined a margin-of-safety factor. The number of additional sampling events required depends on how far the actual soil gas values are below the screening values. For example, if measured soil gas values are 10 times below their screening levels, then additional sampling events are not necessary. Criteria for additional sampling events are also given for margin of safety from 1 to 10.

G.9 Passive Soil Gas Methods

Passive soil gas methods consist of the burial of an adsorbent in the ground with subsequent retrieval and measurement of the adsorbent. With passive sampling, there is no forced movement of soil gas by use of a pump or applied vacuum. Instead, as the vapors move by diffusion, the sorbent acts as a sink for the organic compounds in the soil gas. By collecting samples for periods of days to weeks, this method gives a time-integrated measurement and reduces the uncertainty in soil gas concentrations due to temporal variations. Depending on the sensitivity of the passive sampler, this method may also be used to distinguish between “clean” soils and those displaying characteristics of VOC presence in the subsurface.

This method can be used in investigations to provide a line of evidence on the absence, presence, and intensity of soil vapor contaminants. In general, passive samplers detect VOCs and SVOCs, including aliphatic and aromatic hydrocarbons in the range of C4–C20, volatile PAHs related to, for example, MGP sites, and VOCs related to petroleum refining and blending (such as lead scavengers and other fuel additives). Longer-term exposure times can be used to yield relatively lower detection limits.

Passive soil gas methods directly measure a mass of contaminant that has diffused onto an adsorbent media. The data provide a line of evidence on the presence, absence, and relative measurements of target VOCs and SVOCs in soil gas, as well as identify potential VI pathways into and around existing and future structures, including utility corridors. Compounds present in soil gas can be determined, and the location of sources and subsurface extent can be mapped. Reporting units are typically in terms of mass (micrograms or µg).

Using relative mass levels, passive methods offer a quick and relatively inexpensive method to find vapor migration pathways into a structure or around a structure, such as utility corridors, or in areas with significant aboveground infrastructure like refineries or bulk storage facilities.

Passive soil gas sampling methods can also be useful when active methods may not be applicable, such as in low-permeability and high-moisture settings. Because these methods are simple to deploy and retrieve, a large number of soil gas samples can be taken cost effectively. The relative concentrations can later be mapped to aid in locating sources and subsurface plumes (particularly the edges of plumes) to determine whether contamination is near current or future buildings. These concentrations can also be used to plan additional sampling schemes that focus more complex and intrusive sampling on areas where contamination is observed. Where surveys indicate the absence of petroleum contamination on a site, consider the overall sensitivity of the passive sampler (vapor uptake in the soil and analytical method sensitivity combined) before using results to screen areas out of further investigation.

Based on current regulatory-accepted analytical methods for quantitative analysis, passive soil gas is presently not applicable for stand-alone assessment of VI risk. Published methods describe the procedures to generate contaminant concentration data from a passive sorbent-based sampler in air in the absence of soil (ASTM 2002, ASTM 2003a, b), and efforts are ongoing to demonstrate the applicability of the method to soil gas (ASTM 2012). Knowledge of the passive sampler's method detection limit as a vapor sampler is critical in data evaluation—contact the passive vapor sampler provider to discuss methods used to determine the soil gas concentration.

Passive soil gas sampling is not limited to exterior sampling locations. Subslab, near-slab, crawl space, and groundwater soil gas sampling can be performed using passive samplers. Passive soil gas sampling can be conducted on the ground surface (for example, a flux approach) and at multiple depths, usually in nested boreholes. Consider survey design and sample density and location (laterally and vertically), which may impact active soil gas sampling, when designing and implementing a passive soil gas sampling program. Additional information on use, benefits, and limitations of passive soil gas sampling in the context of VI are available from ITRC (2007), USEPA (2008), and ASTM (2012).

Special considerations include the following:

- *Adsorbent material*. The adsorbent material should be hydrophobic in order to minimize water intake.
- *Exposure time*. Exposure time is depends on the objectives of the sampling program and the adsorbent materials used. Samplers constructed of weaker adsorbents (surface areas less than 100 m^2/g) should be exposed for shorter periods of time to avoid saturation of the adsorbent and potential back diffusion of highly volatile compounds.
- *Desorption and analytical method*. The absorbed compounds can be removed from the adsorbent by thermal desorption or solvent extraction and analyzed using GC or GC/MS, typically following USEPA method protocols when applicable (such as USEPA SW846). Methods using thermal desorption have the benefit of greater method sensitivity than those using solvent extraction.

G.9.1 Installation and Retrieval

For exterior soil gas and subslab soil gas sampling, a narrow diameter hole (for example, 2.54 cm or 1 inch) is advanced to the desired sampling depth (for example, 15 cm to 1 meter). Hole depth and diameter depend on the passive sampler design and sampling objectives. Sampler depths of 3 to 4 feet or less can be accomplished using hand tools (such as a hand auger, slide hammer and tile probe, or rotary hammer drill and carbide-tipped bit). Deeper soil gas sampler installations, or deployment into larger diameter holes, may require more invasive drilling equipment and may require casing the hole. An illustration of various installation options is provided in Figure G-3.

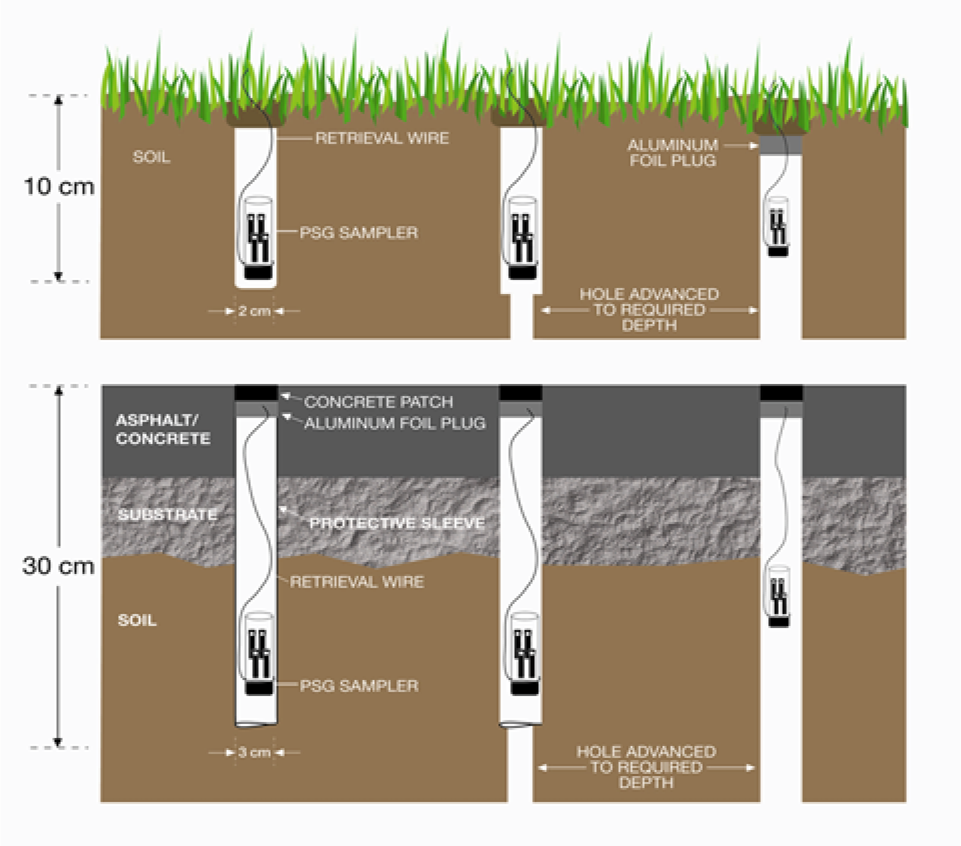


Figure G-3. Passive soil gas sampler installation options.

The sampler is lowered into the hole to the desired sample depth using a wire or string, which is then anchored at the surface by material used to seal the hole (for instance, natural, impermeable cork). This material prevents down-hole vapor infiltration and surface water from entering the hole (Figure G-4). Because there is no sample train and no forced extraction of soil gas, no leak integrity testing is required. Therefore, no sampling equipment remains on the surface after sampler installation, minimizing or eliminating the potential for equipment damage or vandalism, and allowing occupants to continue their site activities unimpeded.

The sampler is retrieved by removing the hole seal, pulling the sampler from the subsurface, and securing it in an appropriate container for transport back to the laboratory. Exposure periods depend on passive sampler design and the target reporting levels. Generally, finer-grained soils, higher soil moisture, less volatile compounds, greater depths to contaminant source, and lower reporting levels extend the sampling period. The exposure period should be long enough to achieve detectable reporting levels. Additional information can be found in the ASTM standard on passive soil gas sampling (ASTM 2012).

Figure G-4. Passive soil vapor sampler installation. Top: Exterior soil vapor sampling using slide hammer and rotary hammer drill, insertion of a passive soil gas sampler, and sealing the hole. Bottom: Subslab soil vapor sampling.

Source: Amplified Geochemical Imaging, LLC.

Passive samplers should be transported in a sealable container to preserve cleanliness prior to use and to prevent additional adsorption during return shipment to the analytical laboratory. Store samples away from potential sources for VOCs. No chemical or temperature preservation is typically required for transport. Passive samplers tightly sealed in their storage container can typically be held for several weeks prior to analysis. Check with the sampler manufacturer for specific hold time instructions.

The following video includes a demonstration of a passive sampling setup.

Play video: Passive Sampling Setup

G.9.2 Passive Survey Design

Because the installation and retrieval of passive soil gas samplers is relatively inexpensive and quick, a large number of samplers can be deployed at a site to achieve good coverage. No firm guidance on soil gas sample spacing appears in current published literature. Recommendations from the New Jersey Field Sampling Procedures Manual (NJDEP 2005), suggest sample spacing on the order of 25 to 75 feet (8 to 23 meters), with smaller distances being used to locate source areas and larger distances within areas suspected to be free of contamination. Sample intervals should be a function of project budget and sampling objectives (ASTM 2006, 2014, 2009). Survey design should attempt to limit oversampling (collecting too many samples and reporting redundant data), but avoid under-sampling (collecting too few samples to resolve the features of interest). A well-designed passive soil gas survey can identify areas of the site no longer requiring further investigation, while focusing subsequent sampling in areas known to be affected.

Additional QA/QC issues regarding passive samplers are included in the ITRC VI guidance (ITRC 2007), Appendix E and Appendix F.

G.10 Active Soil Gas Methods (Exterior)

Active soil gas methods consist of the withdrawal and analysis of the soil gas from the subsurface. These methods give concentration data (for example, $\mu g/m^3$) for COCs, which can be directly compared to risk-based screening levels or used in predictive models.

Soil gas sample collection techniques for VI applications require much greater care than techniques historically used for typical site assessment applications (such as assessing whether a UST has leaked) because the data are being used for risk assessments. The quality of soil gas data depends greatly on the collection protocols. Some of the primary factors that can influence the soil gas sample quality, and in turn the measured results of the sample, are summarized in the following sections. A checklist summarizing some of the key QA/QC issues is included in the ITRC VI guidance, Appendix E (ITRC 2007).

Two techniques are most commonly used to install soil gas probes to collect external active soil gas samples – driven probe rod and burial of soil gas sampling tubes. Both methods have been shown to give reliable, reproducible data in moderate to high permeability soils (DiGiulio et al. 2006a).

G.10.1 Driven Probe Rod

This method consists of the insertion of a hard rod (probe) driven to a target depth, collection of soil gas through the rod while it is in the ground, and subsequent removal of the rod (see Figure G-5). Soil gas probes can be constructed of a variety of materials and installed by a variety of techniques. Typically, probes are constructed of hollow steel rods with an external diameter ranging between 12.5 mm and 50 mm (0.5 inches and 2 inches). Small diameter inert, replaceable tubing runs down the center of the drive rod to eliminate potential contamination from the inside of the rods.

The probes can be driven by hand methods, direct-push systems, or with larger drill rigs using a wire-line hammer. The drive-rod method is typically faster than the buried tube method and also does not leave materials in the ground. Probe installation can be difficult in overconsolidated or coarse-grained soils, especially at greater depths, where the rods are more susceptible to deflection. A surface seal is usually used, but this seal does not prevent cross-flow at greater depths, so driven probes are most applicable in relatively uniform moderate to high permeability materials (generally not in low permeability soils). A tracer/leak check compound is required by most agencies to verify the absence of atmospheric air entry during sampling.

Figure G-5. Driven probe rod.

G.10.2 Burial of Soil Gas Sampling Tubes

This method consists of the burial of a small diameter (typically ⅛ inch to 1 inch outer diameter) inert tube or pipe (stainless steel, Teflon, polyvinyl chloride, high density polyethylene, polyether ether ketone, Nylaflow, or similar) to a target depth with subsequent sampling of the soil gas after a period of time. Tubing may be buried in holes created with hand driven rods, direct-push systems, hand-augers, drills (for subfoundation samples) or drill rigs for deeper samples. Clean sand is used as backfill around the tip, and the remainder of the borehole annulus is sealed, usually with a bentonite and water slurry. This method is sometimes referred to as the semipermanent method (if the tubes are removed after a short period of time) or permanent method (if the tubes are left in the ground for a longer period of time), but can equally be used for temporary sampling. This method offers significant advantages when repeated sampling events are needed, or where the geology is not conducive to driven probes. Multiple tubes can be "nested" in the same borehole, if the seals between intervals are tight, and are often referred to as multilevel soil gas wells or nested probes. These probes can also be installed in nearby individual boreholes, as shown in Figure G-6.

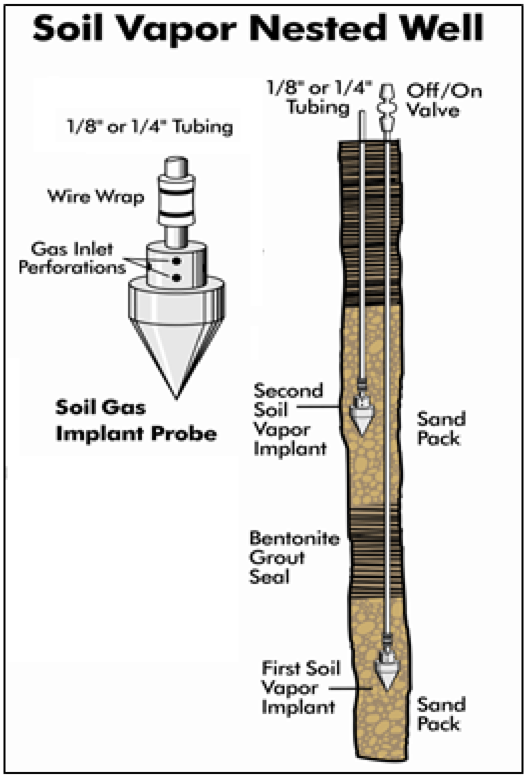


Figure G-6. Typical configuration of nested well.

Source: H&P Mobile Geochemistry.

Figure G-7. Nested soil gas sample points in a single borehole (permanent probes with locking cap for repeated sampling).

Source: H&P Mobile Geochemistry.

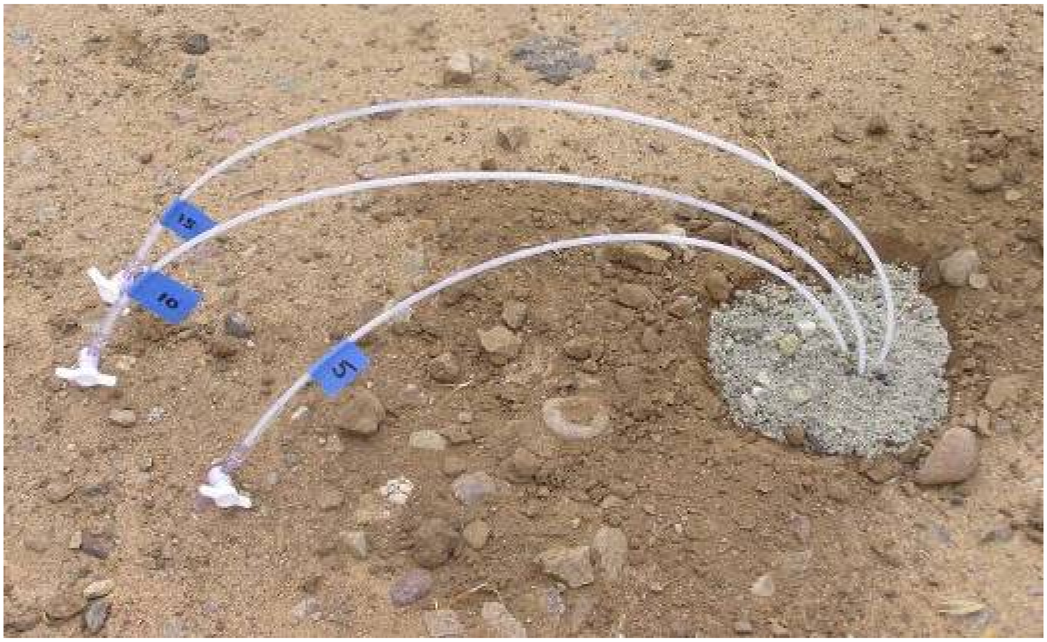


Figure G-8. Temporary probes to be removed after sampling.

Source: H&P Mobile Geochemistry.

G.10.3 Soil Gas Sampling from Existing Groundwater Wells

Soil gas samples can be collected from groundwater wells that are screened across the water table and retrofitted with an air tight cap and valve. If three to five times the well casing gas volume is purged prior to sampling, the resulting soil gas sample should reflect the soil gas in the vadose zone outside of the well screen. If the casing volume is not purged, then the soil gas sample reflects contributions from both the vadose zone and from soil gas emanating from the standing water column within the lower part of the well, which is difficult to interpret and is therefore not recommended. Because of the large purge volumes required for 4 inch or 6 inch wells, the chances for sampling errors are greater than sampling soil gas with dedicated soil gas probes. Field screening with portable meters is useful to demonstrate stable readings before sample collection.

G.10.4 Soil Vapor Probe Installation Issues Specific to UST Sites

At many active service station sites, ground disturbance protocols require special probe installation protocols. Use of an air knife to clear sample locations is not recommended, so soil vapor points are generally installed by burying tubing into an open borehole as opposed to driving a steel rod into the ground and sampling through the rod. Soil vapor sampling points can be installed down a variety of boreholes ranging in diameter from 1 inch to 8 inches. Boreholes may be created with hand equipment (such as a hand auger) or by using direct-push methods when underground utilities are not present. Because of typical ground disturbance protocols, hand augering will likely be the most common method used to create a borehole.

G.10.5 Soil Vapor Probe Materials/Construction

It is important that the correct soil vapor probe materials (see Figure G-2, driven-probe rod) are used and the probes constructed properly. Following are recommended materials and construction issues for soil vapor probes.

G.10.5.1 Tubing

Use tubing material that does not adsorb or off-gas volatile hydrocarbons. Recent studies by USEPA-ORD (Schumacher et al. 2009) show that nylon, Teflon, and stainless steel all give comparable results for typical PHCs. For heavier molecular weight compounds, stainless steel shows the least adsorption, but may be impractical to use. Nylon is recommended over Teflon tubing, because nylon tubing is less expensive and the compression fittings are easier to seal. Polyethylene tubing, commonly used by direct-push firms for groundwater sampling, should not be used for soil vapor samples because the polyethylene tubing has been shown to adsorb hydrocarbons. Check with the direct-push firm prior to the field program to ensure that they have and use proper tubing. In addition, it is important to properly store and handle the tubing. Any type of tubing will become contaminated and contribute to false positives if it is stored unsealed in the back of a truck or near the truck exhaust.

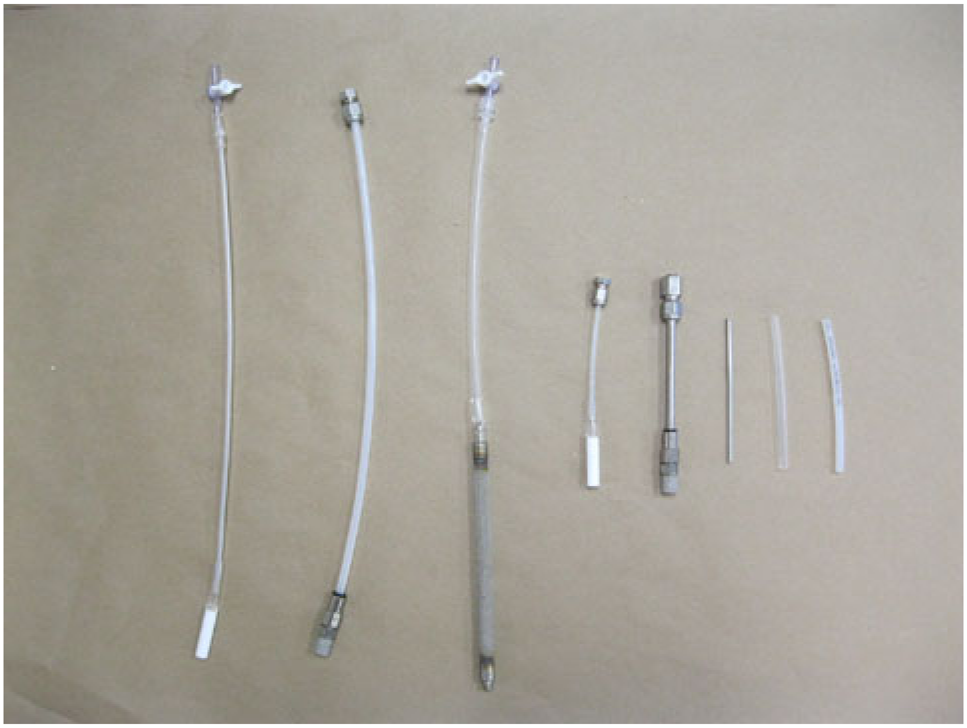


Figure G-9. Vapor sample materials, including ⅛-inch outer diameter tubing, three types of tips (ceramic, aluminum, and braided steel) and two types of surface terminations (stopcock and Swagelok fitting).

Source: H&P Mobile Geochemistry.

G.10.5.2 Tubing Diameter

Nominally ⅛-inch or ¼-inch outer diameter tubing is recommended. Generally, ⅛-inch outer diameter tubing is easier to drop down a borehole than ¼-inch outer diameter tubing. If soil permeability tests are to be performed, the diameter should be a minimum of ¼ inch.

G.10.5.3 Probe Tip

Stainless steel, aluminum, ceramic, or plastic (choice depends upon project specifications) probe tips are recommended. Note: Equipment blanks may have elevated levels of VOCs if probe tips are not properly cleaned (see Section G.10.6).

G.10.5.4 Surface Termination on Tubing

Swagelok fittings or plastic valves (two-way plastic valves or stop cocks) are best for sealing tubing that will remain in the ground for an extended time. It is important to secure the valve tightly to tubing, as the valve is a permanent component of the soil vapor collection system.

G.10.5.5 Surface Termination on Ground Surface

Options for surface termination include flush mounts on the floor/surface, belowground termination (with or without a locking cover), and various aboveground completions that are commercially available.

G.10.6 Equipment Blanks

Collection of an equipment blank is recommended for all VI investigations, especially if metal probe tips are used. Zero-grade air or nitrogen should be drawn through the probe tubing, probe tip, and the sampling train at the start of the field program. The collected sample should be analyzed for the same compounds as the soil vapor samples. This practice confirms that the metal probe tips and other probe parts are clean before putting them in the ground.

G.10.7 Equilibration Time

When probes are installed, the in situ soil vapor can be displaced and a period of time is required for the soil vapor to reequilibrate to their predisturbed values. A recent USEPA study (Tetra Tech EM 2010) showed the following equilibration times were required to reach 80% of the final value, assumed to represent the predisturbed value:

- sampling through probe rod installed by hand: 15 minutes
- sampling through probe rod installed with direct-push methods: 30 minutes
- sampling through probes where tubing is buried in a sand pack in the ground: 8 hours

This study was done in fine-grained soils, and equilibration times may be less in coarse-grained soils.

The time between probe installation and sampling depends on the investigation objectives and the data quality requirements. For example, if a soil vapor survey is conducted using temporary points to map the extent of a vapor plume, and the sample data are not intended for use in risk assessment or site closure decisions, then sampling sooner after installation would be acceptable. To obtain data for risk decision making, soil vapor probes consisting of tubing buried in a sand pack should be allowed to equilibrate for at least 8 hours before sampling.

If rotary drilling or percussion methods are used to place the tubes, longer periods of time are required for the sand pack to equilibrate with the soil vapor. The use of air knives is not recommended. To determine the equilibration time, a test of concentration versus time can be used to determine when values stabilize. Another method is to purge the soil vapor and monitor the soil vapor concentration with a portable meter. When the concentrations stabilize, equilibrium is assumed and a sample can be collected for analysis.

G.10.8 Probe Surface Seals

For collection systems with large purge volumes or designed to collect large sample volumes, it is often necessary to seal the probe at the surface. Seals may also be necessary for small volume systems if the soils are extremely porous and the sampling depth is close to the surface (less than 3 feet). The most common sealing technique is to grout the surface contact of the probe. If any other materials are used to seal the probe, they should be tested to ensure they are free from any COCs.

G.10.9 Purging the Probe and Sampling Train

The sample collection equipment used for soil vapor surveys has an internal volume that is filled with air or some other inert gas prior to insertion into the ground. This internal volume, often called the dead volume, must be completely purged and filled with soil vapor to ensure that a representative soil vapor sample is collected. If tubing is installed and sampled the same day as installation, the air volume of the sand pack should also be included in the total system volume. Probe purging is typically accomplished using a pump or a syringe equipped with a three-way valve (see Figure G-7, Purging a probe with a plastic syringe). Syringes are an inexpensive and simple approach for purging small volumes up to 1 liter. For larger purge volumes, a pump with variable flow rates and a flowmeter is more efficient.

At a minimum, enough vapor should be withdrawn prior to sample collection to purge the probe and collection system of all ambient air or purge gas (1 purge volume). Some agencies define the number of purge volumes in their guidance.

While it is important to collect enough vapors to purge the system, collecting too much vapor can also have drawbacks. The larger the quantity of soil vapor withdrawn, the greater the potential that atmospheric air might be drawn into the probe, especially when sampling at shallow depths (less than 3 feet). Thus, sampling equipment with small internal dead volumes offers advantages over systems with larger dead volumes because the former systems require significantly less vapor to be withdrawn when purging the system.

Prevent Atmospheric Short-Circuiting

- *Soil gas probes should be sealed above the sampling zone with a bentonite slurry to prevent outdoor air infiltration, and the remainder of the borehole backfilled with clean material.*
- *For multiple probe depths, the borehole should be grouted with dry and hydrated bentonite between probes to create discrete sampling zones, or else separate nested probes should be installed (Figure G-6).*
- *Set a protective casing around the top of the probe tubing and grout in place to the top of bentonite; slope the ground surface to direct water away from the borehole.*

Since soil vapor data are often interpreted in a relative fashion, it is important that the purge volume be consistent for all samples collected at the same depth from the same site.

G.10.10 Flow Rate and Applied Vacuum During Sampling

To minimize the potential desorption of contaminants from the soil, soil gas samples should be collected using techniques that minimize the vacuum applied to the soil. Higher vacuums also increase the potential for leaks in the sampling system. Most agencies require flows less than 200 mL/min.

Figure G-10. Purging a probe with a plastic syringe.

Source: H&P Mobile Geochemistry.

Limiting flow rate may not be necessary in soils permeable enough to maintain vacuums less than 15% of atmospheric (about 5 inches of Hg, 60 inches of H_2O). Studies have measured soil gas concentrations over different flow rates ranging from 100 mL/min to 100 L/min at a PHC contaminated site (USEPA 2010b; USEPA 2007c; McAlary and Cramer 2006). No significant differences in measured concentration were observed. This result suggests that for relatively coarse-grained soils (high permeability), flow rate does not appear to be an important variable for soil gas concentration.

Some U.S. agencies require applied vacuums at the probe to be less than 10 to 12 inches of Hg (100 inches water). A simple qualitative method is typically all that is necessary to estimate if there is little permeability and if too much vacuum is likely to be created during sampling. Connect a 20 cc to 50 cc gastight syringe to the probe, and pull on the plunger. If the plunger can be pulled easily, there is high permeability and the applied vacuum will likely be small. If the plunger is hard to pull (compared to pulling outside air) or if the plunger retracts towards the probe after being released, then there is likely too little permeability to obtain an uncompromised sample.

For low permeability soils, a quantitative method is preferable using a vacuum gauge placed between the probe and sample container (see Figure G-10). If canisters are being used to collect the soil vapor sample, be aware that a gauge on the Summa canister measures the vacuum in the canister, not the vacuum applied to the soil vapor probe, so an additional gauge must be emplaced in the sampling train between the flow regulator on the canister and the probe (Figure G-12). For gauges located on the flow restrictors, check with the supplying laboratory to determine whether they measure the vacuum in the canister or vacuum at the probe tip. Vacuum reading should be recorded on a sampling log sheet and compared to specifications set by the oversight agency (typically less than 10 inches of Hg).

G.10.11 Leak Tests

When quantitative soil vapor data are desired (such as for risk assessments), leak testing the system as a quality assurance measure is strongly recommended and required by many state agencies. Leaks in the sampling train or leaks of ambient air into the probe tubing can result in diluting the soil vapor samples with ambient air and will result in underestimating actual contaminant concentrations in subsurface soil gas. Excessive vacuum conditions resulting from low porosity soils or high moisture content soils may exacerbate the potential for ambient air leakage. Two methods of leak detection are recommended: (1) performing a “shut-in” test of the sampling train and applying a leak detection compound or water to the vapor probe at the surface or (2) applying a tracer gas over the probe and over the entire sampling apparatus. Review any local VI sampling guidance for specific requirements for leak testing.

G.10.11. Method 1 – Shut-in Test and Leak Detection Compound at Surface

The shut-in test is performed by sealing the sampling train from the vapor probe tubing termination to the sample container (such as a Summa canister or Tedlar bag) and applying a vacuum to the sampling train. The applied vacuum should hold steady (not decrease) for at least 30 seconds. The start and end vacuum should be recorded and reported.

Figure G-11 shows an example of a simple sampling train arrangement for a shut-in test. The system consists of a two-way valve at the vapor probe termination, a vacuum gauge, and a three-way valve on a gastight syringe. The two-way valve is closed. A vacuum is then applied by drawing back the syringe plunger and the three-way valve is turned to shut off the syringe. The vacuum in the sampling train is then monitored for at least 30 seconds. If the sampling train does not hold the vacuum, then all connections should be rechecked and the shut-in test repeated.

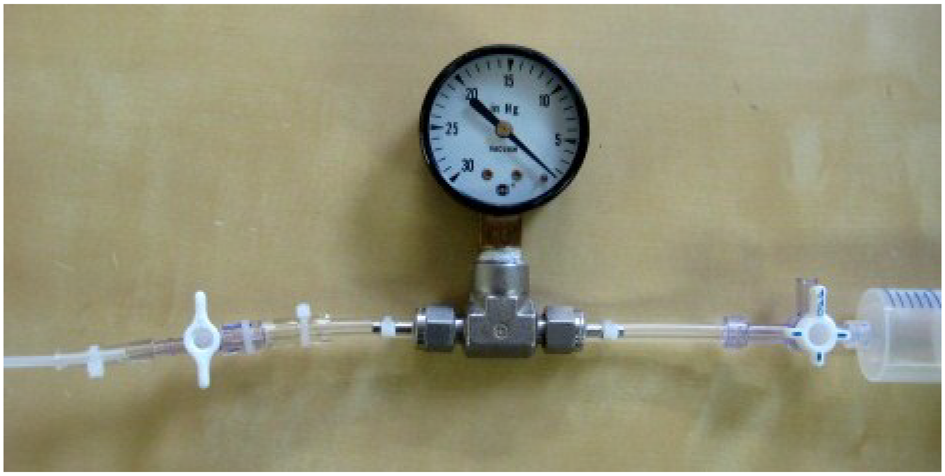


Figure G-11. Simple sampling train arrangement for a shut-in test using a syringe as the vacuum source.

Source: H&P Mobile Geochemistry.

Once the shut-in test has been successfully completed, a leak check compound or water is applied to the surface completion of the probe. The leak check compound can be applied by wetting a towel with a liquid compound (such as isopropanol) and placing it around the probe tubing at the ground surface (see Figure G-12) or by placing a small shroud over the surface completion and filling the shroud with a tracer gas (such as helium; Figure G-13). If water is used, place a pool of water around the probe and watch for changes in the water level. Refer to Appendix J, Section 5.2, in the New Jersey (2013a) guidance for more details of this method.

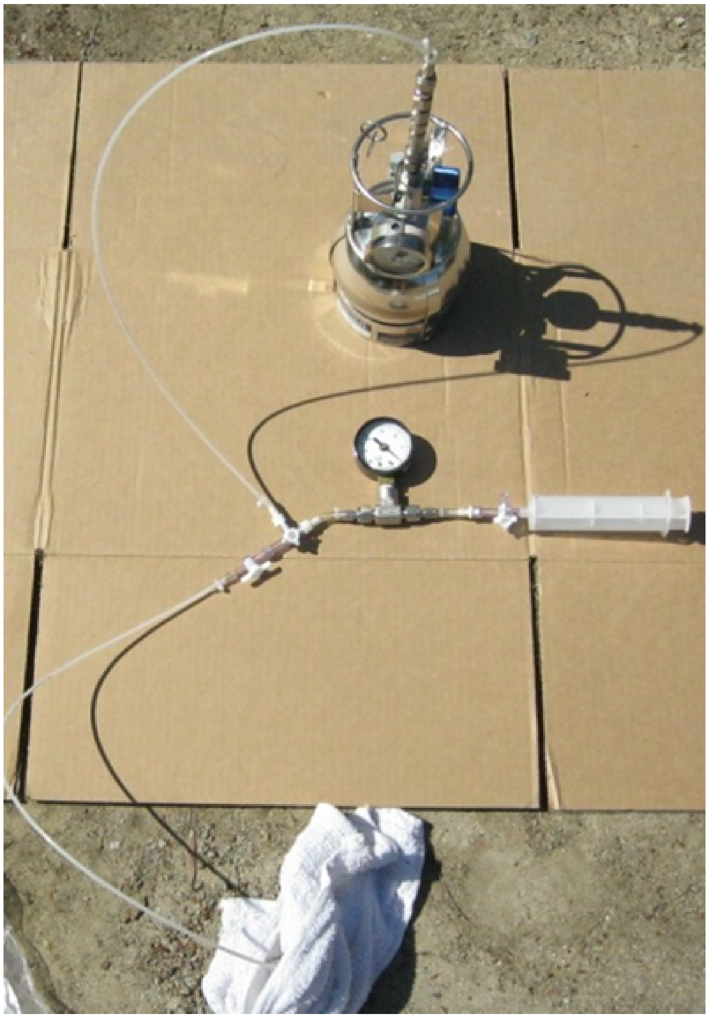


Figure G-12. Sampling arrangement showing probe tubing, leak check compound soaked into towel covering the probe at the ground surface.

Figure G-13. Gas shroud over Vapor Probe Surface Completion. System consists of shroud (blue bucket), helium cylinder, field helium detector and syringe with vacuum gauge for purging.

Source: H&P Mobile Geochemistry.

The following video includes a demonstration of soil vapor sample collection with a Summa Canister:

Play video: Soil Vapor Sample Collection with Summa Canister

G.10.11.2Method 2 – Covering Sampling Train & Probe with Gaseous Tracer

Method 2 involves enclosing the entire sampling apparatus, including sample container, all tubing and connections, and the vapor probe surface completion in a shroud, which is filled with a tracer (see Figure G-14). Disadvantages of this method are that it requires a large amount of gaseous tracer and it is difficult to turn on, turn off, and adjust the collection device once it is under the shroud.

Figure G-14. Covering the entire sampling system and probe with a shroud.

Source: H&P Mobile Geochemistry.

G.10.11.3 Testing the Soil Vapor Sample for Leaks

For the methods described above, measure both the concentration of tracer compound in the shroud and the concentration of tracer compound in the soil vapor sample in the field using a hand-held field meter or with an on-site lab. If canisters are being used, measure the tracer in the probe tubing after purging and prior to opening the canister. If the tracer concentration in the probe tubing is greater than 15% (note: some agencies have a lower allowed leak criterion) of the concentration in the shroud, then the leak should be found and corrected before opening the canister. After the canister has filled, test the probe tubing again. If the tracer concentration in the probe tubing is greater than 15% of the concentration in the shroud, then the sample in the canister may be compromised. The soil vapor sample in the canister should then be tested for the tracer at the laboratory. Fully document in the sampling log sheets both the shroud and probe tracer concentrations. Note that this procedure is more difficult to use if the entire sampling train is under the shroud (Method 2).

An alternative procedure is to first collect the sample in a Tedlar bag. Test the Tedlar bag for the tracer compound. If the tracer concentration in the Tedlar bag is less than 15% of the concentration in the shroud, the sample is considered valid and can be shipped to the laboratory or downloaded on site into a canister (see following section on sampling into Tedlar bags). If the tracer concentration in the Tedlar bag is greater than 15% of the concentration in the shroud (note: same agencies have lower allowed leak criterion), the sample is considered compromised, the leak should be found and corrected, and the sampling procedure repeated (the same Tedlar bag can be reused).

G.10.11.4 Selection of Leak Detection Compound

The selection of leak detection compounds is site- and analysis- specific. Considerations include whether it is a known or suspected contaminant at the site, or included in the laboratory's list of target analytes for the method being used, and whether it can be monitored with portable measurement devices. Common leak detection compounds are isopropanol (rubbing alcohol), helium, and fluorinated ethanes (found in "duster" spray cans found at most office and computer supply stores). Each of the compounds has a variety of advantages and disadvantages (see Table G-2). Always check with the laboratory regarding potential interferences of leak-check compounds.

Isopropanol is readily available, inexpensive, and does not require the use of a shroud, as it can be applied to a towel placed around the vapor probe. Isopropanol can also be used with a shroud by placing the towel inside the shroud. A further advantage of isopropanol is that it can be detected using methods TO-14/15/17 or SW8260 and with a portable PID. Because it is handled at extremely high concentrations, however, it is possible to introduce high concentrations into the sample, which can render the sample useless by raising analytical reporting levels. When using liquid tracer compounds, take extreme care not contaminate the sampling train parts with tracer compound. Gloves should always be worn when handling the tracer compound, and a different pair of gloves should be worn when handling/assembling sampling train components. Although isopropanol can be detected by a portable PID, the PID might be reading other compounds in the soil vapor (such as BTEX) and give a false positive.

Fluorinated ethanes are readily available and simpler to handle than helium cylinders and can be detected using methods TO-14/15/17 or SW8260. However, like isopropanol, selective field meters are not readily available.

Helium concentrations can be readily measured in the field using a selective handheld meter. However, most helium meters such as a thermoconductivity He detector, also respond to methane, so if methane is suspected at the site, false positives on the helium meter are possible A further advantage of helium is that it’s presence in a sample, even at high concentrations, will not interfere with TO-14/15/17 or SW8260 analysis for VOCs. When using helium gas as a leak detection compound, ensure appropriate purity of the helium. Also keep in mind that the laboratory must run a separate analytical method to analyze for helium.

Table G-2. Comparison of common leak check compounds

Compound	Advantages	Disadvantages
Isopropanol	• Inexpensive and readily available • Detected using method TO-14/15/17 and SW8260 • Can be used without a shroud	• Cannot be selectively measured in the field • High concentrations can interfere with laboratory analysis
Helium	• Can be selectively measured in the field with a portable meter • Will not interfere with TO-14/15/17 and SW8260 analysis	• Requires valves and fittings and cylinder • False positives on meters caused by methane
Fluoro-ethanes	• Inexpensive and readily available • Detected using method TO-14/15 and SW8260	• Cannot be selectively measured in the field with a portable meter • High concentrations can interfere with laboratory analysis
Sulfur hexafluoride (SF_6)	• Ability to check for leaks with on-site instrument with very low detection limits	• Field instrument subject to interference with chlorinated solvents • Cannot be analyzed by TO-15 • This is a greenhouse gas and use may be limited in some states.

G.10.11.5 Collection of Samples with Sampling Assemblies

Sampling assemblies (such as connecting tubing, fittings, gauges, and flow controllers) should be confirmed to be leaktight using a shut-in test or tracer compound as described in the previous section and should be cleaned (and possibly blank tested) between soil gas samples if reused. Sample tubing should generally not be reused.

G.10.12 Active Soil Gas Sample Collection into Passivated (Summa) Canisters

After purging, the canister should be connected to the probe tubing, but not opened, before applying the leak detection compound.

A vacuum gauge is used to measure the canister vacuum prior to sampling and the final vacuum after sampling. Prior to sampling, check the canister to ensure that sufficient vacuum is present. Laboratories typically place a vacuum of approximately 28 to 30 inches Hg on the canisters prior to shipment to the site. Field gauge readings, however, may differ. Field gauges typically have an accuracy of +/-5 psig. Additionally, sampling at altitude may impact field gauge readings (that is, for each 1,000 feet of elevation gain, the gauge may decrease by 1 inch Hg. For example, a canister reading 30 inches Hg at sea level may have a vacuum reading of 25 inches Hg at 5,000 feet).

Once the leak detection compound is applied, an aliquot of the soil vapor should be tested for the tracer compound before opening the canister. This test is typically done by having a sampling port next to the canister connection (using a Swagelok tee connection or a three-way plastic luer valve). If the leak detection compound is below acceptable levels, the canister can then safely be opened. If the leak detection compound is above acceptable levels, the canister is not opened, is disconnected, and the source of the leak is found and corrected. Using this procedure avoids filling canisters with soil vapor samples that fail the leak detection test. If a large-volume canister is being used (over 500 cc) or if the sample depth is very close to the surface (for example, subslab samples), the soil vapor probe should be retested for the leak detection compound after the canister is filled. This retest is necessary because the canister cannot be tested for the leak detection compound in the field, so if the soil vapor is leak free after the canister is filled, it is reasonable to conclude the sample in the canister is leak free also.

Flow regulators, available from the laboratory, are placed on the canisters to reduce the flow. Canisters should not be cooled or left in the direct sunlight during storage or transport for analysis.

Soil Gas Grab Samples

For soil gas grab samples, it is recommended that the canisters be filled completely to 0 psig. The lack of a pressure gradient (no residual vacuum in the canister) minimizes the chance of leakage between sample collection and sample analysis.

G.10.13 Active Soil Gas Sample Collection into Gastight (Tedlar) Bags

After purging and application of the leak detection compound over the probe, soil vapor can easily be transferred from the soil vapor probe into a gastight bag using a syringe (see Figure G-15).

Other devices such as a vacuum chamber (available from SKC, Inc. and other vendors) can also be used to fill gastight bags, but pumps upstream of the gastight bag should not be used because cross-contamination between samples will occur. The gastight bag should be filled, while being careful not to overinflate and potentially compromise the bag seals.

Using gastight bags offers the advantage of testing the actual soil vapor sample that will be later analyzed for VOCs for the leak detection compound (this is not possible with canisters as described previously). Connect the portable meter directly to the gastight bag and measure the tracer compound. If it is below acceptable levels, then the soil vapor sample is valid and the remaining amount in the gastight bag can be sent for analysis. If it is above acceptable levels, the gastight bag is easily emptied and can be reused for the same soil vapor sample location once the leak is found and corrected.

Storage time in gastight bags for most PHCs is approximately 48 hours. Gastight bags are generally not suitable for naphthalene. Not all gastight bags are the same, however, so use a bag that has been shown by the manufacturer or the laboratory to be stable for the compounds of interest. Care must be taken to not puncture or compress the bag during storage. It is best, but not necessary, to store the sample in the dark. The bags should never be chilled. If storage times longer than 48 hours are anticipated, or if a more durable storage container is desired, the sample in the gastight bag can easily be transferred into a passivated canister (see Figure G-13).

Figure G-15. (a) Filling a gastight bag using a syringe and three-way Luer valve. Top of the valve is connected to the probe tubing. (b) A vacuum chamber (sometimes called a lung-box) to inflate gastight bags.

Source: H&P Mobile Geochemistry.

Figure G-16. Transferring soil vapor sample from a gastight bag into a 400 cc canister.

Source: H&P Mobile Geochemistry.

Compound-specific isotope analysis (CSIA) can be used in VI investigations to help determine the source of VOCs in indoor air (VI versus indoor VOC source). The CSIA procedure relies on differences in the isotope signature between the subsurface VOC source and potential indoor VOC sources. Biodegradation of VOCs in the subsurface commonly results in an isotope fractionation effect. In contrast, isotope signatures from indoor VOC sources tend to fall within a narrow, and different, range. Sites with evidence of biodegradation are, therefore, likely to have subsurface sources with isotope signatures that are distinct from potential indoor sources. The sampling protocol for a CSIA evaluation involves sampling the subsurface source (for example, groundwater or soil gas) and indoor air, comparing the sample results, and comparing the indoor air results to the known isotope signature from indoor VOC sources.

G.10.14 Active Soil Gas Sample Collection into Gastight Glass Containers

Gastight glass vials and glass containers with valves or stopcocks can also be used for sample collection. Prior to sampling, the gastight vial should be evacuated to a vacuum of approximately -26 to -30 inches Hg. This can be easily done with an electric vacuum pump or with a hand vacuum pump that is typically available at automotive part stores (they are used for automotive brake repairs). A soil vapor sample is withdrawn using a syringe as described previously, except that a needle is placed on one side of the three-way plastic luer valve. The needle is pushed through the rubber septum on the evacuated vial and the soil vapor sample pushed into the vial. The vial is typically overpressured by adding a volume larger than the vial volume.

An evacuated glass container with a valve (BottleVac) is commercially available. This unit is filled similarly to an evacuated metal container. Glass bulbs are generally filled by allowing the soil vapor to flow through the bulb and closing the stopcocks on each end.

Since it is difficult to perform these sampling procedures under a shroud, leak detection is best done by performing a shut-in test on the sample train and then covering the probe with a small shroud or towel (leak test method 1). The soil vapor is tested for the leak detection compound before and after collecting the sample as described previously for canisters.

G.10.15 Active Soil Gas Sample Collection onto Adsorbents

Soil vapor can easily be transferred from the soil vapor probe onto an adsorbent using the same syringe and three-way plastic valve used for Tedlar bags (see Figure G-17). The adsorbent tube is connected between the probe and the syringe so that the syringe pulls the soil vapor through the adsorbent. Other devices such as a low-flow pump can also be used to pass soil vapor over the adsorbent, but pumps upstream of the adsorbent should not be used as cross-contamination between samples will occur. Pumps should be calibrated before use to ensure correct measurement of volumetric flow. Also, the pump flow rate might change if the soil permeability changes. Sample flow rate should be to a flow rate of up to 50 mL/min for sampling in tight formations, and up to a maximum of 200 mL/min for sampling in permeable formations.

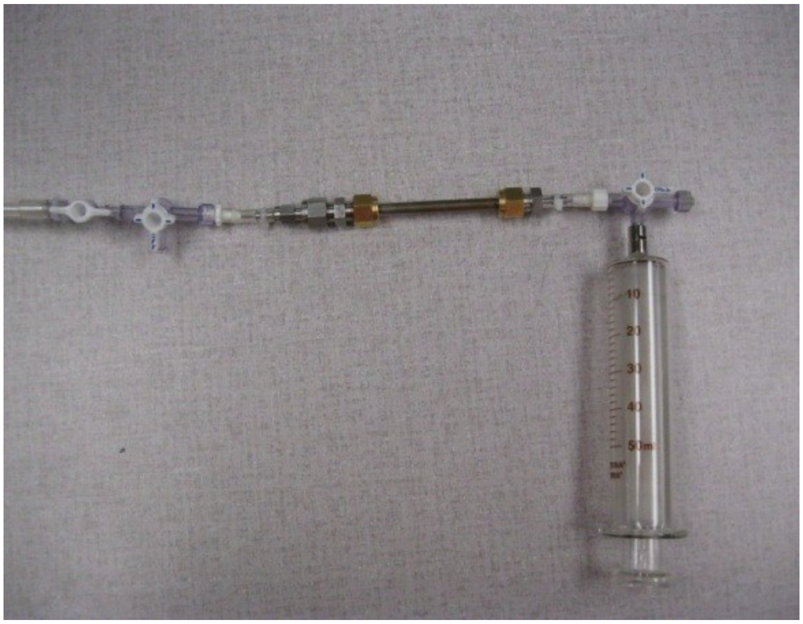


Figure G-17. Sampling arrangement for adsorbent tubes.

Source: H&P Mobile Geochemistry.

The laboratory should provide guidance on the type of adsorbent for the VOCs of interest and on required tube sampling volumes based on their detection limits. Often, two tubes are placed in series in case there is any breakthrough of the COCs from the first tube. An alternative approach is to collect two tubes at each sampling location: one sample at the laboratory recommended sample volume to reach the detection limits and a second sample collected at 10% of the laboratory recommended sample volume. The lower volume sample is then available for analysis if the higher volume sample is saturated by PHCs. The sample volumes might be adjusted downward if high concentrations are expected or detected at the sampling location.

Leak detection is best performed using the shut-in test procedure for the sampling train and a shroud or towel over the surface of the probe.

After sampling, the tubes are sealed, transferred to the laboratory supplied sample container, and stored with ice within a cool box.

G.10.16 Sample Containers and Storage

For fuel related compounds (TPH, BTEX) and biogenic gases (CH_4, CO_2, and O_2), allowable containers include Tedlar bags, gas tight vials (glass or stainless steel), and passivated stainless steel canisters (Summa). Tedlar bags are generally not considered to be reliable for more than 48 hours, but some agencies may have different requirements.

Local Requirements

Check local guidance to determine whether more than one round of soil vapor sampling is required by the agency, regardless of the measured values.

For halogenated compounds (such as TCE, TCA, and PCE), allowable containers must be gas tight, but also dark to eliminate potential effects due to photo destruction. Adsorbents are suitable for most VOCs and SVOCs; however, multiple adsorbents may be required to deal with complex mixtures.

Be aware of sample storage requirements. If stored samples are to be subjected to changes in ambient pressure (such as shipping by air), gastight vials or canisters are recommended. To prevent the chances of rupture, Tedlar bags should only be partially filled if shipped by air. Allowable storage times in canisters vary with each state. Most agencies require analysis within 14 days of collection. It is not necessary to chill soil gas samples during shipping and storage. However, method TO-17 requires adsorbent tubes to be stored at less than 4° C.

G.11 Subslab Soil Gas Samples (Interior)

Subslab samples refer to active or passive soil gas samples collected from immediately below a slab on grade or a basement floor slab. The procedure involves drilling through the concrete slab and collecting a soil gas sample for field or laboratory analysis. Subslab soil gas samples are sometimes collected concurrently with indoor air samples so that the subslab concentrations can be directly compared to indoor air concentrations collected at the same time.

A typical subslab probe is constructed from small diameter (⅛ inch or ¼ inch outer diameter) stainless steel or another inert material and stainless steel compression fittings. Other probe designs consist of a barb fitting at the surface, which offers advantages in that the fitting is less likely to break loose from the cement upon sampling. The probes are cut at a length to either float in the slab or to extend just to the base of the slab (see Figure G-19). If repeated sampling is anticipated, surface completions may need to be flush with the surface (trip-proof) and cosmetically clean, especially in residences.

Figure G-18. Installation of subslab soil gas sample port.

Source: Kansas DHE.

Special considerations for subslab soil gas samples include:

- Subslab samples should be avoided in areas where groundwater might intersect the slab.
- Underground utilities (for instance, electric, gas, water, tension rods, or sewer lines) should be located and avoided.
- If a vapor barrier already exists under the slab, subslab sampling might puncture the barrier, so the hole must be carefully resealed after monitoring is complete.
- For basements, primary entry points for vapors might be through the sidewalls rather than from below the floor slab so subslab samples might need to be augmented with samples through the basement walls.
- Sample collection and analysis is analogous to other types of soil gas sampling as described below, however risk-based screening levels for subslab samples are lower than deeper soil gas samples, requiring an analytical method with lower detection limits.
- Recent studies have confirmed that temporal variations in subslab soil gas concentrations are usually less than a factor of two and occur over longer time scales (weeks), so short duration samples are representative (5 to 30 minutes).
- As a cautionary note, there can be large spatial variability in subslab soil gas samples by factors of 100 or more.

A standard operating procedure for subslab sampling was published by USEPA in March 2006 (USEPA 2006a). NJDEP (2005) has a modified version of these procedures in its guidance document. There is also a standard operating procedure in the EPRI handbook (2005).

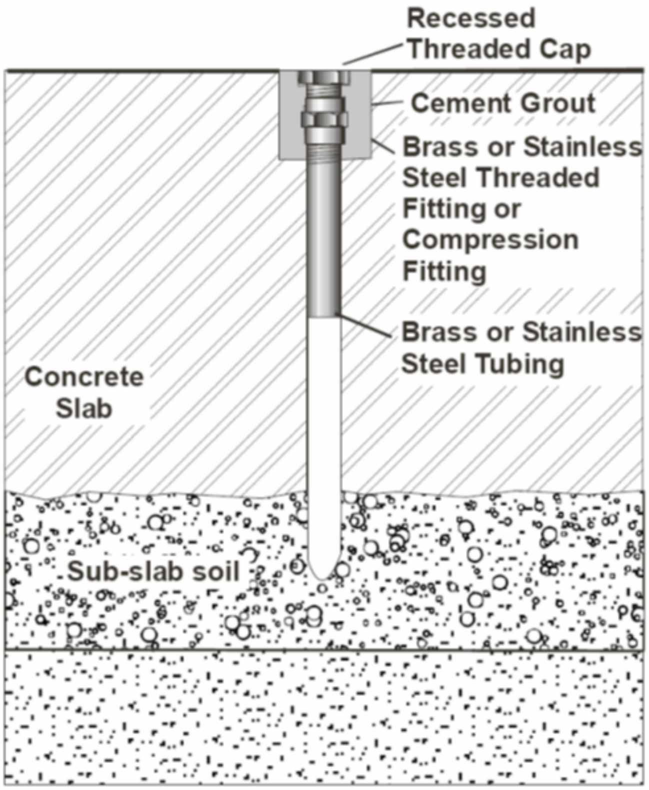


Figure G-19. General schematic for installation of subslab vapor probes.

Source: USEPA 2006.

G.12 Analysis Methods

G.12.1 Overview of Methods for Vapor Samples

A variety of analytical methods are available to measure vapor samples (soil gas, ambient air and indoor air) all of which can give accurate results when followed with appropriate QA/QC (Table G-4).

The primary criteria for choosing the appropriate method are:

- COCs
- concentrations that may be encountered during sampling
- required detection level and other DQOs
- sampling logistics
- cost

Discussions with the laboratory should be included during the planning stages of the investigation to ensure the appropriate analytical method is used.

Method TO-15 is commonly used for VOCs in indoor and ambient air samples. A driver behind using these methods is the ability to achieve very low reporting limits (RLs). Using the method that can achieve the lowest reporting limits is not always the best or most viable option. TO-15 uses a GC/MS. The MS can be run in two different modes: full scan and selective ion monitoring (note that some compound selectivity and the ability to identify unknowns may be lost in the use of selective ion monitoring analysis due to limiting the masses scanned). Standard TO-15 is normally run in the full scan mode and can give a list of approximately 70 compounds with RLs ranging from 0.2 to 0.5 parts per billion by volume (ppbv). This analyte list and RLs are generally more than sufficient when analyzing soil gas. In the selective ion monitoring mode, TO-15 has the ability to reach RLs ranging from 0.002 to 0.010 ppbv for a smaller list of approximately 12 to 15 compounds. Compound lists and achievable reporting limits in the two different modes are laboratory specific, so check with the laboratory to determine which approach they recommend in order to meet DQOs. Because soil gas samples generally have COCs at higher concentrations than the selective ion monitoring method can calibrate to, the selective ion monitoring method is rarely needed for soil gas samples.

Sorbents based methods (TO-17) allow for the capturing of VOCs and SVOC's beyond the capability of TO-15; TO-17 and can be used for compounds in the C3–C28 volatility range. Either method can be used to capture naphthalene based on the laboratory capabilities. For light-end PAHs and diesel range organics, TO-17 is the appropriate method. TO-15 is only appropriate for TPH as gasoline, but TO-17 can be used for TPH gasoline-range and TPH diesel-range organics.

QA/QC protocols may vary greatly between laboratories, so the practices should be reviewed and specified in the work plan prior to data collection. Data validation methods (when required by the regulatory agency) should also be specified and approved in advance. More information is presented in Section G.12.

G.12.2 On-Site Analysis

On-site analysis provides real-time detection of VOCs from any vapor migration sources or pathways, allows additional sampling locations to be added (spatially or vertically) based upon the real-time data, allows recognition of suspect data, and enables measurement of the leak-test compound to ensure valid soil gas samples are collected.

Simple portable instruments can provide both qualitative and quantitative data depending upon the compound and the required detection levels. Field screening with handheld PIDs or FIDs enables rapid screening for vapor migration routes around and into structures. Most field screening instruments, however, are limited to the ppmv range, which does not provide sufficient sensitivity for vapor intrusion investigations. Quantitative O_2, CO_2, and CH_4 data are possible from handheld portable meters for concentrations in the percent range. Helium detectors are available with a range of 0.01% to 100% by volume.

For lower detection limits, mobile laboratories equipped with laboratory grade instruments, including gas chromatographs and mass spectrometers, are capable of fully quantitative results meeting method required QA/QC and detection limits as low as 1 to 100 µg/m^3. Other instruments, such as portable GC/MS and small-footprint gas chromatographs are also available.

G.12.3 TPH Analysis of Vapor Samples

There are a variety of methods to quantify PHCs in vapor samples. In selecting a method, it is important to understand what kind of information is needed and what the ultimate use of the data will be. Some methods will provide a TPH value, and other methods will provide specific fractions (aliphatic hydrocarbons and aromatic hydrocarbons). These fractions typically are reported for a certain carbon range, such as C5–C8 or C9–C12. Table G-3 lists some of the more typical analyses that provide either a TPH value or a petroleum fraction value. It is best to verify with the oversight agency whether they have a required or preferred method for PHC analysis. If no method is specified, it is best to check with the laboratory on the following items when choosing the appropriate method for your site.

A checklist of items to address with the laboratory includes the following:

- suspected source of the contamination and source of the sample (such as a soil vapor sample from a leaking underground storage tank release of gasoline or diesel)
- COCs, such as TPH as gasoline, benzene, MTBE, or others
    - screening levels for the COCs
    - sampling protocols will be followed, including which tracer gas will be used
- with the tracer gas, reporting limit requirements and whether the laboratory may flag the data as estimated if there are high levels
- if requesting TPH, the compound range needed (gasoline, diesel, other)
- calibration standard to be used and how it is quantified
- whether nonhydrocarbon compounds will be subtracted from the TPH reported value

Table G-3. Summary of analytical methods used for quantitation of PHCs in the vapor phase

Method name	Collection device	Sample introduction technique	Detector	Matrix matched calibrationstandards	Quantitation method	Additional information from analysis
TO-3	Tedlar Bag, Canister, Glass vials	Vapor transferred direct to trap	GC/FID	Yes, vapor phase	Total area for a defined carbon range fraction	No
TO-13A	Sorbent tube	Solvent extraction	GC/MS		Total area for a defined carbon range fraction	Yes
TO-14A	Passivated canister	Vapor pulled to trap	Various	Yes, vapor phase	Total area for a defined carbon range fraction	Yes, if MS is used
TO-15	Passivated canister	Vapor pulled to trap	GC/MS	Yes, vapor phase	Total area for a defined carbon range fraction	Yes

Table G-3. Summary of analytical methods used for quantitation of PHCs in the vapor phase (continued)

Method name	Collection device	Sample introduction technique	Detector	Matrix matched calibrationstandards	Quantitation method	Additional information from analysis
TO-17	Sorbent tube	Thermal desorption	GC/MS	Varies, liquid or vapor phase	Total area for a defined carbon range fraction	Yes
8015B/ 8015D	Tedlar bag, canister, glass vials	Purge and trap	GC/FID	Varies, liquid or vapor phase	Total area for a defined carbon range fraction	No
8260B	Tedlar bag, canister, glass vials	Purge and trap	GC/MS	Varies, liquid or vapor phase	Total area for a defined carbon range fraction	Yes
MADE-P APH	Passivated canister	Vapor pulled to trap	GC/MS	Yes, vapor phase	Total area for a defined carbon range fraction	Yes

G.12.3.1 Interferences from Leak Check Compounds

Compounds used as tracer gases during leak check procedures can be problematic to TPH analysis. Certain tracer gas compounds (isobutane, isopropyl alcohol) have a direct impact on the quantitation of PHCs if present at elevated concentrations (greater than 0.01%) by causing (a) a false positive, and (b) elevated reporting limits due to significant dilutions performed by the laboratory. Other tracer gas compounds used (1,1-difluoroethane, sulfur hexafluoride) may not cause a false positive, but may also lead to elevated reporting limits if present at elevated concentrations. Helium is the least problematic tracer gas because it can be measured in the field and does not interfere with PHC analysis for either (a) or (b) listed previously. Helium may require additional analysis at the laboratory.

***Note**: Party grade helium may contain hydrocarbons that could interfere with sample analysis.*

G.12.3.2 Interferences from Nonpetroleum Compounds

Nonpetroleum compounds are detected using either the FID or MS detectors. Compounds such as oxygenates (ethanol, MTBE), methane, CVOCs, and the leak/tracer compound can lead to an increase in the reported TPH value if they are not subtracted from the TPH result by the laboratory.

Naturally occurring non-PHCs, such as limonene and pinenes, can typically cause a high bias in the C9–C12 hydrocarbon range. Other site-related contaminants (CVOCs) and typical indoor air background analytes (such as ethanol, acetone, and 2-butanone) also cause a high bias result, typically in the C4–C8 hydrocarbon range. A study comparing results from analysis by USEPA Method TO-15 to results from the Massachusetts APH method showed high bias in the APH results for both C5–C8 and C9–C12 ranges, in both soil gas and indoor air samples (Goshorn et al. 2012). The various methodologies that are used for PHC quantitation may or may not provide guidance as to how to address the nonpetroleum analytes. In addition, methods that use an FID may not be able to identify the nonpetroleum analytes, whereas methods using the MS detector can identify the nonpetroleum analyte via their mass spectrum and thus exclude the analyte from the PHC quantitation.

G.12.3.3 Lead Scavengers and Oxygenates

CVOCs typically used as lead scavengers (1,2-dichloroethane, ethylene dibromide) in leaded gasoline supplies can typically be analyzed using methods 8260, TO-15, or TO-17. Oxygenates (ethanol, tert-butyl-alcohol, MTBE, tert-amyl-methyl-ether, tert-butyl-ethyl ether and others) can also be readily analyzed using the same methods. Some methods may not reach necessary screening levels, so confirm with the laboratory which methods will meet site-specific screening levels.

G.12.3.4 Naphthalene, PAHs, and Semivolatiles in Air

A variety of methods are currently being used to analyze for naphthalene, such as 8260, TO-15, TO-17, and TO-13. Technically, naphthalene fails the vapor pressure requirement stated in method TO-15 (greater than 0.5 inches of Hg), but many laboratories have demonstrated adequate compound recoveries using this method. It is best to verify with the oversight agency as to what is the preferred method for naphthalene analysis.

For hydrocarbon carbon ranges (C13–C28) and PAHs considered in the semivolatile range, a sorbent-type sampling and analysis is better suited. Method TO-13A is specific for the quantitation of PAHs in air, and method TO-17 can be used for lighter-end PAHs as well as diesel range hydrocarbon analysis.

G.12.3.5 Fixed Gases and Methane Analysis

Fixed gases, typically defined as O_2, nitrogen, CH_4, CO_2, and CO, can readily be analyzed using laboratory-based methods that use a thermal conductivity detector for detection, and also using field monitoring devices (landfill gas monitors). ASTM D1945 and USEPA Method 3C are two of the more common analytical methods and can typically detect concentrations as low as 0.1%. These methods can also be used to analyze for helium, which is often used as a tracer gas during leak check procedures in soil gas sampling. Sorbent tube methods (TO-17, TO-13) are not suitable for fixed gas analysis since the sorbents will not readily adsorb fixed gases.

If source determination of methane is needed (landfill gas, thermogenic, or biogenic), isotopic techniques are available.

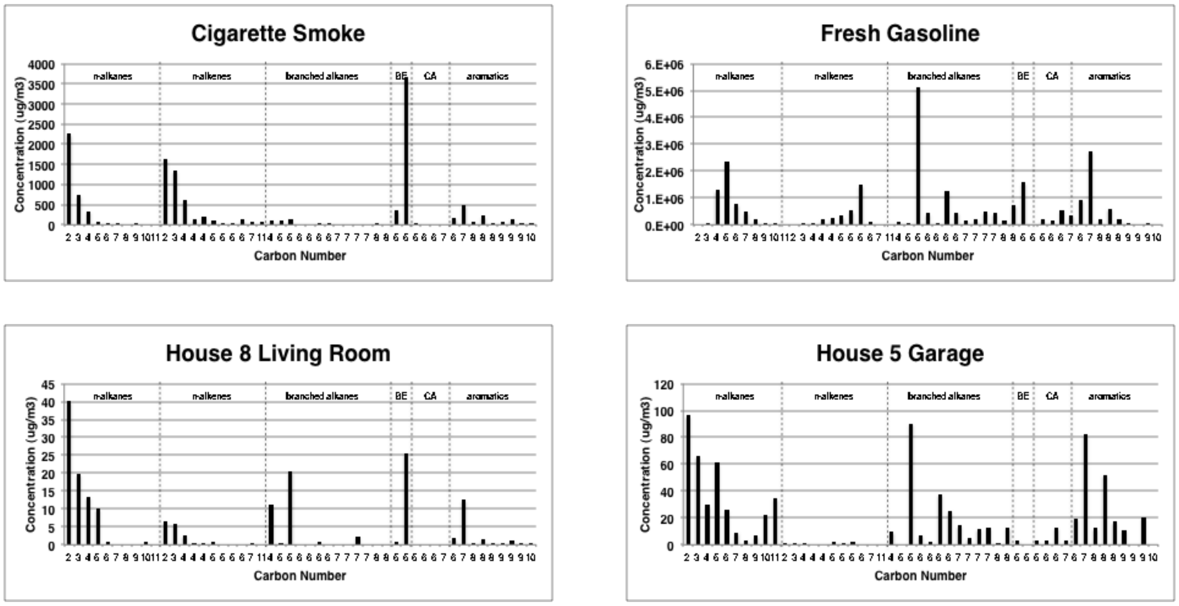
G.12.3.6 1,3-Butadiene Analysis

1,3-butadiene can be a COC at PHC sites and is a by-product of combustion, but not a compound in refined petroleum or crude petroleum. Ultra-low screening values increase the possibility of false positives. Isobutylene, a biogenetically produced gas, can elute closely to 1,3-butadiene on various chromatographic columns and has a similar mass fragment leading to a potential false positive if present at elevated concentrations.

G.12.3.7 Extended Hydrocarbon Analysis Fingerprinting and Forensic Analysis

The hydrocarbon analyte lists that can be reported by Method TO-15 have been extended to include more than 80 individual PHCs covering a carbon range from C5 (n-pentane) to C12 (n-dodecane). The reporting list includes many classes of PHCs such as n-alkanes, branched alkanes, cycloalkanes, alkenes, and aromatic hydrocarbons. Analysis of vapor-phase samples for an extended list of PHCs provides an improved understanding of the actual composition of the sample. These results can be used to more accurately identify the source(s) of the detected PHCs and to evaluate toxicity.

The concentration and distribution of individual PHCs and classes of PHCs in a sample can be used to identify the likely sources of the PHCs. Primary sources can be identified by comparing the overall pattern of detected PHCs between samples (see Figure G-20) or by looking for compounds indicative of specific sources. For example, cigarette smoke contains high concentrations of isoprene (a branched alkene) and weathered gasoline is typically enriched in 2,2,4-trimethylpentane relative to fresh gasoline. In addition, alkenes, which are created during the refining process, are generally absent from crude oil, but present in refined petroleum products such as gasoline. At PVI sites, hydrocarbon fingerprinting analysis may be particularly useful for distinguishing between VI and indoor PHC sources.



VPH Fingerprints for cigarette smoke and Residence 8 indoor air

VPH Fingerprints for fresh gasoline and House 5 garage air

Figure G-20. VPH fingerprints for cigarette smoke vs. House 8 indoor air (left panel) and fresh gasoline vs. House 5 indoor air (right panel).

Source: McHugh et al. 2011.

The hydrocarbon analyte lists that can be reported by Method TO-15 have been extended to include vapor phase PIANO list (paraffin, isoparaffins, aromatics, naphthalenes, and olefins) and additional vapor phase markers for MGP and other distillate fuels. As the carbon number increases over C12, the volatility of the compound limits the performance and recovering of the PHCs from a passivated canister. Method TO-17 samples capture on sorbent with active sampling has some utility in extending the range of the PHCs that can be reported.

Table G-4. Summary of analytical methods for soil gas, indoor, and ambient air samples

Parameter	Method	Sample media/storage	Description	Method holding time	Reporting limit
VOCs					
BTEX, MTBE, TPH	TO-3	Tedlar bag or canister/ambient temperature	GC/FID	3 days Tedlar or 30 days for canister	1–3 µg/m^3
Nonpolar VOCs	TO-14A	Canister/ ambient temperature	GC/ECD/FID or GC/MS	30 days for canister	1–3 µg/m^3
Polar & non-polar VOCs	TO-15	Canister/ ambient temperature	GC/MS	30 days for canister	1–3 µg/m^3
Low level VOCs	TO-15 SIM	Canister/ ambient temperature	GC/MS	30 days	0.011-0.5 µg/m^3
Polar & non-polar VOCs	TO-17[3]	Sorbent tube/chilled <4C	GC/MS	30 days	1–3 µg/m^3
VOCs	8021B modified[4]	Syringe, Tedlar bag, glass vial/ ambient temperature	GC/PID	On-site analysis or up to 30 days (depending on container)	10–60 µg/m^3
VOCs	8260B modified[4]	Syringe, Tedlar bag, glass vial/ ambient temperature	GC/MS	On-site analysis or up to 30 days (depending on container)	50–100 µg/m^3
SVOCs					
SVOCs	TO-13A[3]	High volume collection (may require large sample volume; e.g. 300m^3) /PUF/XAD media/Chilled <4C	GC/MS	Extracted within 7 days of collection; analyzed within 40 days of extraction	5–10 µg/sample

Table G-4. Summary of analytical methods for soil gas, indoor, and ambient air samples (continued)

Parameter	Method	Sample media/storage	Description	Method holding time	Reporting limit
Low level PAHs	TO-13A SIM[3]	High volume collection (may require large sample volume; e.g. 300m^3) /PUF/XAD media/Chilled <4C	GC/MS	Extracted within 7 days of collection; analyzed within 40 days of extraction	0.5–1 µg/sample
SVOCs to C28	TO-173	Sorbent tube/chilled <4C	GC/MS	30 days	1–3 µg/m3
Pesticides & PCBs					
Pesticides & PCBs	TO-4A[3] or TO-10A[3]	High volume collection (may require large sample volume; e.g. 300m^3) /PUF media/Chilled <4C	GC/ECD	Extracted within 7 days of collection; analyzed within 40 days of extraction	Pesticides: 0.5 –1 µg/sample PCBs: 1 – 2 µg/sample
Fixed gases					
Fixed gases (methane, nitrogen, oxygen)	USEPA 3C	Canister or Tedlar bag/ ambient temperature	GC/FID	3 days for Tedlar bag 30 days for Canister	1000–2000 µg/m^3
Fixed cases (methane, nitrogen, oxygen, carbon dioxide, carbon monoxide)	ASTM D-1946	Canister or Tedlar bag/ ambient temperature	GC/TCD/FID	3 days for Tedlar bag 30 days for canister	1000–2000 µg/m^3
Natural gases	ASTM D-1945	Canister or Tedlar bag/ ambient temperature	GC/FID	3 days for Tedlar bag 30 days for canister	1000–2000 µg/m^3
TPH – alkanes					
C4–C24	8015 mod.	Canister or Tedlar bag/ambient temperature	GC/FID	3 days for Tedlar bag 30 days for canister	10 ppmv
C4–C12	8260	Canister or Tedlar bag/ambient temperature	GC/MS	3 days for Tedlar bag 30 days for canister	1 ppmv[3]

Table G-4. Summary of analytical methods for soil gas, indoor, and ambient air samples (continued)

Parameter	Method	Sample media/storage	Description	Method holding time	Reporting limit
C4–C12	TO-15	Canister or Tedlar bag/ambient temperature	GC/FID	3 days for Tedlar bag 30 days for canister	0.1 ppmv

[1] This is not an exhaustive list. Some methods may be more applicable in certain instances. Other proprietary or unpublished methods may also apply.

[2] Reporting limits are compound specific and can depend upon the sample collection and the nature of the sample. Detection limits shown are for the range of compounds reported by the analytical methods.

[3] The indicated methods use a sorbent based sampling technique. The detection limits will be dependent upon the amount of air passed through the media.

GC/MS = gas chromatography/mass spectrometry
GC/FID = gas chromatography/flame ionization detector
GC/TCD = gas chromatography/thermal conductivity detector
GC/ECD = gas chromatography/electron-capture dissociation
VOC = volatile organic compounds
PAH = polycyclic aromatic hydrocarbons
SVOC = semivolatile organic compounds

Table G-5. Matrix of recommendations for various quantitative options to evaluate vapor intrusion

Measurement Approaches	Source at depth (>5ft) directly under building				Shallow source (<5ft) under building				Source in vadose zone adjacent to building				Special conditions			
	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ dirt floor or crawl space	Comm./ Industrial	Undev. Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	Undev, Site	Res. w/ basement or slab-on grade floor	Res. w/ crawl space or dirt floor	Comm./ Industrial	PHCs	Vapor Migration Routes	Wet basement	Very low permeability soils
Shallow groundwater (near water table)	●	●	●	●	●	○	○	○	○	○	○	○	◒	○	●	○
Deep (>5ft) soil gas	●	●	●	●	NA	NA	NA	NA	●	●	●	●	●	○	NA	NA
Shallow (5 ft) soil gas	●	●	●	●	●	●	●	●	●	●	●	●	●	●	NA	NA
Subslab soil gas	NA	●	NA	●	NA	●	NA	●	NA	◒	NA	◒	●	○	NA	●
Vertical profile of soil gas	○	○	○	○	NA	NA	NA	NA	○	○	○	○	●	○	NA	NA
Indoor air	NA	◒	◒	◒	NA	◒	◒	◒	NA	◒	◒	◒	◒	●	◒	◒
Ambient (outdoor) air	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○
Passive soil gas sampling	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	◒	○[1]	◒

Table G-5. Matrix of recommendations for various quantitative options to evaluate vapor intrusion (continued)

Measurement Approaches	**Source at depth (>5ft) directly under building**				**Shallow source (<5ft) under building**				**Source in vadose zone adjacent to building**				**Special conditions**			
	Undev. Site	**Res. w/ basement or slab-on grade floor**	**Res. w/ dirt floor or crawl space**	**Comm./ Industrial**	**Undev. Site**	**Res. w/ basement or slab-on grade floor**	**Res. w/ crawl space or dirt floor**	**Comm./ Industrial**	**Undev, Site**	**Res. w/ basement or slab-on grade floor**	**Res. w/ crawl space or dirt floor**	**Comm./ Industrial**	**PHCs**	**Vapor Migration Routes**	**Wet basement**	**Very low permeability soils**
Emission flux chambers	○	NA	◒	○	○	NA	◒	○	○	NA	◒	○	○	NA	NA	○
Tracers testing for alpha factor	NA	○	○	○	NA	○	○	○	NA	NA	NA	◒	○	○	NA	○
Tracer testing for ventilation rate	NA	○	○	◒	NA	○	○	◒	NA	○	○	○	○	○	○	○
Pressure differential monitoring	NA	○	○	○	NA	○	○	○	NA	○	○	○	○	○	NA	○
Real-time analyzers	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

Table G-5. Matrix of recommendations for various quantitative options to evaluate vapor intrusion (continued)

Measurement Approaches	**Source at depth (>5ft) directly under building**				**Shallow source (<5ft) under building**				**Source in vadose zone adjacent to building**				**Special conditions**			
	Undev. Site	**Res. w/ basement or slab-on grade floor**	**Res. w/ dirt floor or crawl space**	**Comm./ Industrial**	**Undev. Site**	**Res. w/ basement or slab-on grade floor**	**Res. w/ crawl space or dirt floor**	**Comm./ Industrial**	**Undev, Site**	**Res. w/ basement or slab-on grade floor**	**Res. w/ crawl space or dirt floor**	**Comm./ Industrial**	**PHCs**	**Vapor Migration Routes**	**Wet basement**	**Very low permeability soils**
Meteorological data	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○	○

This rating indicates that each tool can be used for the category lower in the hierarchy

[1] This is dependent on the passive sampler device

Key:

● = Primary investigative tool - data can potentially be used as a principle tool for assessing VI

◒ = Secondary investigative tool - can be used to develop CSM and/or as a line of evidence in support of another line of evidence

○ = Optional investigative tool - may be useful to further define VI pathway or as means to focus primary investigative tools

NA = not usually appropriate as an investigative tool for VI assessment

Table G-6. Advantages and disadvantages of various investigative strategies

Measurement	Advantages	Disadvantages	Comments
Deep soil gas (>5 ft. below slab)	• Existing data may already be available for some sites • Less chance of short-circuiting by atmospheric air • Temporal variations in concentration minimal	• Data may not be representative of soil gas concentrations at shallower depths due to intervening soil layers • Does not account for aerobic biodegradation in shallower soil layers	When combined with other data, deep soil gas data can provide evidence of biodegradation as a function of vertical transport distance. However, deep soil gas sampling is conservative for screening purposes.
Shallow soil gas (e.g., <5 ft. below slab or basement floor)	• Standard equipment and approaches have been developed • Media most likely to intrude into receptors • Data can be collected outside the building	• Rate of vapor transport to the building must be estimated • May not reflect subslab concentrations • Greater temporal variability than deeper soil gas data	Building zone of influence must be taken into consideration in sampling design. Shallow soil gas sampling may not be conservative for screening purposes.
Subslab soil gas	• Provides more representative subsurface data for sites with surface releases (e.g., spills & leaks) • Gives concentrations immediately below building and receptors	• May contain contaminants from interior sources • Highly intrusive; requires building access and drilling through slab/floor • Rate of vapor transport into the building must be estimated • Conservative screening levels	Preferred approach of many regulatory agencies Concurrent determination of slab-specific attenuation factor may be useful to interpret data.
Emission flux	• Measure actual contaminant emissions from subsurface • Takes into account all subsurface processes such as biodegradation, advection, sorption	• Equipment and experienced staff may be difficult to find • Selection of representative sampling locations may be difficult • Biased low results if emission "hot spots" are not sampled	This approach is best suited for evaluating future use scenarios on undeveloped land, houses with dirt floor basements or crawl spaces, and to confirm biodegradation in shallow vadose zone (<3' bgs).

Table G-6. Advantages and disadvantages of various investigative strategies (continued)

Measurement	Advantages	Disadvantages	Comments
	• Eliminates interpretation using attenuation factor or model	• Not considered by most regulatory agencies	
Soil gas attenuation (α) factors	• Quick and very easy	• Attenuation factors used for this purpose tend to be very conservative (for instance., <<50th percentile) • Empirical attenuation factors may be biased high due to sources other than VI • No agreed upon attenuation factors for many regulatory jurisdictions	Attenuation factors may be based on empirical measurements of concentration ratios at other sites or on assumed Q_{soil} and building ventilation flow rates.
Slab-specific attenuation factor determination (from subsurface tracer)	• Naturally occurring compounds (for instance., Rn-222) can be used in some cases • Provides a direct measure of attenuation across a slab • Typical values often >10 times lower than default values	• Usually requires separate analytical method than that used for target compounds • If radon is used, investigator may find indoor concentrations exceeding health-risk levels • Radon not present everywhere at levels distinguishable from background	Method assumes that the tracer and subsurface contaminants move into the building at the same rate.
Indoor air	• Relatively simple to collect samples • Direct measurement of contaminant concentrations in buildings • May be more convincing to occupants	• Background sources complicate data interpretation • Requires access to indoor space • For residential sites, a building survey prior to sampling is often necessary • Very low reporting limits	Time-integrated samples are typically collected (e.g., 24-hr samples for residential sites and 8-hr samples for industrial sites).

Table G-6. Advantages and disadvantages of various investigative strategies (continued)

Measurement	Advantages	Disadvantages	Comments
		may be required for some compounds (e.g., TCE) - One time sampling results may not be representative of long-term average concentrations - Poor sample control	
Crawl-space air	- Simple to measure	- Background sources from overlying structure may complicate data interpretation	Most guidance uses an attenuation factor of 1.0 between crawl space and indoor air
Pressure differential	- Relatively simple to measure - Can Provide evidence of direction of vapor transport (in or out)	- Requires subslab port or other subsurface sampling point - Temporal variations complicate interpretation and often requires multiple sampling events	Detection levels down to 1 Pa can be obtained using inexpensive 0 – 0.25” H_2O magnahelic gauge.
Building ventilation rate	- Very simple to measure (standard ASTM method exists) - For many commercial buildings, rate is already known from design specs - Value can be >10 times default parameters allowed in models	- For residences, seasonal variations may be large	Fewer sampling locations are needed if additional mixing of air within building is provided. Most commonly used for commercial receptors.
Forensics	- Can differentiate sources of contaminants	- Typically requires a significant amount of data - Methods still being developed	Forensic approaches are not likely to be used until later rounds of an investigation

Table G-6. Advantages and disadvantages of various investigative strategies (continued)

Measurement	Advantages	Disadvantages	Comments
		• Background sources can complicate interpretation	
Continuous Analyzers	• Provides large amounts of data • Can help sort out temporal variations and background scatter	• Limited use	Larger data sets allow correlation to other variables such as pressure differentials, wind speed, and HVAC systems.
Soil Physical Properties	• Easy to measure • Enable site-specific values to be used in predictive models • Values can be >10 times default parameters in models	• Data collected near a building may not be representative of zone beneath building • Difficult to get rig near most residential buildings (e.g., lawns, landscaping, trees)	Most sensitive soil physical properties to measure are % water content and permeability.
Groundwater data	• none • Monitoring wells already exist for many sites (previous data) • Acceptable to most agencies • Familiar media to most investigators • Temporal effects minimal	• Look-up values, attenuation factors, or models tend to be extremely conservative, so VI risk often overestimated. • Existing data may be from a well that is not optimally screened for upper water table	This approach is often used as an initial screen.
J & E model with groundwater or soil gas data	• Quick and easy • Model can account for various site-specific factors • Potential future scenarios can be evaluated	• Default input values to model tend to be very conservative • Pressure differential always assumed to be present (i.e., Q_{soil} assumed to be positive value) • Model does not account for	The accuracy of the model output is best if the pollutant transport distance is at a minimum (i.e., shallow soil gas is better than deep soil gas) and no partitioning calculations are needed (soil gas data are better than groundwater data).

Table G-6. Advantages and disadvantages of various investigative strategies (continued)

Measurement	Advantages	Disadvantages	Comments
		biodegradation of BTEX or other compounds • Model is designed to evaluate residential scenarios and has some added limitations if used for other scenarios • Regulators may not accept results if depth to groundwater is <5 ft.	
Biodegradation Models	See Appendix H		

APPENDIX H. VAPOR INTRUSION MODELS USING AEROBIC BIODEGRADATION

This section provides an overview of VI models that incorporate aerobic biodegradation. Models for evaluation of VI may be categorized as follows:

- empirical models, or predictions based on observations from other sites (such as attenuation factors)
- analytical models, which are mathematical equations based on a simplification of site conditions (such as the J&E model)
- numerical models, which allow for simulation of multidimensional transport and provide for more realistic representation of site conditions

H.1 Empirical Models

Empirical models are based on observed data for vadose zone attenuation of soil gas concentrations or vapor biodegradation factors (indoor air concentration divided by subsurface soil gas concentration). There are several approaches for inclusion of aerobic biodegradation of PHCs in such a framework, including vertical screening distances (see Chapter 3) and bio-reduction factors (for example, 10X or 100X) applied to attenuation factors.

H.2 Analytical Models

Over the past two decades, analytical models have been developed to predict the transport of VOCs from subsurface sources in soil and groundwater to indoor air, with the primary purpose of supporting risk-based management of contaminated lands (Lahvis 2011). To date, analytical models for soil VI assessment have exclusively consisted of one-dimensional or compartmental models with a uniform planar subsurface source at a specified depth. A primary distinguishing feature of analytical models is whether they incorporate biodegradation. In addition, analytical models vary in how the building foundation is represented (such as slab-on-grade, basement, crawl space, or an earthen floor; see Lahvis 2011). A summary and comparison of the various analytical VI models that incorporate biodegradation is provided in Table H-1.

Table H-1 Summary of analytical vapor intrusion models that incorporate biodegradation

Model (author)	Model class	Source media	Building foundation	Sensitive parameters	Model strengths	Model limitations
Commercially-available/public domain models						
BioVapor (American Petroleum Institute 2010)	SS	SG, GW	Basement, slab-on-grade, earthen floor	Biodegradation rate constant, O_2 boundary condition (e.g., airflow rate) at land surface (e.g., airflow rate), soil moisture	O_2-limited biodegradation model, simple simulation of TPH fractions, multiple building foundation boundary condition options (including earthen floor), user-friendly, peer-reviewed and USEPA-approved	One-dimensional, single soil layer, constant source concentration, difficulty in simulating depth-dependent soil properties
PVIScreen (Weaver 2013)	SS	SG, GW	Basement, slab-on-grade	Biodegradation	O_2-limited biodegradation, sensitivity evaluation	One-dimensional, single soil layer
RISC5 - two biodegradation models included are dominant-layer and O_2-limited models Spence, L. and T. Walden. 2011.	SS	GW, SG, S	Basement, slab-on-grade	Biodegradation rate constant, O_2 boundary condition of O_2-limited model (e.g., O_2 transfer or Ko coefficient), soil moisture	User-specified attenuation (and bioattenuation) factors, constant and depleting (finite) source term, coupling of vapor intrusion and groundwater flow models, ability to select different vapor intrusion models, including Johnson, Kemblowski, and Johnson (1998) and (2000)	One-dimensional, earthen floor building foundations, TPH simulation, O_2 boundary condition model not well defined, transfer coefficient not well defined
Research and development models						
Jeng et al. 1996	T	GW, S	Earthen floor	Biodegradation rate constant, source zone mass/source depletion, organic carbon	Time-variable/ optional source depletion, can evaluate influence of sorption due to soil organic carbon	One-dimensional, no advective flux, biodegradation only in the aqueous phase regardless of whether there is sufficient O_2, TPH simulation

Table H-1 Summary of analytical vapor intrusion models that incorporate biodegradation (continued)

Model (author)	Model class	Source media	Building foundation	Sensitive parameters	Model strengths	Model limitations
Modified J&E Model or Dominant-Layer Johnson, Kemblowski, and Johnson 1998	SS	SG, S	Basement, slab-on-grade	Biodegradation rate constant, dominant layer thickness	Dominant layer defined from site-specific soil gas depth profile	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation
Oxygen-Limited Model Johnson, Hermes, and Roggemans 2000	SS	SG, S	Basement, slab-on-grade, earthen floor	Biodegradation rate constant, O_2-transfer coefficient at the upper boundary	Only simulates biodegradation when there is sufficient O_2	Requires specifying an O_2-transfer coefficient that may not be available at many sites and may be difficult to estimate
Behavior Assessment Model Jury,Spencer, and Farmer 1983	T	S	Earthen floor	Biodegradation rate constant, source zone mass, organic carbon, leaching rate	Time-variable, can evaluate influence of sorption due to soil organic carbon	Simulates biodegradation regardless of whether there is sufficient O_2, does not apply Raoult's law for soil sources (i.e., no limit on soil gas concentrations when source concentrations exceed soil saturation), TPH simulation
Modified Behavior Assessment Model Jury et al. 1990	T	S	Earthen floor	Biodegradation rate constant, source zone mass, organic carbon, leaching rate	Time-variable; can evaluate influence of sorption due to soil organic carbon	Simulates biodegradation regardless of whether there is sufficient O_2, does not apply Raoult's law for soil sources (i.e., no limit on soil gas concentrations when source concentrations exceed soil saturation), TPH simulation
Vapor Intrusion Model (VIM) Mills et al. 2007	T	AA, GW, S	Combined basement & crawl space	Biodegradation rate constant, organic carbon, building foundation properties	Time-variable, crawl space simulation, basement, dwelling space air	One-dimensional, simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation, requires more inputs than steady state models

Table H-1 Summary of analytical vapor intrusion models that incorporate biodegradation (continued)

Model (author)	Model class	Source media	Building foundation	Sensitive parameters	Model strengths	Model limitations
Modified Orange County Health Care Agency (OCHCA) Model Ririe et al. 1998	SS	GW, NAPL	Basement, slab-on-grade, earthen floor	Biodegradation factor	Biodegradation factor determined from site-specific soil gas depth profile	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation, default slab attenuation factor (0.01) assumed
T&R Model Robinson (2003); Robinson and Turczynowicz (2005)	T	S	Basement, slab-on-grade, crawl space	Biodegradation rate constant, organic carbon, building foundation properties	Time-variable, incorporates building foundation processes, can be run as 1D or 3D	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation, requires more inputs than steady state models
Sanders and Stern Model Sanders and Stern 1994	T	S	Earthen floor	Biodegradation rate constant, source zone mass, organic carbon	Time-variable/ optional source depletion, can evaluate influence of sorption due to soil organic carbon	Simulates biodegradation regardless of whether there is sufficient O_2, TPH simulation
Notes: AA = Ambient Air GW = Groundwater NAPL = nonaqueous phase liquid S = Soil SG = Soil Gas SS = Steady state compartmental model derived from Johnson and Ettinger model that incorporates first-order biodecay T = Transient model adapted from Jury model that incorporates diffusion, sorption, first-order biodecay and optional source depletion.						

For purposes of this evaluation, the discussion below categorizes analytical models into four classes, depending on their key characteristics: steady-state compartmental models, transient models, combined models, and simple models that include diffusion, first-order decay, and a slab attenuation factor.

The first class of analytical models for the purposes of this discussion, which incorporate biodegradation, are steady state compartmental type models derived from the original J&E Model (Johnson and Ettinger 1991), including:

- Modified Johnson and Ettinger model based on the dominant-layer model (Johnson, Kemblowski, and Johnson 1998)
- Oxygen-limited model (Johnson, Hermes, and Roggemans 2000)
- RISC5, which contains the modified J&E model based on dominant-layer model and oxygen-limited models (Spence and Walden 2011b)

- BioVapor model (API 2010; DeVaull 2007)
- PVIScreen model (Weaver 2013)

All of the above models incorporate first-order biodecay. The main difference between these models is that the O_2-limited model only includes biodegradation when there is sufficient O_2, whereas the dominant-layer model does not. The BioVapor model also incorporates O_2-limited biodegradation and advancements with respect to boundary conditions for O_2 ingress to the subsurface. Another distinguishing feature of the above models is that a solid foundation (basement or slab-on-grade) is assumed with soil gas advection limited to penetrations in the foundation such as cracks and construction joints. RISC5 and BioVapor are commercially-available models.

The second class of analytical models is transient models, in which concentrations may vary over time. These models are adapted from the Jury model (Jury, Spencer, and Farmer 1983), which incorporates diffusion, sorption, first-order biodecay and optional source depletion, described in modeling studies by Sanders and Stern (1994) and Jeng et al. (1996). These models assume an earthen floor. The advantage of the Jury model and its adaptations is that transient processes and the influence of sorption due to soil organic carbon may be evaluated. A disadvantage is that potential O_2 limitations are not represented.

The third class of analytical model, through more complex mathematical solutions, combines various subsurface processes and different building foundations (solid foundation or crawl space), and includes:

- Vapor intrusion model (VIM) (Mills et al. 2007)
- T&R model (Turczynowicz and Robinson 2001)

The VIM and T&R models include the following subsurface processes: diffusion; soil gas advection (in the soil column, VIM model only); sorption; first-order biodecay and mixing of vapor-phase chemicals within the crawl space and building air-space; and contaminant source depletion. These models have similar advantages and disadvantages relative to the adaptations of the Jury model, but have the advantage of including building foundation processes.

The fourth class of analytical model includes relatively simple models that incorporate diffusion and first-order biodecay (but no O_2 limitations), combined with an empirical slab attenuation factor to represent attenuation across the building foundation (such as 0.01). One example of this type of model is the modified Orange County Health Care Agency model (Ririe et al. 1998).

H.3 Numerical Models

Numerical models allow representations of additional detail, such as heterogeneity, geometric complexity, and temporal variability. To date, PVI numerical models have typically been applied only for research purposes, in order to obtain a more detailed understanding of causes and effects of vapor transport and attenuation. Because of their complexity, numerical models require additional data and effort (and therefore increased cost) relative to analytical models. Thus for practical applications, the potentially improved accuracy of a numerical model should be weighed against the increased effort and cost.

While numerical models have been applied for over three decades as tools for gaining a better understanding of the VI pathway, only a few numerical models have been developed that represent aerobic biodegradation of PHC in the subsurface. Lahvis and Baehr (1998) modeled the simultaneous transport and reaction of hydrocarbon and O_2 vapors under diffusive-dominated conditions and open surface boundary conditions. Nevertheless, such models do not describe the supply of O_2 from the atmosphere to beneath a building, which usually occurs via a combination of diffusion and advection.

Abreu and Johnson (Abreu and Johnson 2006) developed a more complex numerical model capable of simulating the simultaneous transport of multiple PHC and O_2, the diffusive and advective resupply of O_2 from the atmosphere to beneath a building, and the rate of VI into the building using user-defined building characteristics (such as basement or slab-on-grade). The model is capable of simulating biodegradation with user-defined kinetics. Simulations with the Abreu and Johnson model were used by USEPA to describe and analyze the biodegradation of PHC vapors (USEPA 2012b). Another example of a multidimensional numerical code used for VI studies is the computational fluid dynamic model developed by Pennell and others (Pennell, Bozkurt, and Suuberg 2009).

The MIN3P-Dusty model is a multicomponent reactive transport model that has been adapted for simulation of VI (Hers et al. 2014). This model was initially designed to simulate geochemical reactions involving solid mineral, aqueous, and gaseous species; advective-diffusive transport of gases; and advective-dispersive transport of dissolved species (Mayer, Frind, and Blowes 2002; Molins and Mayer 2007; Molins et al. 2010). The MIN3P-Dusty model is capable of simulating O_2-limited biodegradation, and has potential advantages relative to other models in that mechanisms for soil gas advection, such as non-equimolar diffusion and biodegradation, are included.

APPENDIX I. BIODEGRADATION MODEL PROCESSES, INPUTS, AND CASE EXAMPLES

This appendix presents three main topics:

- a description of the different compartments for the subsurface to indoor air transport pathway and a coupled model for mass transfer between compartments (excluding biodegradation), which provides valuable insight on the relative attenuation between different compartments
- a description of biodegradation models, a compilation of biodegradation rate constants, and a discussion on how to interpret and use rate constants; these tools and resources are intended to support site-specific modeling applications. This discussion is aligned with conceptual models and parameter definitions as applied in the BioVapor model and the PVIScreen model. Other models (Appendix H) may use similar or closely related parameters.
- case examples of BioVapor model applications

I.1 Subsurface to Indoor Air Vapor Pathway and Model Compartments

This section presents a description for subsurface to indoor air vapor migration in terms of coupled model compartments, each described briefly as follows:

- *Indoor building environment.* This area is the indoor, occupied living space.
- *Building foundation.* This area of the building is in contact with soil and can include basements, slab-on-grade foundations, or crawl space foundations.
- *Subsurface environment.* This area includes the soil and groundwater below and adjacent to the building, as well as between the building and the subsurface chemical vapor source.
- *Vapor Source.* Vapors may originate from residual LNAPL or from a downgradient groundwater plume resulting from dissolving LNAPL.

Flux between these compartments must be balanced using conservation of mass principles. For example, the indoor air concentration times the air exchange rate in the building rate must equal the rate of mass flux through the floor. If the exchange rate goes up, then the concentration in indoor air will go down.

Biodegradation is a key process that reduces mass flux. Biodegradation can significantly attenuate PHC concentrations in soils under aerobic soil conditions. O_2 depletion may occur in the subsurface when O_2 demand due to degradation exceeds the available O_2 flux to the subsurface.

I.1.1 Indoor Building Environment

The indoor living space occupied by people is defined most simply by an indoor volume V (m^3) and air exchange rate ER (1/day), where ER is the air volume changes in the building per day. Air enters and leaves the enclosure through windows, doors, walls, ceilings, and floors, and by mechanical ventilation. Air exchange varies over time because of weather, operation of the building (mechanical ventilation systems), and building use patterns. The indoor volume is equivalently defined as equal to the building foundation area, A_f, times an effective mixing height, $L_{mix} = V/A_f$. Chemical mass transfer through the building occurs at a rate proportional to $(ER \cdot L_{mix})$. More complex representations of the indoor environment can include multiple indoor compartments, including varied floors and rooms of a building, and air exchange across each of the indoor air spaces.

I.1.2 Building Foundation

The building foundation is the area of the building in contact with soil, through which chemicals in the subsurface may migrate to indoor air by either advection or diffusion of soil gas (or both) through the building foundation. Foundation types include basement, slab-on-grade, and crawl space. Materials of construction for a foundation may vary and can include, for example, bare earth, cobbles, wood, cinder block, and concrete. In addition to materials of construction, air infiltration through a foundation may also be affected by penetrations, such as cracks, underground utilities (water, gas, sewer, and electric), and sumps or drains, through which chemicals may preferentially enter a building. Chemicals can enter either through the conduit itself (a sewer line, for example) or through the backfill soils surrounding the conduit. Chemical mass transfer through a building foundation can be defined in terms of either effective air flow, as Q_f/A_f, or effective diffusion, as D_{eff}/L_f, where Q_f is foundation airflow, D_{eff} is the diffusion coefficient through the foundation, A_f is the area of the foundation, and L_f is the thickness of the foundation.

For convenience, vapor transfer through a building foundation is often described in terms of a foundation airflow Q_f for a specified foundation area, A_f, based on measured chemical concentrations in and below the building. This use of Q_f is convenient but may not represent the underlying physical mechanisms, which may be a combination of both diffusion and advection. An average range of approximately $Q_f = 1$ to 10 L-air/min for a concrete foundation of area $A_f = 100$ m^2 in contact with the ground is suggested (Hers et al. 2003).

For an open soil surface, such as a dirt floor or crawl space foundation, rates of O_2 mass transfer into the subsurface are higher and can be represented in the BioVapor model by specifying a constant O_2 concentration at the soil surface.

I.1.3 Subsurface Environment – Vadose Zone

The subsurface environment includes the soil and groundwater below and adjacent to the building, as well as between the building and the subsurface chemical vapor source. The subsurface environment may include vadose zone soils, a capillary fringe, and a water-saturated groundwater zone. The capillary fringe interface separates the vadose zone and groundwater. This description is simplified; subsurface stratigraphy can be complex. Chemical vapor mass transfer through a layer of soil where diffusion dominates is proportionate to D_{eff}/L_T, where D_{eff} is the effective diffusion coefficient through the soil layer and L_T is the thickness of the soil layer. In a layered system, overall diffusion can be estimated from sequential diffusion through each of the layers. The overall rate of diffusion in such systems tends to be controlled by the rate of diffusion through the finest-grained layers because of lower air-filled porosity.

Vapor and gas diffusion rates through a porous soil matrix are significantly higher when the air space in the soil matrix is connected. This connection occurs when the air filled fraction of soil θ_a (cm^3-air/cm^3-soil) is greater than approximately 0.2, depending on soil structure. Vapor diffusion is significantly less when the air-filled fraction of soil porosity is disconnected. Disconnection occurs in wetter soils and near the water table capillary fringe. Soil moisture, θ_w (cm^3-water/cm^3-soil), which occupies the remaining soil void can therefore significantly affect diffusion in the soil matrix.

I.1.4 Vapor Source

Persistent sources of subsurface vapors in the subsurface originate from residual LNAPL resulting from a spill or release to the environment. Vapors may either originate directly from LNAPL or from a down gradient groundwater plume resulting from dissolving LNAPL. PHCs are lighter than water, and LNAPL from a release is most often trapped at the water table interface and within the capillary fringe.

Soil gas concentrations from dissolved groundwater concentrations are typically estimated by an equilibrium partitioning model and the Henry’s law constant. Soil gas concentrations adjacent to LNAPL are estimated with Raoult’s law. Partitioning of specific components using Raoult’s law is an essential consideration when predicting vapor intrusion from petroleum LNAPL sources. This consideration is typically unnecessary when predicting vapor intrusion at sites with releases of single chemicals, such as sites with chlorinated solvent releases. In both cases measured vapor concentrations may be lower than equilibrium estimates because of diffusion-limited mass transfer either through water-saturated soil zones or through bulk LNAPL thickness and biodegradation.

I.1.5 Comparison of Mass Transfer Rates and Relative Attenuation

Migration rates of vapors through buildings, foundations, and soils may be qualitatively compared using mass transfer parameters. Choosing nominal parameter ranges, the mass transfer rates and relative attenuation are calculated as shown in Table I-1. The relative attenuation is calculated by simultaneously solving an equation for mass transfer rate for each compartment considered.

Table I-1 Comparison of relative attenuation across compartments. The apportionment in column (1) includes the resistance of wet soils in a capillary fringe; column (2) neglects the contribution of capillary fringe resistance.

Compartment	Nominal parameters	Coefficient	Mass transfer rate	Relative contribution to attenuation (1)	Relative contribution to attenuation (2)
Indoors	ER = 12/day, L_{mix} = 2.44 m	$L_{mix} \cdot ER$	29 m/day	1.6E-5	0.001
Foundation	Q_f = 5 L/min, A_f = 100 m^2	Q_f/A_f	0.072 m/day	0.007	0.35
Soils – Air connected	D_{eff} = 0.12 m^2/day, L_T = 3 m	D_{eff} / L_T	0.04 m/day	0.012	0.64

Table I-1 Comparison of relative attenuation across compartments. The apportionment in column (1) includes the resistance of wet soils in a capillary fringe; column (2) neglects the contribution of capillary fringe resistance. (continued)

Compartment	Nominal parameters	Coefficient	Mass transfer rate	Relative contribution to attenuation (1)	Relative contribution to attenuation (2)
Soils- wet	D_{eff} = 0.15E-4 m^2/day, L_T = 3 cm	D_{eff} / L_T	0.0005 m/day	0.98	--
			Sum:	1.0	1.0

Note: Capillary fringe contribution included (1) and neglected (2).
ER = exchange rate
L_{mix} = mixing zone height
Q_f = soil gas flux into building
A_f = foundation area
D_{eff} = effective diffusion coefficient
L_t = layer thickness

The table illustrates that, when present, diffusive attenuation across a capillary fringe can be substantial. Attenuation across a typical (concrete) foundation is equivalent to that through several meters of soil. Biodegradation is not included in Table I-1, but is discussed in a later section.

I.2 Biodegradation Processes and Rates

Biological degradation of PHC vapors can occur relatively rapidly in aerobic subsurface soils. In aerobic conditions, PHC vapors, in the presence of microbial enzymes, react with O_2 to produce carbon dioxide and water.

The mass ratio of chemical to O_2 consumption for PHCs (neglecting biomass growth), based on the above equation, is approximately 0.3 g-hydrocarbon/g-O_2 for many fuel hydrocarbons. O_2 concentrations in ambient air are approximately 280 g/m^3. O_2 from the soil surface is often a substantial source of O_2 for aerobic degradation of PHC vapors in the subsurface.

Anaerobic degradation with alternate electron acceptors (nitrate, sulfate, iron, etc.) can occur with petroleum, but is often neglected in VI estimates as there is not a ready source for replenishment of these electron acceptors. Petroleum can also degrade under fermentative/methanogenic conditions, to produce methane and carbon dioxide.

Petroleum, including both chemicals of direct concern (benzene for example) and other constituent chemicals, biodegrade and consume O_2 in soils. Aerobic biodegradation depends on the O_2 ingress to the subsurface. Assumptions applied in modeling O_2 limited biodegradation are important as described for BioVapor model in Section 5.3: BioVapor Model.

I.2.1 Degradation Rate Constants

Modeling requires consistent definition and use of degradation rate constants. Tabulated values without specific definition, or developed for other uses (such as groundwater transport or wastewater biotreatment) should not be directly applied in vapor fate and transport modeling. In the BioVapor model, for example, degradation is defined in terms of a first-order water-phase aerobic degradation rate, k_w (1/hr). That is, degradation is presumed to occur only in the water phase of the soil matrix, at a rate proportional to chemical concentration in the water phase, and when O_2 is present.

Different types of rates, including zero-order rates (independent of concentration), instantaneous rates, and rates proportional to soil concentrations (rather than water concentration) have been applied in various soil vapor transport models. More complex forms of rate parameters can also be specified and defined, including Monod-type kinetics (Monod 1949), which is a combination of asymptotic zero and first-order rates; dual Monod kinetics (Kissel, McCarty, and Street 1984, 1985) which includes both O_2 and hydrocarbon in the rate definition, and formulations that include biomass growth and decay estimates. More comprehensive discussion of these forms of rate parameters is discussed elsewhere (Alexander 1999; Hers et al. 2000b). The more complex forms are not necessarily better because there is often a lack of valid and generally available estimates for the needed additional model parameters.

A compilation of first-order water phase biodegradation rate statistics from laboratory and field studies is shown by DeVaull (DeVaull 2007, 2011), for air-connected vadose zone soils is shown in Figure I-1 and Table I-2. Note that the values in Table I-2 and Figure I-1 are based on field data. As part of a sensitivity analysis, a range of rate constants should be simulated. The most likely rates in the distribution are the median (or geometric mean) values in Table I-2 and are a reasonable starting point for modeling. The lowest rates in this empirical data set may have been derived, in some cases, for soils which were not actually uniformly aerobic soils.

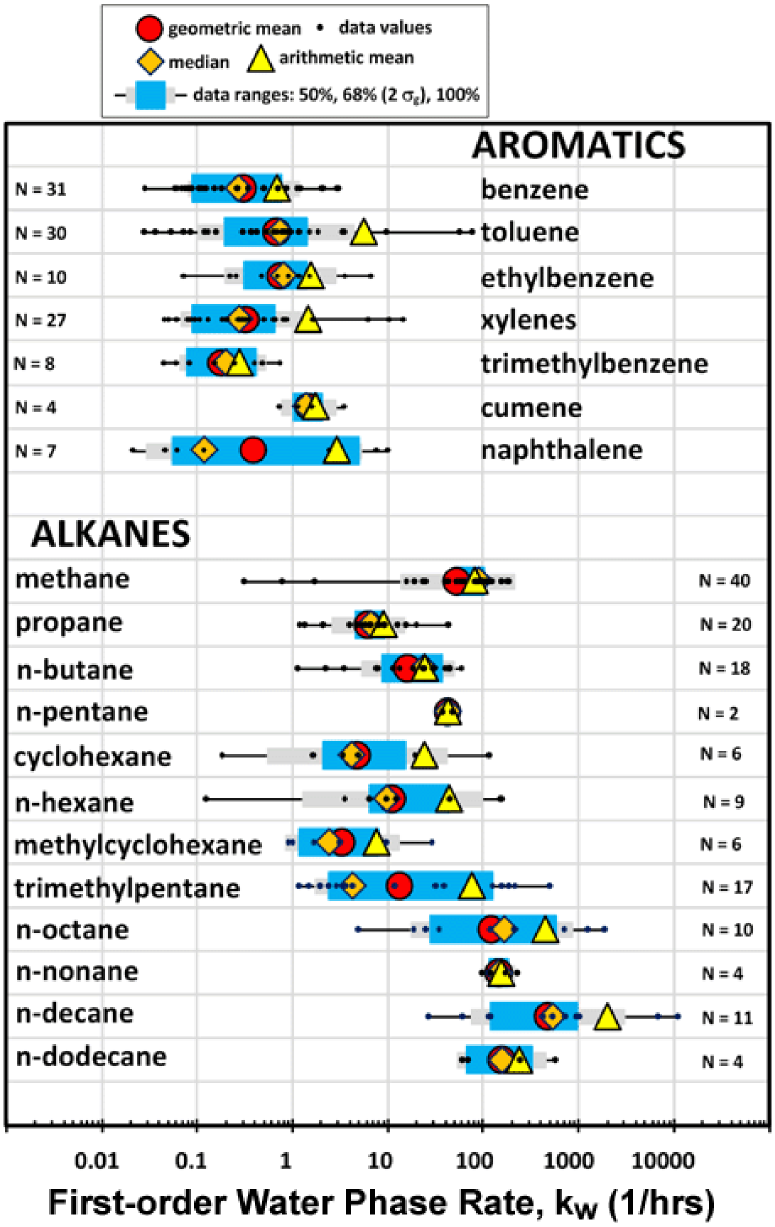


Figure I-1. First-order water phase biodegradation rates (1 / hr) in aerobic vadose zone soils. N is the number of samples in the chemical-specific distribution.

Source: DeVaull 2011.

Table I-2. First-order water phase biodegradation rates (1 / hr) in aerobic vadose zone soils (DeVaull 2011)

Chemical	Data count	Median	Data range: (1st to 3rd quartiles)	Geometric mean, μ_g	Geometric mean, x / ÷ Geometric standard deviation (μ_g/σ_g to $\mu_g \cdot \sigma_g$)	Geometric standard deviation, σ_g	Arithmetic mean, μ_a	Arithmetic mean estimated from lognormal distribution $\mu_a = \mu_g \cdot \exp(0.5 \cdot \ln(\sigma_g)^2)$	Data range (minimum to maximum)	95% bound on lognormal distribution estimate
Aromatics										
Benzene	31	0.27	(0.087–0.78)	0.3	(0.079–1.2)	3.8	0.67	0.75	(0.028–3)	(0.04–2.3)
Toluene	30	0.72	(0.19–1.4)	0.67	(0.1–4.4)	6.6	5.5	4	(0.028–77)	(0.052–8.6)
Ethylbenzene	10	0.79	(0.31–1.4)	0.74	(0.19–2.8)	3.8	1.5	1.8	(0.072–6.6)	(0.098–5.5)
Xylenes	27	0.27	(0.089–0.64)	0.32	(0.067–1.5)	4.7	1.4	1.1	(0.045–14)	(0.034–2.9)
Tri-methylbenzene	8	0.2	(0.077–0.42)	0.18	(0.064–0.51)	2.8	0.27	0.31	(0.044–0.73)	(0.033–0.99)
Cumene	4	1.4	(1–2)	1.5	(0.76–2.8)	1.9	1.7	1.8	(0.73–3.4)	(0.39–5.5)
Naphthalene	7	0.12	(0.054–5)	0.38	(0.028–5.2)	13	2.9	11	(0.021–9.8)	(0.015–10)
Aliphatics										
Methane	40	88	(50–100)	53	(13–210)	4	80	140	(0.31–190)	(6.8–410)
Propane	20	6.5	(4.5–9.3)	6.1	(2.5–15)	2.4	8.9	9.1	(1.2–42)	(1.3–29)
N-butane	18	24	(8.7–38)	16	(5.1–49)	3.1	24	30	(1.1–59)	(2.6–96)
N-pentane	2	42	(40–45)	42	(36–49)	1.2	42	42	(37–47)	(18–97)
Cyclohexane	6	4.1	(2.1–16)	4.7	(0.53–42)	8.9	24	51	(0.18–110)	(0.27–82)
N-hexane	9	9.6	(6.3–44)	11	(1.2–96)	8.8	43	120	(0.12–160)	(0.63–190)
Methyl-cyclohexane	6	2.4	(1.2–8)	3.3	(0.83–13)	4	7.5	8.5	(0.9–29)	(0.43–26)
Tri-methylpentane	17	4.2	(2.4–130)	13	(1.7–110)	8	75	110	(1.2–490)	(0.85–210)

Table I-2. First-order water phase biodegradation rates (1 / hr) in aerobic vadose zone soils (DeVaull 2011)

Chemical	**Data count**	**Median**	**Data range: (1st to 3rd quartiles)**	**Geometric mean, μ_g**	**Geometric mean, x / ÷ Geometric standard deviation (μ_g/σ_g to $\mu_g \cdot \sigma_g$)**	**Geometric standard deviation, σ_g**	**Arithmetic mean, μ_a**	**Arithmetic mean estimated from lognormal distribution $\mu_a = \mu_g \cdot \exp(0.5 \cdot \ln(\sigma_g)^2)$**	**Data range (minimum to maximum)**	**95% bound on lognormal distribution estimate**
N-octane	10	160	(27–580)	120	(17–860)	7.1	440	820	(4.9–1900)	(8.7–1700)
N-nonane	4	140	(110–180)	150	(100–210)	1.5	150	160	(97–230)	(51–410)
N-decane	11	530	(120–980)	470	(73–3000)	6.5	2000	2700	(26–11000)	(37–6000)
N-dodecane	4	160	(67–320)	150	(53–450)	2.9	240	280	(60–570)	(27–890)
Note: The values in Table I-2 and Figure I-1 are based on field data.										

I.2.2 Interpretation of Degradation Rates

The first-order water-phase degradation rates in Table 1-2 may be related to the attenuation in PHC vapor concentrations using several soil parameters and properties. Assuming a one-dimensional transport model that incorporates diffusion and first-order biodegradation, with O_2 present and far from soil surface boundaries, the hydrocarbon concentration profile decreases exponentially with distance from the source, as follows:

As a physical value L_R is a "diffusion-reaction distance," or the distance for the PHC vapor concentration to decrease to exp(-1) [~ 0.37] of its original value. This distance depends on the soil moisture, θ_w, effective diffusivity in the soil, D_{eff}, and Henry's law constant, H, as well as the water-phase degradation rate, k_w. For the distributions of data, see Figure I-2 (assuming first-order biodegradation under aerobic soil conditions). The diffusion-reaction distance is calculated with assumptions of:

- water-phase degradation rate in Table I-2
- nominal soil moisture, $\theta_w = 0.13\ cm^3/cm^3$ (selected midpoint of 0.039 to 0.22 range)
- nominal soil porosity, $\theta_T = 0.425\ cm^3/cm^3$ (selected within 0.36 to 0.49 range)
- chemical-specific parameters at reference temperature (varies from 20°C to 25°C)
- effective diffusivity, D_{eff}, from the Millington-Quirk expression (after Jury, 1984)

The calculated diffusion-reaction distances for the defined soil conditions are shown in Figure I-3.

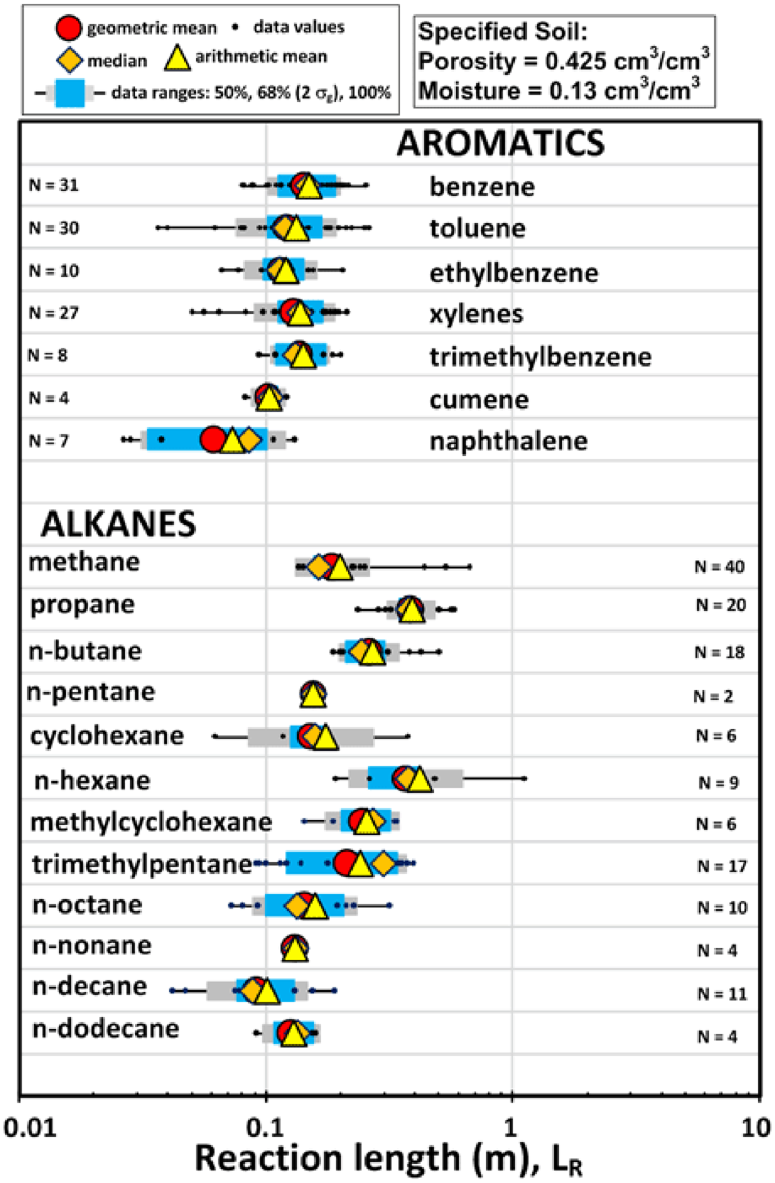


Figure I-2 Diffusion-reaction length for various PHC chemicals assuming first-order biodegradation under aerobic soil conditions. N is the number of samples in the distribution (DeVaull 2011).

In this specific example, diffusion-reaction lengths for many PHCs are on the order of 10 to 20 cm. All else equal, wetter soils tend to yield smaller reaction lengths. With this range of diffusion-reaction length, concentrations would decrease by approximately three to five orders of magnitude in 100 cm [exp(-5) to exp(-10)]. A broader range of reaction lengths, calculated for varied soil conditions, are presented in DeVaull's study (DeVaull 2007).

The reaction rates in Table 1-2 are tabulated for air-connected soils. Observed water-phase rates will be slower in wetter soils ($\theta_a < 0.20$), because of effects of diffusion-limited reaction at the soil matrix pore scale (Thiele 1939; Atkinson 1968; Bosma et al. 1997; Hesse et al. 2010). Degradation rates in very wet soils are more difficult to generally quantify, as limits may be due to depletion of either or both hydrocarbon and O_2 at the soil matrix pore scale.

Diffusion-reaction length can be directly estimated from measured soil gas profiles. An example is illustrated in Figure 1-3, including measured soil gas data and a regression fit to the exponential profile. The concentration data in Figure 1-3 decrease over four orders of magnitude in 12 feet; the fitted diffusion-reaction length L_R is 1.1 foot. More succinctly, between two measured data points, the equation for L_R is:

The estimation of water-phase degradation rate k_w from L_R requires more site-specific parameters (equation for fitted diffusion-reaction length above).

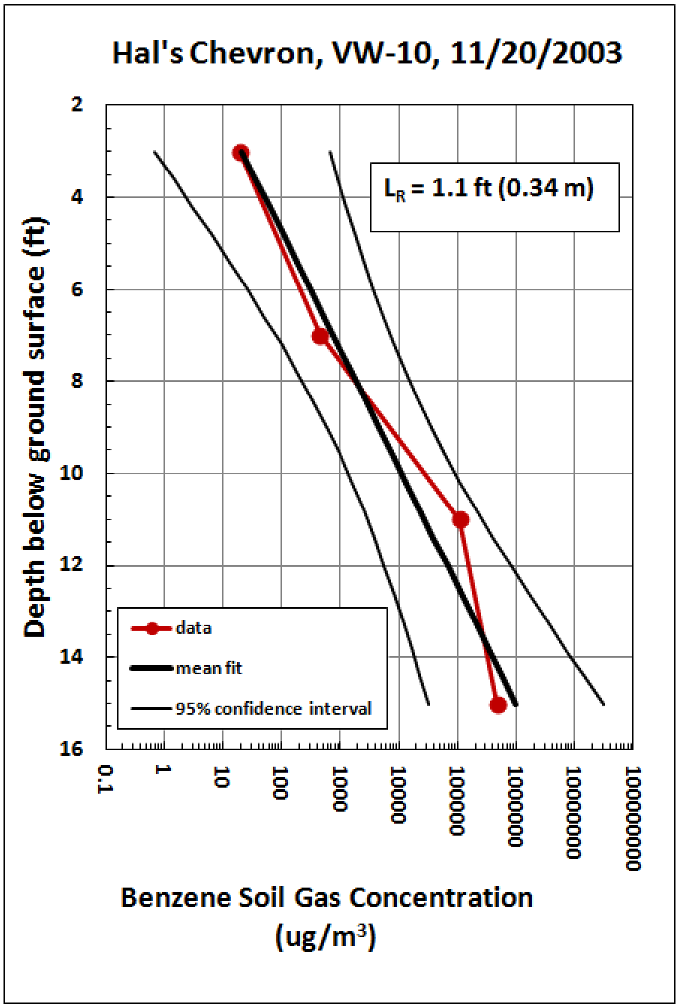


Figure I-3. Comparison of measured soil gas to a fitted value of diffusion-reaction length. L_R (based on data included in USEPA 2013h).

I.3 Limits to First-Order Aerobic Biodegradation Model

A first-order degradation model (and the rate constants in Table I-2) would apply when O_2 is present in excess throughout the reaction zone and there are no biomass limitations, which can sometimes occur at high hydrocarbon concentrations where a zero-order model may be a better approximation. However, biomass limitations are not often directly observed for PHCs; concentrations of dissolved PHCs which would reach this limit often drive soil conditions anaerobic, and therefore the aerobic degradation rates would not apply. Limiting O_2 conditions may be included in models as an externally-imposed limit (API 2010b), in the BioVapor model, or through a more complex rate parameter, such as dual-Monod kinetics. These O_2 limitations may also include competing O_2 requirements from multiple fuel constituents.

Observed aerobic degradation rates may also sometimes be limited by the ratio of active biomass concentration to water-dissolved PHCs per unit volume of soil. This situation is not often directly observed for PHCs; concentrations of dissolved PHCs which would reach this limit are often anaerobic, and therefore the aerobic degradation rates would not apply. Biomass-limited degradation may occur for higher concentrations of ethanol, which is miscible in water.

Aerobic biodegradation reaction rates for PHCs are generally much faster than anaerobic rate and therefore attenuation due to anaerobic degradation may be neglected. Under methanogenic conditions, methane and carbon dioxide gas may be generated from either released petroleum, soil organic matter, or from other sources, including released ethanol. If the release is very large this gas generation may induce subsurface advective gas flow, similar to that often observed at municipal landfills. Advective gas flow is inferred to have occurred at some refinery sites with large releases.

I.4 Case Examples

This section includes examples of biodegradation model applications using the BioVapor Model v2.0, 8 January 2010 (API 2010b). Model applications include:

- Case 1. A comparison of source-to-indoor-air attenuation factors for multiple sites.
- Case 2. An application using measured soil gas profile data where no building exists.
- Case 3. An application using measured soil gas profile data under a building.

In addition, two comprehensive site case examples are discussed, illustrating the role of modeling within the greater context of investigating the site and interpreting the site data:

- Case 4. Stafford, New Jersey
- Case 5. Perth, Western Australia

I.4.1 Case 1. Comparison of Source to Indoor Attenuation Factors, Multiple Sites

Measured indoor air to source vapor concentration ratios for PHC constituent chemicals are available for a number of sites. The consolidated values in Table I-3 (Hers et al. 2003) show cases where: a separation distance exists between a primary vapor source (LNAPL) and the bottom of a building foundation; source vapor concentrations are significantly greater than indoor air concentration; the quality and quantity of characterization data is reasonable; and indoor air impacts are readily differentiated from background levels.

The tabulated cases show source-zone soil vapor concentrations for benzene ranging up to 0.6E+6 µg/m^3 for vapors from gasoline; the Chatterton site is a hydrocarbon solvent release site with up to 15E+6 µg/m^3 benzene vapor concentrations. All of the measured attenuation factors are for vapor sources originating from residual LNAPL near (3 m or less) a building foundation. Measurement of the ratios for residual sources at further distances, or which are partially weathered and depleted in volatile chemicals, will generally be limited to upper bound estimates (<) by the minimum measurable indoor air background limit or detection limit.

No cases are included in Table I-3 for vapors originating from groundwater sources. The authors are unaware of any documented and verified cases of subsurface to indoor air impacts from dissolved PHC chemicals in groundwater to indoor air, where a separation distance exists between the primary vapor source (groundwater) and the bottom of a building foundation.

Saturated benzene vapor concentration above gasoline LNAPL (of 1% w/w benzene) is approximately 3.2E+6 µg/m^3 (at 20°C). With an indoor air background limit or detection limit in the range of 0.3 to 3 µg/m^3, the minimum physically measurable indoor air to source vapor concentration ratio is in the range of approximately 1.0E-7 to 1.0E-6. Dilution of the saturated source vapor concentration raises this minimum limit. The actual minimum measured value in the table is 5.3E-7, for the Chatterton site, at which the LNAPL composition is >1% w/w benzene.

Table I-3. Measured source to indoor air vapor concentrations, Case 1 - Multiple Sites

Site Identifier and chemical constituent	Source vapor concentration (µg/m^3)	Source to foundation separation distance (m)	Indoor air to source vapor concentration ratio (--)
Virginia (Fan and Quinn 2000)			
Benzene	410,000	0.5	8.3E-6
Chatterton (Hers and Zapf-Gilje 1998; Hers et al. 2000a)			
Benzene	15,000,000	1.4	5.3E-7, <4.0E-7 to <9.9E-5
Toluene	20,000,000	1.4	1.9E-6, <5.9E-7 to <1.3E-4
Paulsboro (Laubacher et al. 1997)			
Benzene	576,000	2.74	<1.6E-6
Alameda (Fischer et al. 1996)			
Benzene	200,000	0.7	<9.0E-6
Isopentane	28,000,000	0.7	<9.0E-7
Stafford (Sanders, Hers, and Lewis 2004; Sanders and Hers 2006, NJDEP 2006)			
Benzene	600,000; 390,000	1.65; 2.9	<8.3E-6; <5.1E-6
Toluene	1,100,000; 540,000	1.65; 2.9	4.2E-5; 5.9E-6
2,2,4-trimethylpentane	1,900,000; 2,400,000	1.65; 2.9	2.3E-4; <8.3E-7

Table I-3. Measured source to indoor air vapor concentrations, Case 1 - Multiple Sites (continued)

Site Identifier and chemical constituent	Source vapor concentration (µg/m³)	Source to foundation separation distance (m)	Indoor air to source vapor concentration ratio (--)
Cyclohexane	1,100,000; 710,000	1.65; 2.9	7.1E-5; <2.8E-6
Notes: attenuation factors indicated as 'less than' (<) if indoor air concentrations are below background levels or detection limits.			

For comparison with the data set, the BioVapor model v2.0, 8 January 2010 (API 2010b) was run with default residential assumptions, a range of source to foundation separation distances, and a selection of aerobic depths. The model results, for benzene, are plotted in Figure I-4 in comparison with the tabulated indoor to source attenuation data.

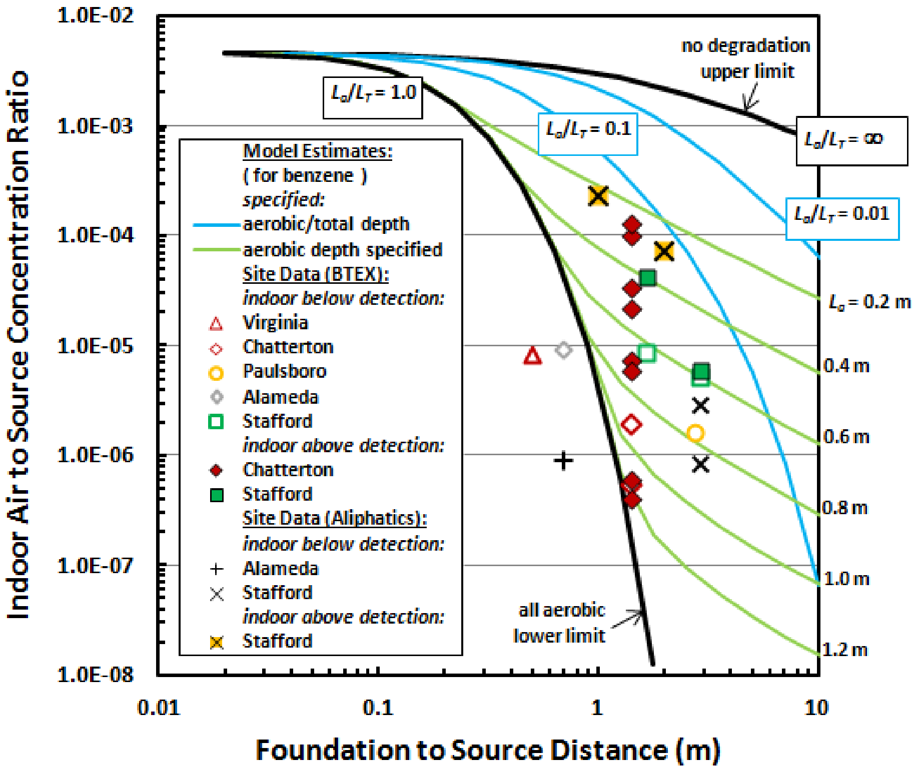


Figure I-4. Comparison of measured indoor air to source vapor (benzene) concentrations to BioVapor model estimates. Case 1 - Multiple Sites.

This is a qualitative comparison of the model to data. The agreement is reasonable. All of the measured data, which are not limited by detection or background, fall between the lower and upper bounds of the model estimates. The sensitivity of decreased attenuation to increased aerobic depth is also seen in the figure. A variation in aerobic depth from 0.2 to 1.2 m is sufficient to bound all of the measured site data by the model estimates. Further refinement could be included in this comparison by including additional measured site-specific parameters in the modeled estimates. The modeled data in Figure I-4 is for benzene; other light aromatic chemicals, including toluene, ethylbenzene, and xylenes show very similar behavior.

The chemicals in Table I-3 include both aromatics (benzene, toluene) and aliphatics (isopentane, 2,2,4-trimethylpentane, cyclohexane). The measured indoor air to source vapor concentration ratios for some of the aliphatic chemicals are up to approximately an order of magnitude larger than those for the aromatic chemicals in the same scenario. With the BioVapor model, aliphatic chemicals also show larger indoor to source concentration ratios than benzene, for the same scenario parameters. This is consistent with qualitative observations from the data set in Table I-3. A direct comparison and plot of the BioVapor model results for aliphatic chemicals is not shown here, as the data is too sparse to draw more general conclusions.

I.4.2 Case 2. Soil Gas Profile Comparison, Beaufort, South Carolina

The BioVapor model can be used to estimate the aerobic depth and soil gas O_2 profile from the coupled O_2 demand due to summed soil respiration and hydrocarbon degradation. This section shows a comparison of these estimates to a comprehensive set of measured soil gas profile data from a specific site, with LNAPL at depth, under an open ground surface.

I.4.2.1 Site Data Description/Methodology

Field measurement were made at up to 9 soil vapor points and two groundwater depths along a vertical profile in a 3.3 m (approximately) vadose zone at a gasoline release site near Beaufort, South Carolina (Lahvis, Baehr, and Baker 1999). Analysis included fixed gases (O_2, CO_2), hydrocarbon vapors species (benzene, toluene, ethylbenzene, mixed xylenes, cyclohexane), and grouped hydrocarbon vapors (C6–C9 aliphatics, C6–C9 aromatics). Aqueous-phase chemical concentrations were measured below the water table. Continuous soil cores were analyzed for porosity, moisture content, air-filled porosity, and diffusion rates as a function of air-filled porosity. A numerical model calibrated with the measured field data, including site-specific soil heterogeneity, was developed and applied in estimating depth-dependent zero order reaction rates.

I.4.2.2 Modeling Discussion

The measured soil gas profile data is compared to estimates made using the BioVapor Model v2.0, 8 January 2010 (API 2010b). Measured soil moisture and porosity profiles show highly varied soil moisture in the deeper profile, from 0 to 43 cm above the water table in a capillary fringe, and relatively uniform air porosity in the shallower zone, from 43 cm to 332 cm above the water table. The lowest 43 cm are not included in the comparison to the BioVapor model. Source vapor concentrations in the model/data comparison are specified at the 43 cm (above the water table) depth.

For depths below 43 cm (not included in the BioVapor modeling), ratios of chemical-specific concentration relative to that at 43 cm are plotted in Figure I-5. The measured values include both soil gas and water concentration (below the water table). The water concentrations are all converted to consistent vapor-phase concentrations using the Henry’s law coefficient in the paper. For data below the water table the ratios (compared to the 43 cm datum) are at least a factor of ten or greater. The BioVapor model manual suggests a factor of 10 for this ratio.

Model parameters, other than those varied from the default BioVapor model values, are shown in Table I-4. The database of properties, parameters, and degradation rates included with the BioVapor model are otherwise applied. Results of the modeling, compared with measured data are included in Figure I-6.

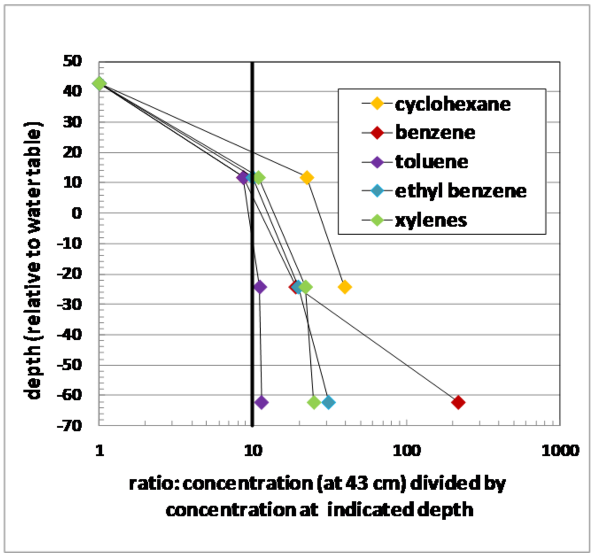


Figure I-5. Ratio of concentration at 43 cm depth divided by concentration at indicated depth, for measured chemical species. Data points are connected to aid visualization. Case 2 - Beaufort.

Table I-4. BioVapor model parameters, Case 2 - Beaufort

O_2 Surface Boundary Condition	
Earthen Floor Foundation (e.g., Specify O_2 Surface Concentration)	
Building Parameters	
Airflow Through Basement Foundation, Q_s (cm^3-air/sec)	8333.3
Note: A very high value is chosen, such that foundation resistance is negligible.	
Soil Parameters	
Soil Porosity θ_T (cm^3/cm^3)	0.3846
Note: Arithmetic average, Lahvis, Baehr, and Baker 1999, Table 2, 12 to 332 cm depth range	
Soil Water Content θ_w (cm^3/cm^3)	0.0919
Note: Arithmetic average, Lahvis, Baehr, and Baker 1999, Table 2, 55 to 332 cm depth range, above capillary fringe	
O_2 Concentration Under Foundation $C_{O2\text{-}e}$ (%)	21
Note: no foundation layer, atmospheric O_2 level is specified	
Annual Median Soil Temperature T (°C)	23

Table I-4. BioVapor model parameters, Case 2 - Beaufort (continued)

Note: Lahvis, Baehr, and Baehr 1999.	
Depth to Source (from bottom of foundation) L_T (cm)	289
Note: depth above capillary fringe (332 cm–43 cm)	
Soil organic carbon fraction f_{oc} (g-oc/g-soil)	0.0005
Note: not measured, see discussion	
Source Vapor Concentration (at 43 cm depth)	(mg/m^3)
Benzene	16.7
Toluene	623
Ethyl benzene	59.2
Xylenes	287
Cyclohexane	102
other aliphatic hydrocarbons (as reported, minus cyclohexane)	388
other aromatic hydrocarbons (as reported, minus summed BTEX)	324.1

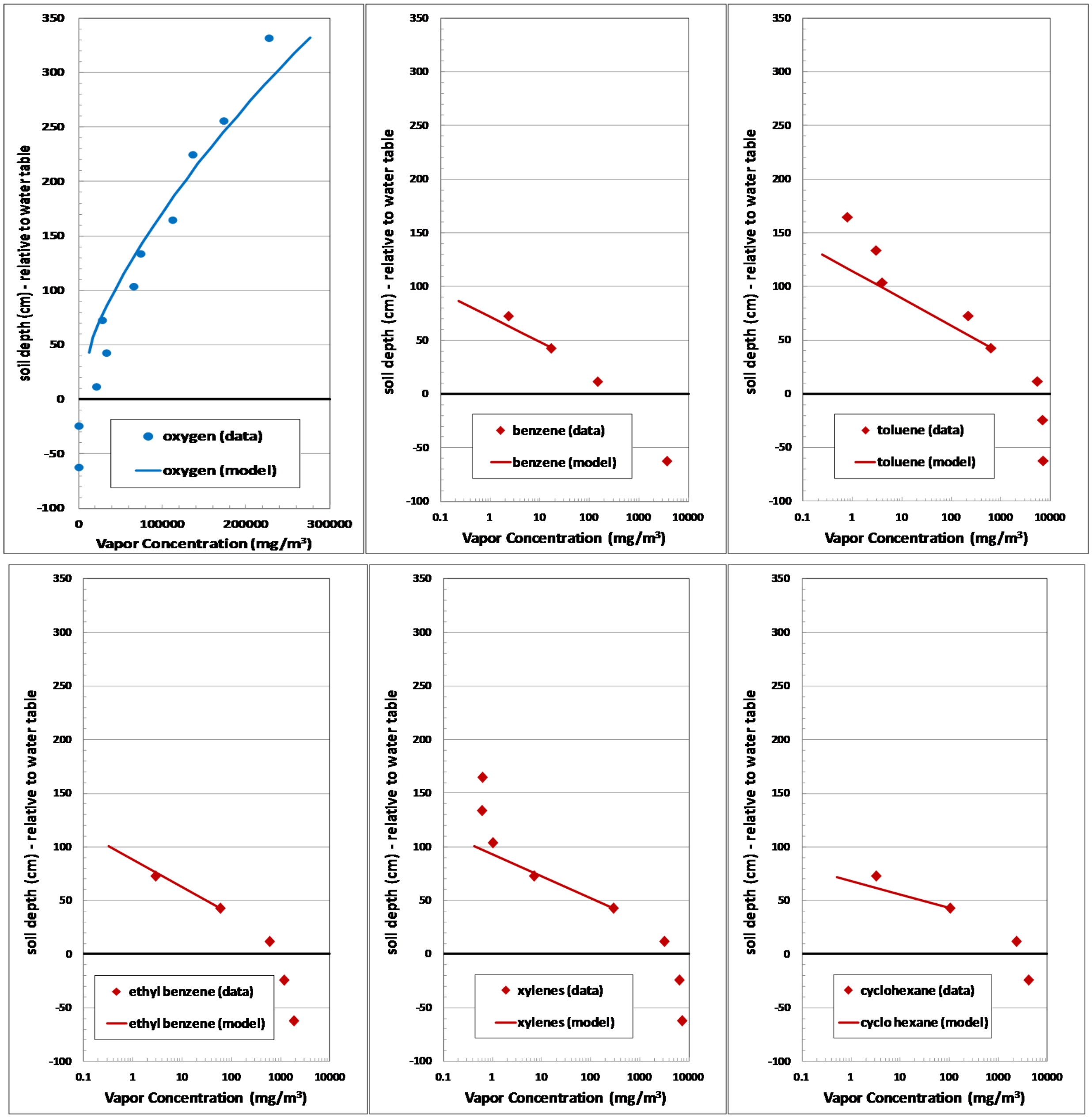


Figure I-6. Comparison of measured data to model estimates, Case 2 - Beaufort.

The comparison of the estimated measured profiles of O_2 and the speciated chemical concentrations to the model is very favorable. Differences in the speciated concentrations are noted principally at low measured vapor concentrations (<1 mg/m³), which are near the detection level, for xylenes and toluene, in this study. The model indicates that O_2 penetrates to the modeled depth (43 cm) consistent with the data.

O_2 concentration in the model is the result of the sum of demand from the individual chemicals, along with demand from baseline soil respiration. Modeled baseline respiration in the BioVapor model is presumed proportional to soil organic carbon concentration, which was not measured in the study. The specified soil organic carbon level (f_{oc} = 0.0005 g/g-oc), and proportionate baseline soil O_2 demand in this comparison, is a factor of ten less than the default BioVapor value (f_{oc} = 0.005 g/g-oc). The sensitivity of aerobic depth, as a function of varied soil organic carbon, is shown in Table I-5.

Table I-5. Sensitivity of aerobic depth versus soil organic carbon, Case 2 - Beaufort

Specified soil organic carbon level f_{oc}(g/g-soil)	Modeled aerobic depth (cm)	O_2 demand due to baseline respiration (%)
0.005	246.6	97.1
0.001	289	58.6
0.0005	289	41.4

I.4.2.3 Summary

- Overall the model to data comparison is good.
- The default soil organic carbon and the dependent baseline soil respiration rate in the BioVapor model are higher than the data suggests in this case. Using the default soil respiration rate overestimates O_2 demand and overestimates vapor transport to shallower soil depths compared to the measured data.
- The BioVapor model user's guide suggests a factor of 0.1 in relating measured groundwater concentrations to soil gas concentrations above the capillary fringe (i.e., soil vapor concentration predicted from Henry's law constant is multiplied by 0.1). Data for this site shows this factor to be reasonable or conservative (overestimating soil gas concentrations) in this case.

I.4.3 Case 3. Soil Gas Profile Comparison, Alameda, California

The BioVapor model can be used to estimate the aerobic depth and soil gas O_2 profile from the coupled O_2 demand due to summed soil respiration and hydrocarbon degradation. This section shows a comparison of these estimates to a comprehensive set of measured soil gas profile data from a specific site, with LNAPL at depth, under a concrete slab building foundation.

I.4.3.1 Site Data Description/Methodology

Soil gas measured at multiple sample points below and adjacent to a slab-on-grade building above a residual aviation gasoline source (Fischer et al. 1996), to a depth of approximately 0.65 m. Vertical profiles were measured and reported for methane, 2-methyl butane (isopentane), O_2, and CO_2. Soil gas diffusion rates were estimated using SF_6 tracer gas.

I.4.3.2 Modeling Discussion

The measured soil gas profile data is compared to estimates made using the BioVapor Model v2.0, 8 January 2010 (API, 2010b). The residual hydrocarbon smear layer suggests a 0.65 m source depth below the on-site building; vapor concentrations at depths greater than 0.65 m are near -constant. The slab-on-grade building includes a foundation thickness of approximately 0.10 cm.

While other chemicals were measured at the site, the dominant source vapor constituents include methane and isopentane.

Shallow O_2 concentrations below the slab are near ambient levels (21% v/v); airflow either through or around the foundation slab is apparently not limiting the O_2 concentration in shallow soils. Effective airflow through the foundation is estimable from SF_6 tracer concentration measurements across the foundation. With indoor to subsurface SF_6 tracer concentration ratios between 0.00025 to 0.00045, air exchange rate of 1.5 /hr, and building volume of 50 m^3, effective airflow through the 50 m^2 foundation is in the range of 0.6 to 1.1 L/min, consistent with a concrete slab-on-grade building.

Applied BioVapor model parameters are shown in Table I-6. The database of properties, parameters, and degradation rates included with the BioVapor model are otherwise applied.

Results of the modeling, compared with measured soil gas data, are included in Figure I-7. For the 'base case' the BioVapor model tends to underestimate O_2 penetration, and underestimate both methane and isopentane degradation. As a check on model sensitivity, the effective diffusion coefficient in the model was divided by factors of 2.5 and 5. The results are included in the figure, and may indicate a potential overestimate of diffusion rate in the model.

Table I-6. BioVapor model parameters

O_2 Surface Boundary Condition	
Earthen Floor Foundation; O_2 concentration (as measured) is specified below the foundation	
Building Parameters	
Airflow Through Basement Foundation, Q_s(cm^3-air/sec)	833.3
Note: Value is based on measured isopentane concentration ratio across foundation	
Soil Parameters	
Soil Porosity θ_T (cm^3/cm^3)	0.368
Note: Measured arithmetic average, 20 to 62 cm depth range	
Soil Water Content θ_w (cm^3/cm^3)	0.152
Note: Measured arithmetic average, 20 to 62 cm depth range	
O_2 Concentration Under Foundation C_{O2-e} (%)	21
Note: atmospheric O_2 level is measured below foundation	
Annual Median Soil Temperature T (°C)	15
Note: from paper	
Depth to Source (from bottom of foundation) L_T (cm)	55
Note: depth above capillary fringe (65 cm–10 cm)	
Soil organic carbon fraction f_{oc} (g-oc/g-soil)	0.0034
Note: as measured average, 20 to 62 cm depth range	
Soil bulk density (g/cm^3)	1.6

Table I-6. BioVapor model parameters (continued)

Note: as measured average, 20 to 62 cm depth range	
Source concentration (at 65 cm depth)	(mg/m^3)
Methane	80,000
Isopentane	55,000
n-pentane	6,800
C6–7 aliphatics (sum of 2,3-dimethylpentane & 4-methyl-hexane)	5,500
Benzene	200
Toluene	200

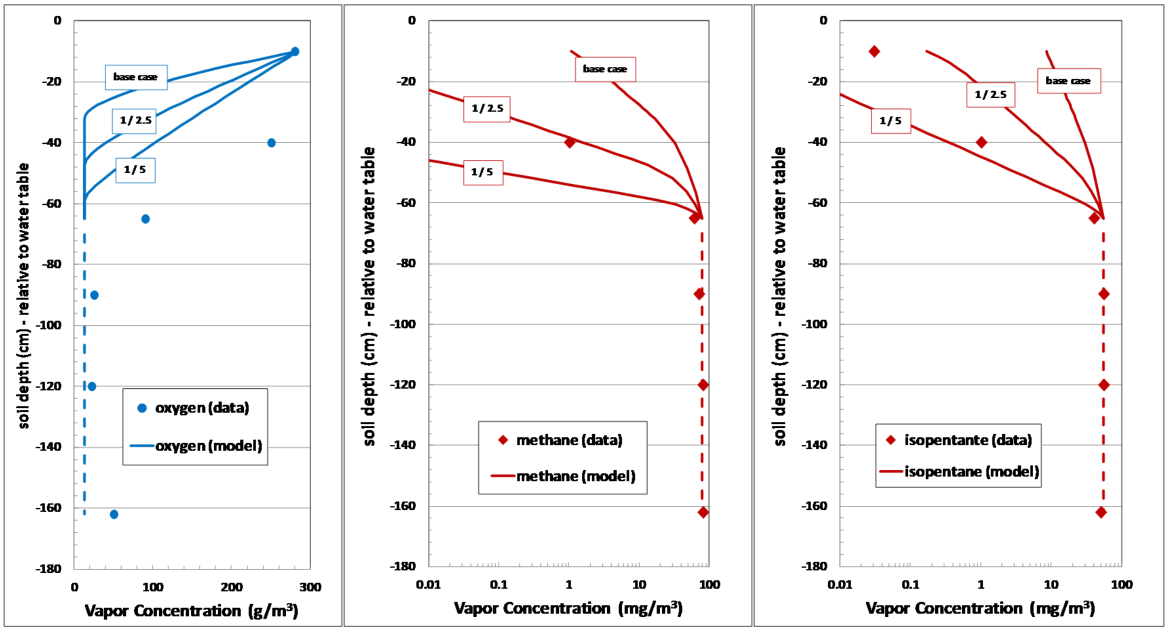


Figure I-7. Comparison of the BioVapor model to measured data below the building. The 'base case' shows results for the applied parameters. Results presuming a lower effective diffusion coefficient, by factors of 2.5 and 5, are also shown in the plots.

I.4.3.3 Summary

- Overall the model overestimates shallow concentrations of PHCs.
- Greater O_2 penetration is seen in the data than the model suggests.
- The paper includes data measured below an adjacent asphalt forecourt, which is very similar to that shown below the building and is therefore not included here.
- Variation between the model and the data suggests a zone may exist very near the foundation with enhanced mixing or diffusion (due to the foundation), compared to deeper levels.

I.4.4 Case 4. Application to Stafford Township, New Jersey

This example shows the use of the BioVapor model in aiding the interpretation of site assessment data. An early version of the BioVapor model V2.0 beta 4, 2 November 2009 (API 2010) was applied in the model estimates.

All the assessment data are published and available (Sanders and Hers 2006; Sanders, Hers, and Lewis 2004; NJDEP 2006). Extensive site information is included, including soil gas and indoor air data. Parameters and results for a numerical vapor intrusion model are included in the reports. These reported model parameters are applied in running the BioVapor model in this example.

I.4.4.1 Scenario Description

The site scenario is a gasoline leak from underground gasoline storage tank site. The leaking tank has been removed. Down gradient soil and groundwater is affected. The nominal groundwater depth below ground surface is 3.3 m.

There are buildings and residences above the affected groundwater zone, some with basements to depth of 1.8 m below ground surface, leaving a separation distance between basements and groundwater of approximately 1.65 m. Shallow soils are sand. The site is in southern, coastal New Jersey, USA.

I.4.4.2 Risk Management and Site Investigation

This investigation conducted under the direction of the NJDEP with their contractors. It is used here as an example, in model/data comparisons. Occupied commercial and residential structures were included in the investigation. The investigation, analysis, and interpretation, as discussed in the cited reports, was conducted as a research project, to better understand subsurface to indoor air vapor intrusion issues and risks. Typical vapor intrusion investigations would not be as detailed or extensive.

I.4.4.3 Criteria Levels

The residential indoor air criteria concentration (µg/m^3) levels applied in this example are from the responsible regulatory agency (NJDEP). An extensive summary has been compiled in the referenced report of background indoor air concentrations. Site-specific background values are used for comparison in this example. The values are as shown in Table I-7.

Table I-7. Indoor air criteria and background concentrations, Case 4 - Stafford

Chemical	Indoor air screening level concentration (µg/m^3)	Indoor air screening level concentration (ppbv)	Background indoor air concentration levels (µg/m^3)	Background indoor air concentration levels (ppbv)
Benzene	2	0.6	<1.6 to 3.9	<0.5 to 1.2
Toluene	5,200	1,360	14 to 33	3.6 to 8.7

Table I-7. Indoor air criteria and background concentrations, Case 4 - Stafford (continued)

Chemical	Indoor air screening level concentration (µg/m³)	Indoor air screening level concentration (ppbv)	Background indoor air concentration levels (µg/m³)	Background indoor air concentration levels (ppbv)
Ethylbenzene	2	0.45	<2.2 to 5.7	<0.5 to 1.3
Xylenes	100	23	11 to 25	2.4 to 5.7
MTBE	9	2.5	2.3 to 9.5	0.62 to 2.6
2,2,4-trimethylpentane	Unavailable	Unavailable	<2.4 to 11	<0.5 to 2.3
Cyclohexane	6,300	1,800	<1.7	<0.5

Screening Levels: New Jersey Department of Environmental Protection, Site Remediation Program, Vapor Intrusion Guidance, Updated Vapor Intrusion Screening Level Tables (revised March 2013, accessed October 2014), Table 1, residential. http://www.state.nj.us/dep/srp/guidance/vaporintrusion
Background Concentrations: Reports on Investigation of Indoor Air Quality in Structures Located Above VOC-Contaminated Groundwater, for New Jersey Department of Environmental Protection by Golder Associates, Inc., 2005-2006. http://www.state.nj.us/dep/dsr/air/air.htm, Soil Vapor Intrusion - Year 1 - Research Study at Stafford Township & Egg Harbor Sites, New Jersey - (March 2005), Table 3-15; 20°C assumed for ppbv to mg/m³ conversion; xylenes total is sum of m-,p-,o- isomers.

I.4.4.4 Qualitative Site Evaluation

Preliminary Questions and Checks:

Is the scenario consistent with conceptual model assumptions?

Are there other relevant issues that may need to be addressed?

The qualitative criteria for identifying potential issues in vapor intrusion from subsurface to indoor air, and possible model exceptions include:

- The presence of highly affected water or gasoline directly within or in direct contact with basement, crawl spaces, sumps, or conduits. No.
- The presence of very large subsurface petroleum NAPL releases near foundations or subsurface enclosures. Yes. Based on the reported site data, it is evident that LNAPL is likely to be present in the immediate vicinity of several buildings on the site, at and near the water table. A screening analysis follows.
- Confined lithology and pressure-driven vapor flow, where pressure may originate from rising or falling water tables and/or methane gas generation. No.

In addition, for VI estimates from hydrocarbons, estimates of O_2 demand (and O_2 presence in the subsurface) are needed.

- Baseline O_2 demand in sand soil is low (site measured f_{oc} = 0.006 g-oc/g-soil).
- Additional O_2 demand originates from PHC vapors evolved from groundwater and from residual gasoline.

Relevant criteria for determining either the confirmed or suspected presence of an LNAPL, as tabulated and discussed in ASTM E2531-06 and EA (2003), can include any of the following direct and indirect methods:

- Observed LNAPL in wells or samples; positive field screening tests (for example, paint filter test, dye test, shake test); fluorescence indicative of LNAPL;
- Measured concentrations near an effective solubility (in water) or saturated vapor limit (in air); TPH levels indicative of LNAPL presence; organic vapor analyzer results; or
- Dissolved plume persistence and center-of mass stability over time.

If LNAPL is suspect or confirmed, establish:

- Confidence in adequate delineation of suspected or confirmed NAPL zones, including at the water table and in soils from the water table to the ground surface.
- Presence of an aerobic soil buffer zone between NAPL vapor sources and building foundations, either through estimation or measurement.
- Screening of potentially flammable vapors proximate to building foundations or subsurface enclosures.

Based on the reported site data, it is evident that LNAPL is likely to be present in the immediate vicinity of several buildings on the site, at and near the water table. Figure I-8 is a comparison of ratios of site data to a number of criteria based on ASTM E2531-06 (water-dissolved and vapor concentrations); there are other relevant criteria (soils concentration data, for example). The LNAPL 'screening' values chosen here are nominally representative for gasoline and may vary for other petroleum products and compositions.

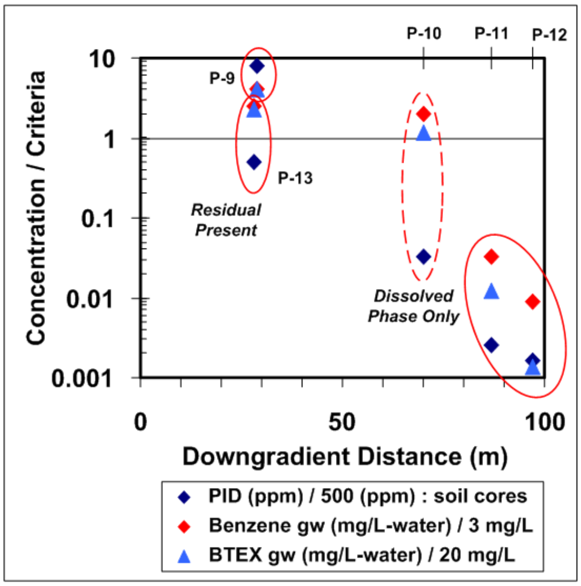


Figure I-8. Comparison of LNAPL screening values to site data, Case 4 - Stafford.

These screening criteria are used on a plan view map of the site, in Figure I-9. This illustrates a near-zone region with LNAPL impacts likely under several buildings and a far-zone region with dissolved-phase only groundwater impacts underneath buildings. Open points on the plan view map indicate vapor sources from groundwater only (labeled "GW only"); closed points indicate the vapor source is likely to originate from residual PHC or LNAPL (labeled "Resid.").

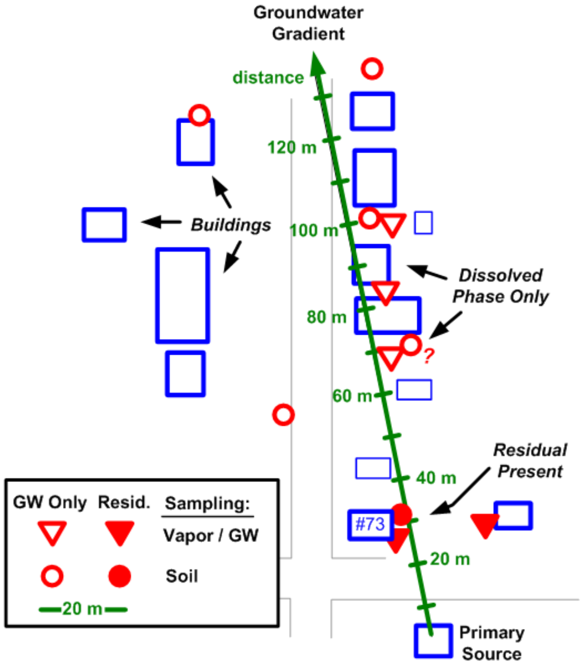


Figure I-9. Plan view map of site with zones of impact indicated, Case 4 - Stafford.

I.4.4.5 Modeling and Site Data Interpretation

Chemicals of Interest

A database of chemicals is included in the BioVapor model, and may be edited as appropriate. If selected measured chemicals of potential interest in vapor and groundwater at the site are not included in the BioVapor model database, they may be added, using available parameters. Indoor air criteria concentrations (µg/m^3), as available from the local agency (NJDEP), were entered into the BioVapor chemical database.

Modeling and analysis

For vapor intrusion screening, this site is divided into two subunits: Subunit (1) dissolved plume only; and Subunit (2) LNAPL present or suspected.

Subunit (1) Dissolved Contaminants in Soluble Groundwater Plume

For this subunit (1) case example building and scenario parameters are included in Table I-8 under ‘case A’. The building parameters are similar to a residential building with a basement and include site-specific measured, calculated, and derived parameters. The soil parameters correspond to sand, but include site-specific measured values.

Table I-8. Applied model parameters, Case 4 - Stafford

Key:

specified values used in calculating other values

values applied in model

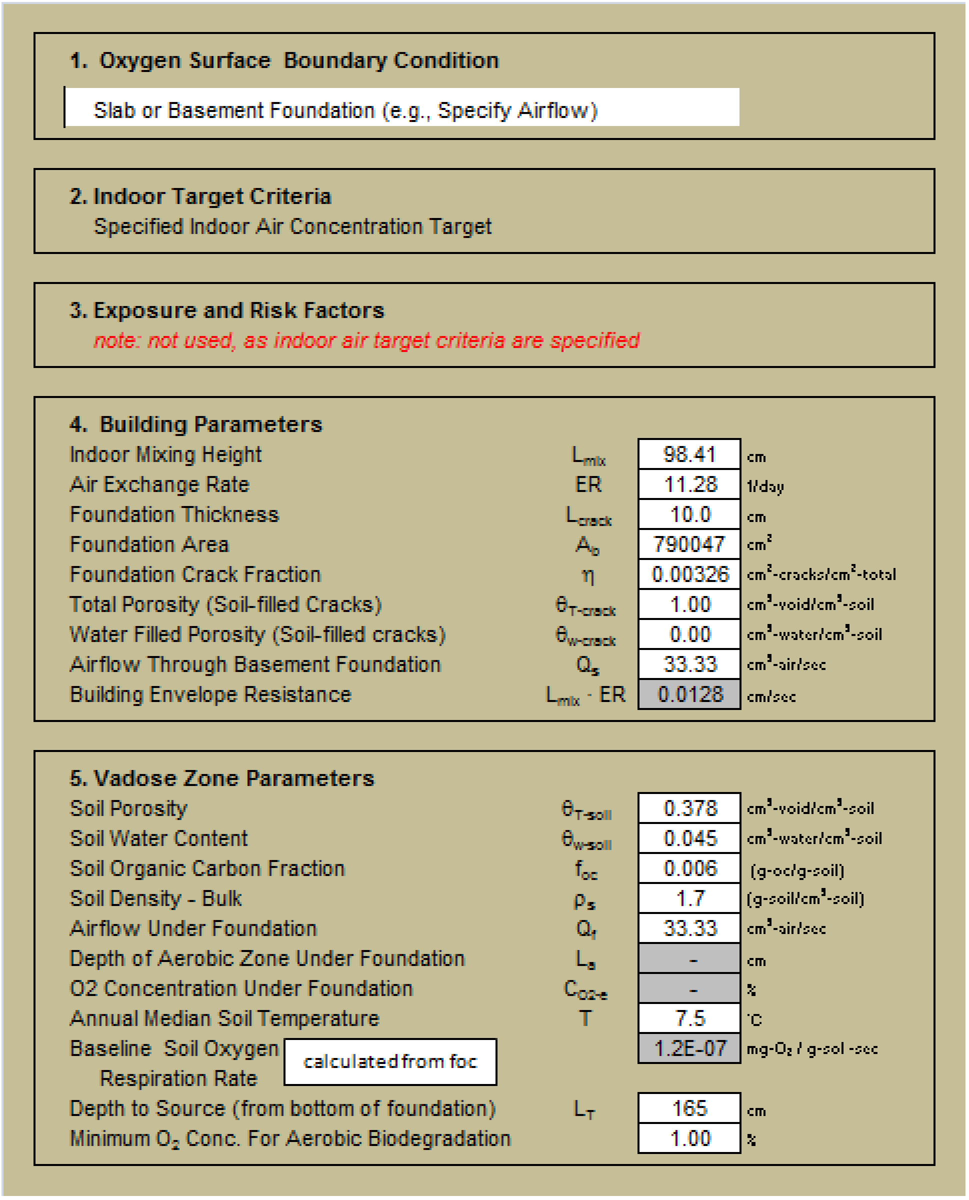
values changed from case A to B

Case A	Case B	Symbol	Parameters
			Logic and control parameters
			O_2 conditions (slab or basement foundation present, ambient O_2 in air)
			Vapor inhalation exposure parameters
			not used; directly compared with indoor concentration criteria
			Building parameters and geometry
421	421	W_b	(cm) building width
867	867	L_b	(cm) building length
365007	365007	$W_b \cdot L_b$	(cm^2) building footprint area
213	213	H_b	(cm) building height
165	165	D_b	(cm) depth to base foundation below grade
98.41	98.41	L_{mix}	(cm) enclosed space volume/infiltration area ratio, or mixing height $= Q_b / (A_b \cdot ER)$
11.28	11.28	ER	(1/day) enclosed space air exchange rate
77746491	77746491	V_b	(cm^3) building volume $= W_b \cdot L_b \cdot H_b$
10150.24	10150.24	Q_b	(cm^3/sec) building airflow $= V_b \cdot ER$
0.609	0.609	Q_b	(m^3/min) building airflow
790047	790047	A_b	(cm^2) subsurface foundation area in contact with soil $= W_b \cdot L_b + D_b \cdot 2 \cdot (W_b + L_b)$
10	10	L_{crack}	(cm) enclosed-space foundation or wall thickness
1	1	W_{crack}	(cm) crack width - perimeter crack
2576	2576	A_{crack}	(cm^2) crack area $= W_{crack} \cdot 2 \cdot (W_b + L_b)$
0.00326	0.00326	η	(cm^2-cracks/cm^2-total area) foundation crack fraction $= A_{crack} / A_b$
2	5.98	Q_s	(L/min) soil gas advection rate
33.33	99.7	Q_s	(cm^3-air/sec) convective airflow through basement foundation
33.33	99.7	Q_f	(cm^3-air/sec) convective airflow under basement foundation, $Q_f = Q_s$ or $Q_f > Q_s$

Case A	Case B	Symbol	Parameters
165	165	L_T	(cm) depth - below basement slab to groundwater depth vapor source
330	330		(cm) depth - soil surface to groundwater vapor source depth = L_T + D_b
			Soil parameters
sand	sand		soil type
0.378	0.378	θ_T	(cm^3-void/cm^3-soil) soil porosity, vadose-zone soils
0.045	0.045	θ_w	(cm^3-water/cm^3-soil) soil water content, vadose-zone soils
0.378	0.378	θ_T	(cm^3-void/cm^3-soil) soil porosity, soil filled basement cracks
0	0	θ_w	(cm^3-water/cm^3-soil) soil water content, soil-filled basement cracks
6.0E-03	6.0E-03	f_{oc}	(g-oc/g-soil) soil organic carbon fraction, vadose-zone soils
1.7	1.7	ρ_s	(g-soil/cm^3-soil) soil density – bulk
			Environmental parameters
7.5	7.5	T_{amb}	(°C) ambient temperature
760	760	P_{amb}	(mmHg) atmospheric pressure
			Measured subfoundation to average indoor air concentration ratio
	0.00982	c_e / c_f	(--) average measured ratio

A subset of the values from Table I-8 are entered into the BioVapor model, as illustrated in Table I-9.

Table I-9. BioVapor model scenario parameters, Case 4 - Stafford



1. Oxygen Surface Boundary Condition

Slab or Basement Foundation (e.g., Specify Airflow)

2. Indoor Target Criteria

Specified Indoor Air Concentration Target

3. Exposure and Risk Factors

note: not used, as indoor air target criteria are specified

4. Building Parameters

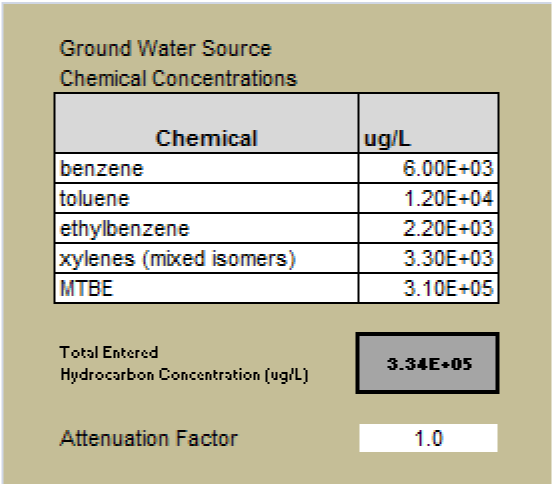
Indoor Mixing Height	L_{mix}	98.41	cm
Air Exchange Rate	ER	11.28	1/day
Foundation Thickness	L_{crack}	10.0	cm
Foundation Area	A_b	790047	cm^2
Foundation Crack Fraction	η	0.00326	cm^2-cracks/cm^2-total
Total Porosity (Soil-filled Cracks)	$\theta_{T\text{-}crack}$	1.00	cm^3-void/cm^3-soil
Water Filled Porosity (Soil-filled cracks)	$\theta_{w\text{-}crack}$	0.00	cm^3-water/cm^3-soil
Airflow Through Basement Foundation	Q_s	33.33	cm^3-air/sec
Building Envelope Resistance	$L_{mix} \cdot ER$	0.0128	cm/sec

5. Vadose Zone Parameters

Soil Porosity	$\theta_{T\text{-}soil}$	0.378	cm^3-void/cm^3-soil
Soil Water Content	$\theta_{w\text{-}soil}$	0.045	cm^3-water/cm^3-soil
Soil Organic Carbon Fraction	f_{oc}	0.006	(g-oc/g-soil)
Soil Density - Bulk	ρ_s	1.7	(g-soil/cm^3-soil)
Airflow Under Foundation	Q_f	33.33	cm^3-air/sec
Depth of Aerobic Zone Under Foundation	L_a	-	cm
O2 Concentration Under Foundation	$C_{O2\text{-}e}$	-	%
Annual Median Soil Temperature	T	7.5	°C
Baseline Soil Oxygen Respiration Rate calculated from foc		1.2E-07	mg-O_2 / g-sol -sec
Depth to Source (from bottom of foundation)	L_T	165	cm
Minimum O_2 Conc. For Aerobic Biodegradation		1.00	%

For the likely “(1) Dissolved plume only” portion of the site, shallow maximum groundwater concentrations are entered into the BioVapor model. The groundwater concentrations are in units of µg/L and a "groundwater to deep soil gas attenuation factor" (across the capillary fringe) is entered as 1.

Table I-10. BioVapor model source groundwater concentrations, Case 4 - Stafford



Ground Water Source
Chemical Concentrations

Chemical	ug/L
benzene	6.00E+03
toluene	1.20E+04
ethylbenzene	2.20E+03
xylenes (mixed isomers)	3.30E+03
MTBE	3.10E+05

Total Entered Hydrocarbon Concentration (ug/L)	3.34E+05
Attenuation Factor	1.0

The entered groundwater concentrations are maximum values measured in the dissolved phase portion of the plume. All values are for the same groundwater monitoring well. The entered 12,000 µg/L-water for toluene is 'nondetect' at this well, but is included in the source composition as it is detectable co-located with BTEX chemicals in other monitoring wells at the site. Cyclohexane is measured but not detected in any groundwater well above detection limits and is therefore not included in the source groundwater composition.

The BioVapor model results compared with applied screening-level concentrations and background concentrations are shown in Table I-11. The screening criteria concentrations are exceeded, with these model assumptions, for MTBE and benzene in the 'biodegradation' model results. The criteria are exceeded for benzene, ethylbenzene, xylenes, and MTBE in the 'no biodegradation' model results.

Table I-11. Comparison of model results to indoor air criteria using groundwater data. For dissolved contaminants in soluble groundwater plume, Case 4 - Stafford

Chemical	Groundwater source concentration (µg/L-water)	Predicted soil gas source concentration (µg/m³-air)	Predicted indoor air concentration (µg/m³-air)	Indoor air concentration criteria (µg/m³-air)		Upper background concentration (µg/m³-air)	
Model results with biodegradation neglected					Exceeded?		Exceeded?
Benzene	6,000	615,000	1,120	2	Y	3.9	Y
Toluene	12,000	1,340,000	2,430	5,200		33	Y
Ethylbenzene	2,200	262,000	444	2	Y	5.7	Y
Xylenes (total)	3,300	259,000	428	100	Y	25	Y
MTBE	310,000	4,390,000	7,640	9	Y	9.5	Y
Model results with biodegradation included					Exceeded?		Exceeded?
Benzene	6,000	615,000	2.73	2	Y	3.9	

Table I-11. Comparison of model results to indoor air criteria using groundwater data. For dissolved contaminants in soluble groundwater plume, Case 4 - Stafford (continued)

Chemical	Groundwater source concentration (μg/L-water)	Predicted soil gas source concentration (μg/m^3-air)	Predicted indoor air concentration (μg/m^3-air)	Indoor air concentration criteria (μg/m^3-air)		Upper background concentration (μg/m^3-air)	
Toluene	12,000	1,340,000	7.16	5,200		33	
Ethylbenzene	2,200	262,000	1.13	2		5.7	
Xylenes (total)	3,300	259,000	0.292	100		25	
MTBE	310,000	4,390,000	3,090	9	Y	9.5	Y

In comparison with the local upper background concentration values, the 'no biodegradation' model results indicate all of the tabulated chemicals would be significantly above background concentrations in indoor air.

The biodegradation model results indicate that MTBE would be significantly above background, with the remaining chemicals below 'background'. No NJDEP screening criteria are exceeded for toluene, ethylbenzene, and xylenes in the dissolved-phase portion of the plume in the 'biodegradation' model results. Toluene in groundwater is <12,000 µg/L-water, or 'nondetect' due to matrix interferences (other chemicals in the same groundwater sample). Even with entered toluene groundwater source concentration of 12,000 µg/L-water, the calculated indoor criteria are met for toluene.

With the "Groundwater to Deep Soil Gas Attenuation Factor" specified equal to 1, attenuation across the water table capillary fringe is neglected in the prior modeled case. Site soil gas data has been measured above and adjacent to the groundwater samples. Comparison of maximum soil gas values with measured maximum groundwater concentrations are shown in Table I-12 for the dissolved phase groundwater plume.

Table I-12. Comparison of estimated (from groundwater partitioning) and measured deep soil gas concentrations, Case 4 - Stafford

Chemical	Groundwater source concentration (μg/L)	Henry law coefficient [at 7.5°C] (cm^3/cm^3)	Equilibrium calculated soil gas source Concentration (μg/m^3)	Measured deep soil gas concentration (μg/m^3)	Ratio
Benzene	6,000	0.102	6.15E+5	<2,100	<0.003-4
Toluene	<12,000	0.112	<1.34E+6	3,300	~0.002-5
Ethylbenzene	2,200	0.119	2.62E+5	<2,800	<0.011
Xylenes	3,300	0.079	2.59E+5	<5,700	<0.022
MTBE	310,000	0.014	4.39E+6	56,000	<0.013
2,2,4-tri-	not measured	52.7	--	1,700	--

Table I-12. Comparison of estimated (from groundwater partitioning) and measured deep soil gas concentrations, Case 4 - Stafford (continued)

Chemical	Groundwater source concentration (µg/L)	Henry law coefficient [at 7.5°C] (cm³/cm³)	Equilibrium calculated soil gas source Concentration (µg/m³)	Measured deep soil gas concentration (µg/m³)	Ratio
methylpentane					
Cyclohexane	<12,000	2.88	<3.46E+7	<2,300	--

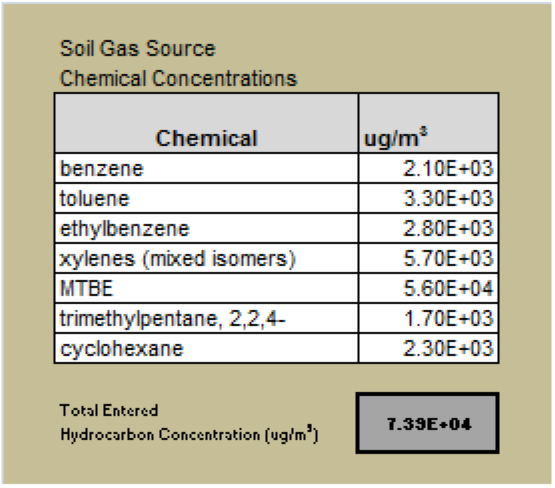
The "Groundwater to Deep Soil Gas Attenuation Factor" based on measured data for these chemicals is nominally 0.01 to 0.001, or may be smaller, due to detection limits.

For the measured 2,2,4-trimethylpentane vapors, an equilibrium-calculated groundwater source concentration of 0.032 µg/L-water is estimated. This would be below detection limits in water, if measurement was attempted.

The measured concentration ratios and inferred gradients from groundwater to deep soil vapor indicate the direction of chemical flow is from groundwater to soil vapor, with high confidence, for all of the tabulated chemicals measured above detection limits. The magnitude of chemical mass flow depends on resistance across the capillary fringe and possible degradation losses.

The BioVapor model results can be refined by entering the measured deep soil gas data, rather than the groundwater concentration data. Other model scenario assumptions are included in Table I-8, Case A.

Table I-13. BioVapor model source soil vapor concentrations, Case 4 - Stafford



Soil Gas Source
Chemical Concentrations

Chemical	ug/m³
benzene	2.10E+03
toluene	3.30E+03
ethylbenzene	2.80E+03
xylenes (mixed isomers)	5.70E+03
MTBE	5.60E+04
trimethylpentane, 2,2,4-	1.70E+03
cyclohexane	2.30E+03

Total Entered Hydrocarbon Concentration (ug/m³) 7.39E+04

Consolidated BioVapor model results for the specified source vapor concentrations are shown in Table I-14. The target indoor air concentrations are NJDEP residential screening criteria. The screening criteria concentrations are exceeded, with these model assumptions and source concentrations, for MTBE. Local upper background concentration is exceeded for MTBE.

Table I-14. Comparison of BioVapor model results to indoor air criteria, Case 4 - Stafford

Chemical	Soil gas source concentration (µg/m^3-air)	Predicted indoor air concentration (µg/m^3-air)	Target indoor air concentration (µg/m^3-air)		Upper background concentration (µg/m^3-air)	
Model results with biodegradation neglected						
Benzene	2,100	3.83	2	Y	3.9	
Toluene	3,300	5.99	5,200		33	
Ethylbenzene	2,800	4.74	2	Y	5.7	
Xylenes (total)	5,700	9.43	100		25	
MTBE	56,000	97.4	9	Y	9.5	Y
Cyclohexane	2,300	2.51	6,300		<1.7	
2,2,4-trimethylpentane	1,700	3.98	--		11	
Model results with biodegradation included						
Benzene	2,100	6.87E-3	2		3.9	
Toluene	3,300	1.32E-2	5,200		33	
Ethylbenzene	2,800	8.88E-3	2		5.7	
Xylenes (total)	5,700	4.35E-3	100		25	
MTBE	56,000	37.5	9	Y	9.5	Y
Cyclohexane	2,300	6.87E-5	6,300		<1.7	
2,2,4-trimethylpentane	1,700	8.86E-2	--		11	
Note: predicted indoor air concentrations noted as exceeding indoor air criteria (y) or as above local background ranges (y).						

Measurements of soil vapor below foundations and indoor air were collected and reported for buildings in the ‘dissolved plume only’ region of the site. The building measurements included basements, the first occupied floor, and soil vapor below the building foundation. Summary results are shown in Table I-15.

All reported indoor concentration values were either in the indoor ‘background’ range, below the indoor criteria, or both. More detailed attempts at analysis of indoor concentration measurement in this example would be significantly biased by indoor background concentrations.

All below-foundation measurements were within a factor of 4 of the basement measurements. This low foundation to indoor concentration ratio is insufficient to confirm, with confidence, either chemical flow to indoors from below the foundation or the converse (chemical flow from indoors to below the foundation).

Table I-15. Measured soil vapor concentrations below foundations and within buildings compared to criteria, Case 4 - Stafford

Chemical	Measured below foundation vapor (μg/m^3)	Measured indoor vapor (μg/m^3)	Indoor air concentration criteria (μg/m^3-air)	Indoor background concentration (μg/m^3)
Benzene	<3–2.1	<2–3.9	2	<1.6–3.9
Toluene	36–38	13–34	5,200	14–33
Ethylbenzene	15–18	3–5.8	2	<2.2–5.7
Xylenes (mixed)	75–94	18–27	100	11–25
MTBE	<4–5.2	<2–9.6	9	2.3–9.5
Cyclohexane	<2–<4	<2	6,300	<1.7

The analysis for the dissolved phase portion of the site data is complete. In possible further analysis, soil vapor samples (including O_2) can be measured at vertical profiles adjacent to buildings, not through and below building foundations. The BioVapor model may be applied in examining possible greater O_2 depletion (and possibly higher hydrocarbon vapor levels) below the buildings, than adjacent to buildings. This may include:

- estimates of vertical soil gas profiles adjacent to buildings, for which the open ground surface has ambient O_2 (21%v/v) and the depth from surface to vapor source is 3.3 m
- estimates of vertical profile below buildings, for which foundations are present, airflow (and available O_2 flux) may be limited below the foundation, and the depth from the foundation to the vapor source is 1.65 m

Subunit (2) Likely LNAPL Presence at Water Table

For the Subunit (2) "LNAPL Present" zone, maximum measured shallow groundwater concentrations, along with calculated equilibrium vapor concentrations are included in Table I-16. The values are compared to adjacent measured deep soil gas concentrations.

Table I-16. Dissolved groundwater to soil gas concentration comparison near LNAPL, Case 4 - Stafford

Chemical	Groundwater concentration (μg/L-water)	Henry's law coefficient (L/L) [at 7.5C]	Calculated equilibrium vapor concentration (μg/m^3)	Measured deep soil vapor concentration (μg/m^3)	Ratio measured /calculated
Benzene	12,000	0.102	1,224,000	660,000	0.54
Toluene	43,000	0.112	4,816,000	1,100,000	0.23
Ethylbenzene	4,200	0.119	499,800	<150,000	<0.30
Xylenes (total)	24,000	0.079	1,896,000	<150,000	<0.08
MTBE	590,000	0.014	8,260,000	5,900,000	0.71
2,2,4-Tri-	–	52.7	–	2,400,000	–

Table I-16. Dissolved groundwater to soil gas concentration comparison near LNAPL, Case 4 - Stafford (continued)

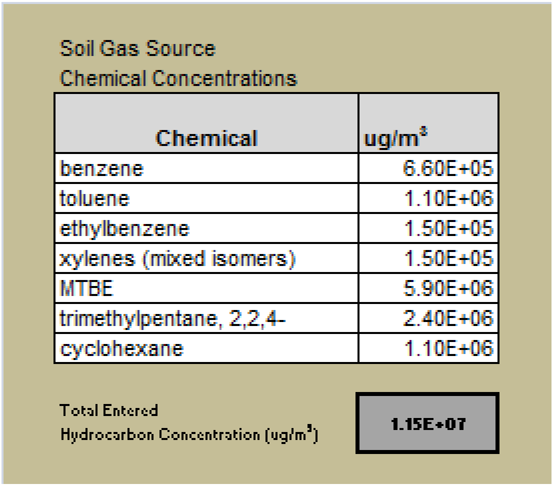
Chemical	Groundwater concentration (µg/L-water)	Henry's law coefficient (L/L) [at 7.5C]	Calculated equilibrium vapor concentration (µg/m³)	Measured deep soil vapor concentration (µg/m³)	Ratio measured /calculated
methylpentane					
Cyclohexane	<5,000	2.88	<14,400,000	1,100,000	--

The measured "Groundwater to Deep Soil Gas Attenuation Factor" for the chemicals with detectable concentrations in both deep soil vapor and groundwater is nominally near one. The concentration ratios and gradients are insufficient to establish that chemical flow is from groundwater to deep soil vapor or vice versa. The ratio is significantly higher than the nominal range of 0.01 to 0.001 seen in the prior 'dissolved plume only' analysis.

Because of detection limits, groundwater measurements do not adequately quantify chemical vapor concentrations for compounds with high Henry's law coefficients (This would potentially be an issue in areas where relatively insoluble LNAPL would be present). The high 2,2,4-trimethylpentane and cyclohexane vapor concentrations are therefore not detected (or measured) in groundwater. Measured soil vapor concentrations (including 2,2,4-trimethylpentane and cyclohexane) have been applied in the model.

Indoor air concentrations for these chemicals are estimated using the BioVapor model. Relevant and applicable model parameters, based on site-specific information, parameter assumptions applied by the local agency, and prior site reports are included as Case A in Table I-8. The indoor air criteria concentrations are from the local regulatory agency presuming residential building use, as in Table I-7. The applicable source vapor concentrations are shown in Table I-17.

Table I-17. BioVapor model source vapor concentrations, Case 4 - Stafford



Soil Gas Source
Chemical Concentrations

Chemical	ug/m³
benzene	6.60E+05
toluene	1.10E+06
ethylbenzene	1.50E+05
xylenes (mixed isomers)	1.50E+05
MTBE	5.90E+06
trimethylpentane, 2,2,4-	2.40E+06
cyclohexane	1.10E+06

Total Entered Hydrocarbon Concentration (ug/m³): 1.15E+07

The consolidated BioVapor model results for the specified source vapor concentrations are included in Table I-18. The screening criteria concentrations are exceeded, in the ‘biodegradation neglected’ results, for benzene, ethylbenzene, xylenes, and MTBE. In the ‘biodegradation included’ results, screening levels are exceeded for benzene and MTBE. The ‘no biodegradation’ estimates exceed background for all chemicals in the table. For the ‘biodegradation’ results, indoor concentration estimates exceed background for MTBE and 2,2,4-trimethylpentane.

Table I-18. Comparison of BioVapor model results to indoor air criteria, Case 4 - Stafford

Chemical	Soil gas source voncentration (µg/m^3-air)	Predicted indoor air concentration (µg/m^3-air)	Target indoor air concentration (µg/m^3-air)		Upper background concentration (µg/m^3-air)	
Model results with biodegradation neglected						
Benzene	660,000	1,200	2	Y	3.9	Y
Toluene	1,100,000	2,000	5,200		33	Y
Ethylbenzene	150,000	254	2	Y	5.7	Y
xylenes (total)	150,000	248	100	Y	25	Y
MTBE	5,900,000	10,300	9	Y	9.5	Y
Cyclohexane	1,100,000	1,900	6,300		<1.7	Y
2,2,4-trimethylpentane	2,400,000	3,540	--		11	Y
Model results with biodegradation included						
Benzene	660,000	3.6	2	Y	3.9	
Toluene	1,100,000	7.18	5,200		33	
Ethylbenzene	150,000	0.795	2		5.7	
Xylenes (total)	150,000	0.22	100		25	
MTBE	5,900,000	4,290	9	Y	9.5	Y
Cyclohexane	1,100,000	0.0884	6,300		<1.7	
2,2,4-trimethylpentane	2,400,000	162	--		11	Y

Note: predicted indoor air concentrations noted as exceeding indoor air criteria (y) or as above local background ranges (y).

Note that BTEX attenuation is three to four orders of magnitude greater with ‘biodegradation’ included versus neglected. In this scenario, biodegradation significantly contributes to BTEX attenuation. MTBE attenuation is similar (approximately within a factor of 2) with and without biodegradation included. Water-phase aerobic biodegradation rates for MTBE are slow compared to BTEX chemicals. 2,2,4-Trimethylpentane attenuation is within a factor of 20 with and without biodegradation included. While the water-phase aerobic biodegradation rate for 2,2,4-Trimethylpentane is significant (k_w = 11/hr), the high Henry’s law coefficient and relatively low soil moisture means that this chemical is partitioned predominately into the vapor phase, and is therefore not available for biodegradation in the water phase. Cyclohexane attenuation is four orders of magnitude greater with biodegradation included. The moderate Henry’s law coefficient and significant aerobic degradation rate contributes to this estimate.

For this site, follow-up measurements of soil vapor and indoor air were collected and reported for a number of buildings. This included air samples in basements, the first occupied floor, and soil vapor below the building foundation. For a single building (#73), three chemicals were measured above background concentrations in the basement, and with sub-foundation to indoor air ratios greater than 10, including MTBE, 2,2,4-trimethylpentane, and cyclohexane. The BTEX chemical concentrations measured indoors in all buildings were at or below nominal ‘background’ levels.

For empirical matching (or checking) of model parameters to measured data across a building foundation, where ‘background’ contributions can be neglected:

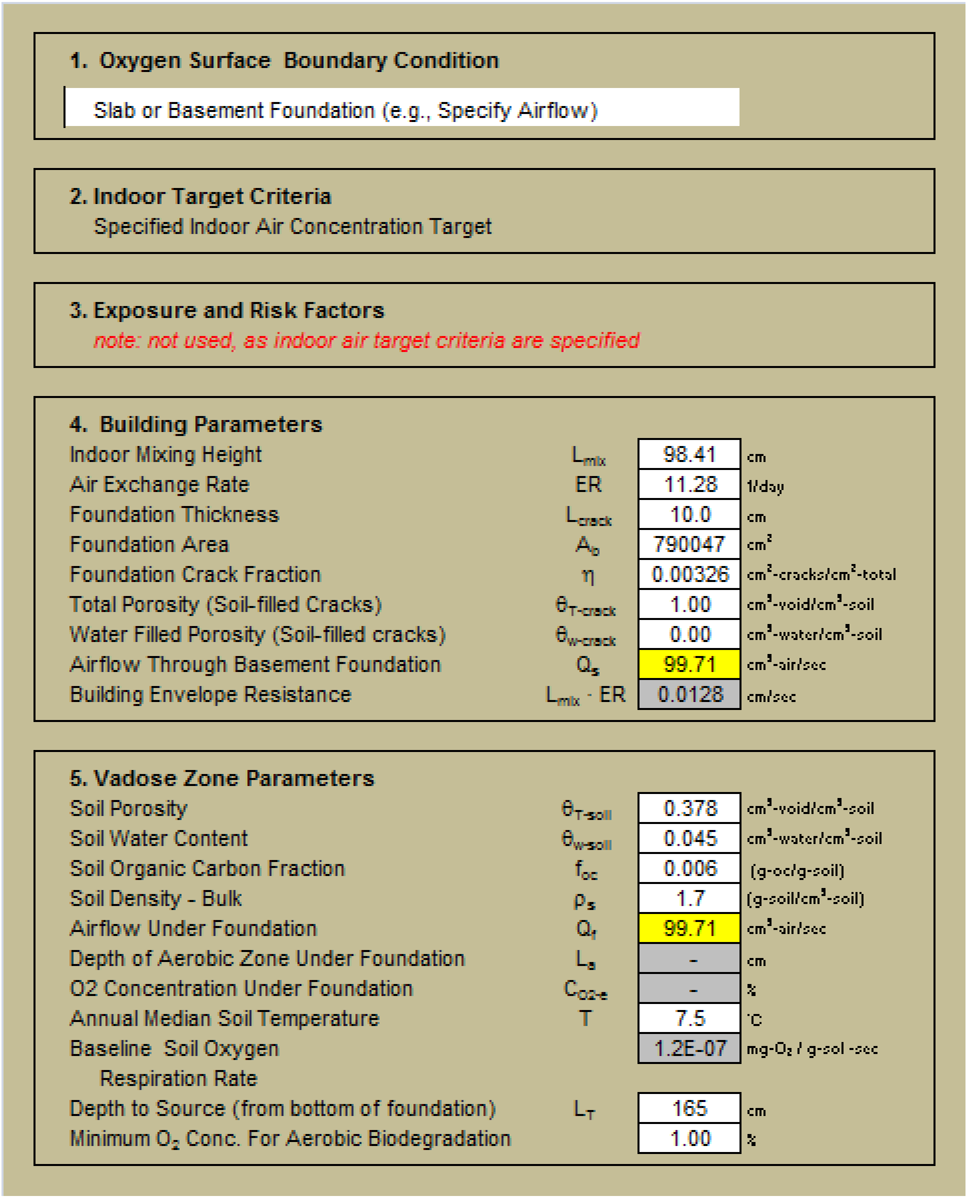
This indicates the ratio of foundation to building airflow is equal to the building to below foundation chemical concentration ratio. Values of c_e / c_f calculated from the data, with nominal-estimated building airflow presumed, as in Table I-8, can be used to estimate foundation airflow. Indoor air, c_e, in Table I-19 is the average of basement and ground floor concentration measurements.

Table I-19. Foundation airflow estimates based on indoor to below foundation concentration ratios, Case 4 - Stafford

Chemical	Measured below foundation vapor (µg/m^3)	Measured basement air (µg/m^3)	Measured ground floor air (µg/m^3)	Indoor ambient (median, literature) (µg/m^3)	Indoor to foundation ratio, c_e / $c_{f\,(--)}$	Foundation airflow, Q_s	
						(cm^3 /sec)	(L/min)
MTBE	18,000	130	52	6	0.010	103	6.16
2,2,4-Trimethylpentane	96,000	700	160		0.0090	90.9	5.46
Cyclohexane	15,000	130	26	<5	0.010	106	6.33
average:					0.0098	99.7	5.98

This site-specific (building-specific) estimate of Q_s is within the expected range (1 to 10 L/min) for a residential building. It is higher than the initially modeled value by approximately a factor of three. The model has been recalculated with this revised value of Q_s, with $Q_s = Q_f$, and all other parameters fixed, as in Case B Table I-8. Values entered in BioVapor are shown in Table I-20.

Table I-20. BioVapor model scenario parameters, Case 4 - Stafford; highlighted values are changed from Table I-9



1. Oxygen Surface Boundary Condition

Slab or Basement Foundation (e.g., Specify Airflow)

2. Indoor Target Criteria

Specified Indoor Air Concentration Target

3. Exposure and Risk Factors

note: not used, as indoor air target criteria are specified

4. Building Parameters

Indoor Mixing Height	L_{mix}	98.41	cm
Air Exchange Rate	ER	11.28	1/day
Foundation Thickness	L_{crack}	10.0	cm
Foundation Area	A_b	790047	cm^2
Foundation Crack Fraction	η	0.00326	cm^2-cracks/cm^2-total
Total Porosity (Soil-filled Cracks)	$\theta_{T\text{-}crack}$	1.00	cm^3-void/cm^3-soil
Water Filled Porosity (Soil-filled cracks)	$\theta_{w\text{-}crack}$	0.00	cm^3-water/cm^3-soil
Airflow Through Basement Foundation	Q_s	99.71	cm^3-air/sec
Building Envelope Resistance	$L_{mix} \cdot ER$	0.0128	cm/sec

5. Vadose Zone Parameters

Soil Porosity	$\theta_{T\text{-}soil}$	0.378	cm^3-void/cm^3-soil
Soil Water Content	$\theta_{w\text{-}soil}$	0.045	cm^3-water/cm^3-soil
Soil Organic Carbon Fraction	f_{oc}	0.006	(g-oc/g-soil)
Soil Density - Bulk	ρ_s	1.7	(g-soil/cm^3-soil)
Airflow Under Foundation	Q_f	99.71	cm^3-air/sec
Depth of Aerobic Zone Under Foundation	L_a	-	cm
O2 Concentration Under Foundation	$C_{O2\text{-}e}$	-	%
Annual Median Soil Temperature	T	7.5	°C
Baseline Soil Oxygen Respiration Rate		1.2E-07	mg-O_2 / g-sol -sec
Depth to Source (from bottom of foundation)	L_T	165	cm
Minimum O_2 Conc. For Aerobic Biodegradation		1.00	%

Model results are shown in Table I-21.Note that, while the model comparisons to criteria are similar as the last case, the increased foundation airflow has increased all of the 'no biodegradation' indoor concentration estimates. With biodegradation included, indoor concentrations are decreased for BTEX and cyclohexane, due to increased O_2 availability below the building foundation. Estimates of MTBE and 2,2,4-trimethylpentane indoor air concentrations are slightly increased in indoor air.

This completes the analysis for the LNAPL portion of the site. In possible further analysis, an additional analysis can check the sensitivity of indoor air concentration estimates to airflow below the building foundation (Q_f) while holding the foundation airflow through the foundation (Q_s) constant. This modeling simulates the effect of sub-foundation venting, without changing the mass transfer characteristics through the foundation.

Table I-21. Comparison of BioVapor model results to indoor air criteria, Case 4 - Stafford

Chemical	Soil gas source concentration (µg/m^3-air)	Predicted indoor air concentration (µg/m^3-air)	Target indoor air concentration (µg/m^3-air)		Upper background concentration (µg/m^3-air)	
Model results with biodegradation neglected						
Benzene	660,000	1,910	2	Y	3.9	Y
Toluene	1,100,000	3,160	5,200		33	Y
Ethylbenzene	150,000	387	2	Y	5.7	Y
Xylenes (total)	150,000	373	100	Y	25	Y
MTBE	5,900,000	15,800	9	Y	9.5	Y
Cyclohexane	1,100,000	2,930	6,300		<1.7	Y
2,2,4-tri-methylpentane	2,400,000	5,050	--		11	Y
Model results with biodegradation included						
Benzene	660,000	0.00295	2		3.9	
Toluene	1,100,000	0.00803	5,200		33	
Ethylbenzene	150,000	6.21E-4	2		5.7	
Xylenes (total)	150,000	1.78E-5	100		25	
MTBE	5,900,000	3140	9	Y	9.5	Y
Cyclohexane	1,100,000	3.21E-8	6,300		<1.7	
2,2,4-tri-methylpentane	2,400,000	7.62	--		11	Y
Note: Predicted indoor air concentrations are noted as exceeding indoor air criteria (Y) or as above local background ranges (y).						

I.4.5 Case 5. Application to Perth, Western Australia

This example shows use of the BioVapor model to aid the interpretation of site assessment data. The assessment data are published and available (Patterson and Davis 2009). An early version of the BioVapor model V2.0 beta 4, 2 Nov. 2009 (API, 2010b) was used in the model estimates.

I.4.5.1 Scenario Description

The site scenario is an existing abandoned and unoccupied slab on grade building, 18 by 13.5 m (width by length), with a 10 m wide concrete apron on three sides. The building is located on a petroleum refinery site. The groundwater depth below ground surface is approximately 3.3 m depth. There is kerosene reported in the capillary smear zone at the water table depth. Sand soil is present at the site. The site is located approximately 50 km south of Perth, Western Australia.

I.4.5.2 Qualitative Evaluation

Preliminary Questions and Checks:

Is the scenario consistent with conceptual model assumptions?

Are there other relevant issues that may need to be addressed?

The Qualitative criteria for identifying potential issues in vapor intrusion from subsurface to indoor air, and possible model exceptions include:

- The presence of highly affected water or gasoline directly within or in direct contact with basement, crawl spaces, sumps, or conduits. No.
- The presence of very large subsurface petroleum NAPL releases near foundations or subsurface enclosures. Yes. LNAPL under foundation.
- Confined lithology and pressure-driven vapor flow, where pressure may originate from rising or falling water tables and/or methane gas generation. No.

In addition, estimates of O_2 demand (and O_2 presence in the subsurface) are needed:

- O_2 demand in sand soil is low (site measured f_{oc} = 0.0048 g-oc/g-soil).
- Additional O_2 demand originates from PHC vapors evolved from the NAPL or residual petroleum present at water table depth below the building and adjacent to the building.

Criteria for identifying the suspect or confirmed presence of LNAPL are available in ASTM E2531 and EA (2003).

I.4.5.3 Chemical Vapor Source

Chemical analysis of soil gas indoors, and at the source, below and adjacent to the building is provided in the cited reference. The source vapor includes specific resolved hydrocarbon chemical components, and a significant unresolved petroleum hydrocarbon fraction. A soil vapor source concentration mixture is included in Table I-22.

Table I-22. Source vapor concentration, Case 5 - Perth

Chemical	Concentration (µg/m^3)	Concentration (g/m^3)
Benzene	<150	<0.00015
Toluene	<150	<0.00015
Ethylbenzene	140,000	0.14
Xylenes (mixed isomers)	<300	<0.0003
Cyclohexane	1,600,000	1.6
Methylcyclohexane	7,300,000	7.30
Unresolved TPH (~C8 aliphatics)	37,959,400	37.95
Total	47,000,000	47

Nondetects are set at the detection limit in the model estimates. The unresolved hydrocarbons in Table I-22, defined as C8 aliphatics, are reported as dimethylcyclohexanes, branched alkanes and cycloalkanes, and an unresolved mixture of aliphatic hydrocarbons. Qualitative interpretation of the gas chromatography result shows little source vapor contribution greater than approximately C10 in the mixture. The C8 aliphatic fraction in the mixture is a significant fraction of the total mixture, and a significant contributor to O_2 demand in this scenario.

Kerosene includes hydrocarbon chemicals of greater molecular weight than C10. These are relatively non-volatile, and would not be quantified in a soil vapor analysis. Groundwater analysis in the vicinity of the building shows detection of ethylbenzene (140 µg/L) and xylenes (220 µg/L). The reported vapor results and groundwater results are reasonably consistent with expectations for a kerosene –range hydrocarbon source. No methane soil gas analysis is reported.

Below open ground, adjacent to the building, reported total source vapor concentrations are lower than in Table I-22, totaling approximately 21,000,000 µg/m³ (21 g/m³). As volume concentrations, the measured source vapor concentrations below the building and adjacent to the building are, at a 3.3 m depth, approximately:

$(47\ \text{g/m}^3)\ (0.08206)\ (293.15)\ /\ (100\ \text{g/g-mol}) = 11.3\%\ \text{v/v}$ [below building]

$(21\ \text{g/m}^3)\ (0.08206)\ (293.15)\ /\ (100\ \text{g/g-mol}) = 5.0\%\ \text{v/v}$ [adjacent to building]

The lower flammability limit (LFL) for most fuel hydrocarbons in air (at 21% O_2) is approximately 1% v/v. A flammability screening level in air is often set at 25% of LFL, or nominally, 0.25% v/v (ANSI/API RP 505; NFPA 30). Source vapor concentration levels are above this 25% of LFL criteria. Note that exceeding this LFL criterion alone does not indicate 'flammable' levels or conditions within the soil matrix because: (1) the balance of soil gas is not 'air' at the subsurface source, but is depleted in O_2, and enriched in carbon dioxide; and (2) the thermal capacity of the soil matrix will quench flame propagation. It does indicate that flammability may be of potential concern if the vapors could accumulate in a subsurface enclosed space, at and above the flammability criteria limit, in the presence of O_2.

I.4.5.4 Modeling and Analysis

Based on the reference information, the evaluation of vapor intrusion for conditions reported at this site is presented for three scenarios:

- Scenario 1: Below and within the building.
- Scenario 2: Open ground surface adjacent to the building
- Scenario 3: Below and within the building, with the sealed building artificially depressurized by a ventilation fan.

Scenario 1: Below and within the building

Several permutations of building ventilation have been documented (Patterson and Davis 2009). This scenario includes variations for which the building was both well sealed and when an open window was simulated. A building depressurization case is described in Scenario 3.

For these scenarios, long-term chemical mass transfer through the building foundation can be estimated through indoor and subslab concentration measurements. The advective portion has also been estimated using the time-averaged measured results from a flux chamber placed over a hole drilled through the center of the building foundation (a simulated foundation 'crack').

From indoor and subsurface measurements of chemical concentrations, and from separate measurement of building air exchange rates, estimates of mass transfer across the building foundation are as follows. For purpose of data-fitting, advection-dominated chemical mass transfer through a building foundation is:

'Background' indoor and ambient contributions can be neglected. Indoor air tracer tests for the 'fully sealed building' and the 'partly sealed building - open window' yielded air exchange rates of 0.66 and 1.3 /hr respectively. These exchange rates and the building volume (760 m^3) yield estimates of building airflow, Q_b. With indoor (c_e) and subslab (c_f) concentration measurements of cyclohexane and methylcyclohexane, net airflow through the foundation, Q_s, is estimated as shown in Table I-23.

Table I-23. Estimates of foundation airflow based on indoor to below foundation concentration ratios, Case 5 - Perth

Chemical	Building	c_e Indoor (mg/m^3)	c_f Subslab (mg/m^3)	Q_s Foundation airflow (L/min)
Cyclohexane	Fully sealed	.071	800	0.74
Methyl-cyclohexane	Fully sealed	.29	1,700	1.05
Cyclohexane	Partly sealed	.033	800	0.68
Methyl-cyclohexane	Partly sealed	.079	1,700	0.57

Estimates can also be made using reported chemical flux into the building (through the flux chamber), and subslab concentrations, to estimate air flow rates in the range of $Q_s = 1$ L/min. This value. As shown in Table I-23, is calculated from the reported flux values of 11 and 31 mg/m^2-day for cyclohexane and methylcyclohexane, respectively, multiplied by a foundation area (243 m^2) and divided by the measured subslab concentrations of 800 and 1700 mg/m^3.

Table I-24. Estimates of Foundation Airflow Based on Foundation Flux Measurements. Case 5 - Perth

Chemical	Flux mg/m²-day	A_f (m²)	c_f Subslab (mg/m³)	Q_s Foundation airflow (L/min)
Cyclohexane	11	243	800	0.93
Methyl-cyclohexane	31	243	1,700	1.23

All of the values for Q_s are in reasonable agreement. Some variation may be due to the variable chemical concentrations below the building foundation (from the edge to the center), and due to the chosen location for the drilled foundation hole (the simulated foundation 'crack'). Note this value for Q_s is empirically determined from concentration data. It is a mass transfer coefficient, not an actual or net flow rate of air into the building from the subsurface. Concurrently measured pressure data for the building indicated alternate positive/negative pressure gradients across the building foundation; this confirms two-way advective flow through the foundation.

Nominally, in the modeling, 2.3 L/min (38.3 cm³/sec) Q_s is chosen as an air flow value through the foundation. Other calculated values for foundation airflow values are in a similar range and yield similar results. Other applied modeling parameters, based on the reference information, are included in Table I-25. The airflow through the foundation, Q_s, is set equal to the airflow below the foundation, Q_f.

Key: specified, derived, and required model parameters are tabulated for case 1.

Table I-25. Applied BioVapor model parameters, Case 5 - Perth

Value	Symbol	Parameters
		Oxygen surface boundary condition
		slab or basement foundation (e.g., specify airflow)
		Vapor inhalation exposure parameters
		not applied directly in this case example
		Building parameters and geometry
1,800	W_b	(cm) building width
1,300	L_b	(cm) building length
2,340,000	$W_b \cdot L_b$	(cm²) building footprint area
324.8	H_b	(cm) building height
0	D_b	(cm) depth to base foundation below grade
324.8	L_{mix}	(cm) enclosed space volume/infiltration area ratio, or mixing height = $Q_b / (A_b \cdot ER)$
15.84	ER	(1/day) enclosed space air exchange rate
760,000,000	V_b	(cm³) building volume = $W_b \cdot L_b \cdot H_b$
139,333	Q_b	(cm³/sec) building airflow = $V_b \cdot ER$
8.36	Q_b	(m³/min) building airflow
2,340,000	A_b	(cm²) subsurface foundation area in contact with soil = $W_b \cdot L_b + D_b \cdot 2 \cdot (W_b + L_b)$
19	L_{crack}	(cm) enclosed-space foundation or wall thickness
0.0001984	W_{crack}	(cm) crack width - perimeter crack

Table I-25. Applied BioVapor model parameters, Case 5 - Perth (continued)

Value	Symbol	Parameters
1.23	A_{crack}	(cm^2) crack area = $W_{crack} \cdot 2 \cdot (W_b + L_b)$
5.26E-7	η	(cm^2-cracks/cm^2-total area) foundation crack fraction = A_{crack} / A_b
2.298	Q_s	(L/min) soil gas advection rate
38.3	Q_s	(cm^3-air/sec) convective airflow through basement foundation
38.3	Q_f	(cm^3-air/sec) convective airflow under basement foundation, $Q_f = Q_s$ or $Q_f > Q_s$
330	L_T	(cm) depth - below basement slab to groundwater depth vapor source
330		(cm) depth - soil surface to groundwater vapor source depth = $L_T + D_b$
		Soil parameters
Sand		soil type
0.5	θ_T	(cm^3-void/cm^3-soil) soil porosity, vadose-zone soils
0.11	θ_w	(cm^3-water/cm^3-soil) soil water content, vadose-zone soils
1	θ_T	(cm^3-void/cm^3-soil) soil porosity, soil filled basement cracks
0	θ_w	(cm^3-water/cm^3-soil) soil water content, soil-filled basement cracks
0.0048	f_{oc}	(g-oc/g-soil) soil organic carbon fraction, vadose-zone soils
1.32	ρ_s	(g-soil/cm^3-soil) soil density – bulk
		Environmental parameters
20	T_{amb}	(°C) ambient temperature
760	P_{amb}	(mmHg) atmospheric pressure

Table I-26. BioVapor model results, Case 5 - Perth

Chemical	Subslab concentration (µg/ m^3)	Subslab concentration (µg/ m^3)	Indoor air concentration (µg/m^3)	Indoor air concentration (µg/m^3)
	Measured	Estimated	Measured	Estimated
Benzene	NM	28.9	NM	7.94E-3
Toluene	NM	32.2	NM	8.86E-3
Ethylbenzene	NM	2.96E+4	NM	8.14
Xylenes (mixed)	NM	44.9	NM	1.23E-2
Cyclohexane	8.0E+5 ± 4.7E+5	1.08E+5	110+/-100	29.7
Methylcyclohexane	2.3E+7 ± 1.4E+7	2.47E+6	300 +/- 240	678
C8 Aliphatic	NM	1.5E+7	NM	4,130
Total	4.7E+7 ± 1.4E+7	1.76E+7	<50,000	4,840
NM- not measured or reported.				

Results are shown in Table I-26. These results indicate reasonable agreement between measured values and modeled values. Both the modeled and measured indoor air concentrations are below nominal chronic indoor air inhalation concentration criteria.

The model results estimate an aerobic depth below the building foundation of 1.35 cm. This minimal value is consistent with the measured and reported absence of O_2 in profiles below the center of the building foundation.

The total estimated subslab vapor concentration from the model is:

(17.6 g/m^3) (0.08206) (293.15) / (100 g/g-mol) = 4.2% v/v

Total measured subslab concentrations are in the same range:

(47 g/m^3 ± 14 g/m^3) (0.08206) (293.15) / (100 g/g-mol) = 11.3 ± 3.7% v/v

In both the measured data and the modeled results, the subslab concentrations are above the nominal criteria for the hydrocarbon flammability limit (25% LFL = 0.25% v/v).

Further, the reference document discusses measured long-term advective flux values of 11 and 31 mg/m^2-day for cyclohexane and methylcyclohexane, respectively, from the created foundation ‘crack’. These values include a time-average over which air flows cyclically through the foundation crack, from the subsurface into the building and vice-versa. Short-term flux values of up to 4200 and 12000 mg/m^2-day, are reported during the period when soil gas was flowing into the building. These peak flux values in the vicinity of the foundation crack are 380 times the long-term flux mean values. The concentration of soil vapor in the immediate vicinity of a crack is nearly equal to the subslab soil vapor concentration. Once mixed into the building, and averaged over time, concentrations are substantially lower.

These results indicate:

- Long-term chronic exposure criteria for vapors are met within the building.
- There is the potential for flammable levels of subslab soil vapors to flow into the building, immediately adjacent to foundation cracks. Flammability criteria are short-term; and are best evaluated against short-term concentration estimates or measurements.
- Meeting chronic long-term chemical toxicity criteria are not necessarily protective of potential short-term flammability hazards.

Scenario 1. Notes on vapor diffusion through the concrete slab

Diffusion rates through concrete are documented in measurement for a number of chemicals, including measurements made on a concrete core removed from the building under test in the present example. Most of the measured chemical-specific values fall in a one order-of-magnitude range of 3.0E-8 to 4.6E-7 m^2/sec, presumably for ‘air dry’ concrete. The ‘water-wet’ concrete diffusion value for O_2 is two orders of magnitude less (4E-10 m^2/sec), which is consistent with expectations, due to reduced air-filled porosity. As a nominal effective diffusion rate (for dry concrete), an average value from this data has been selected.

Table I-27. Diffusion rates through concrete, Case 5 - Perth

Value	Symbol	Units	Comments
4.6E-7	D_{eff}	(m^2/sec)	Methane. Haghighat, Lee, and Ghaly (2002)
5.1 E-8 to 3.9E-7	D_{eff}	(m^2/sec)	Ethyl acetate. Haghighat, Lee, and Ghaly (2002)
1.0E-7 to 3.0E-7	D_{eff}	(m^2/sec)	N-octane. Haghighat, Lee and, Ghaly (2002)
2.4E-7	D_{eff}	(m^2/sec)	N-dodecane. Haghighat, Lee, and Ghaly (2002)
5.1E-8 to 4.6E-7	D_{eff}	(m^2/sec)	Cyclohexane. Haghighat, Lee, and Ghaly (2002)
3.0E-8	D_{eff}	(m^2/sec)	Cyclohexane. Patterson and Davis (2009)
4E-8 (dry)	D_{eff}	(m^2/sec)	O_2. Nominal, effective diffusion through air-dry and water-wet concrete. (Kobayashi and Shuttoh, 1991; Tittarelli 2009) [investigated to attribute steel rebar corrosion rates]
4E-10 (wet)			
4.3 E-8	D_{eff}	(m^2/sec)	Nominal average effective vapor diffusion rate through dry concrete.
2.6E-6	D_{eff}	(m^2/min)	[unit change]

An equivalent advective airflow through the foundation, Q_s, which results in the same mass transfer as a diffusion estimate through the concrete slab, is:

$$Q_s = (18\ \text{m})\cdot(13\ \text{m})\cdot(2.6\text{E-}6\ \text{m}^2/\text{min})/(0.19\ \text{m}) = 0.0032\ \text{m}^3/\text{min} = 3.2\ \text{L/min}$$

This calculation indicates diffusive mass transfer through the concrete foundation is approximately of the same order as empirically estimated using the indoor/subslab concentration measurements and the flux measurements in the vicinity of the created crack. In the absence of advection, mass transfer through a foundation is not zero. Diffusive mass transfer through the intact foundation still occurs. Both chemicals and O_2 diffuse through concrete. The diffusive estimate provides a lower limit for minimal mass transfer through an intact foundation, and can be re-normalized for larger or smaller foundation areas.

Scenario 1. Notes on chemical-specific vapor attenuation

Tabulated subslab and indoor vapor concentrations can be divided by the vapor source concentration. Resulting values are shown in Table I-28.

Table I-28. Chemical-specific concentration ratios, Case 5 - Perth

Chemical	Subslab/source (measured)	Subslab/ source (estimated)	Indoor air/ source (measured)	Indoor air/ source (estimated)
Benzene	NM	>0.19	NM	>5.3E-5
Toluene	NM	>0.22	NM	>5.9E-5
Ethylbenzene	NM	0.21	NM	5.8E-5
Xylenes (mixed)	NM	>0.15	NM	>4.1E-5
Cyclohexane	0.5 ± 0.3	0.068	6.9E-5 ± 6.2E-5	1.9E-5
Methylcyclohexane	3.2 ± 2.0	0.34	4.1E-5 ± 3.3E-5	9.2E-5
C8 Aliphatic	NM	0.4	NM	1.1E-4
Total	1.0 ± 0.3	0.37	<1.0E-3	1.0E-4

NM indicates a concentration value that is not measured or reported.
> indicates the actual value is greater than the value shown (the source concentration in the denominator is below the detection limit).
< indicates the actual value is smaller than the value shown (the indoor or subslab concentration in the numerator is below the detection limit).

All of the measured subslab to source concentration ratios are approximately equal to one; the modeled subslab to source values are within a order of magnitude of the measured values. Both the measured and modeled subslab to source ratios indicate slightly greater attenuation for cyclohexane than methylcyclohexane. All of the unqualified (no <, >, or NM) indoor air to source concentration ratios are in the 1E-4 to 1E-5 range.

Suggested further evaluation for Case 5:

As further evaluation of this Case, running a series of scenarios for varied source concentrations (but the same relative source composition), and tabulating the subslab total hydrocarbon vapor concentrations and estimated subslab O_2 concentrations would establish an acceptable source concentration, below which subslab soil gas would be below flammable criteria limits.

Scenario 2: Open ground surface adjacent to the building

As a permutation, Scenario 2 is run with the BioVapor model with an 'open' ground surface boundary. This is a change of O_2 boundary condition from 'constant airflow' to 'constant concentration', with 21% O_2 fixed just above the soil surface. This change results in an increase of the calculated aerobic depth from 1.35 cm to 229.4 cm. This result is consistent with site data measurements. Measurable O_2 is monitored at significant concentrations at depth, at the site, in an area where the soil surface is open to the atmosphere and significant vapor concentrations are measured at depth.

Scenario 3: Sealed building artificially depressurized by a ventilation fan

In this evaluation, the sealed building is depressurized by a ventilation fan. In tracer tests, this depressurization increased the building ventilation rate to ER = 2 /hr, and also resulted in an imposed negative pressure gradient from the soil to indoors of approximately -12 Pa. Monitored indoor concentrations of cyclohexane and methylcyclohexane, respectively, following the depressurization, were reported as 1100 and 3400 μg/m^3.

With these increased indoor air concentrations, airflow through the foundation, using

is estimated to increase to Q_s = 34.8 or 37.4 L/min, with the applicable calculations shown in Table I-29.

Table I-29. Foundation airflow estimates based on indoor to below foundation concentration ratios for the depressurized building, Case 5 - Perth

Table I-29. Foundation airflow estimates based on indoor to below foundation concentration ratios for the de-pressurized building, Case 5 - Perth

Chemical	Building	c_e Indoor (mg/m^3)	c_f Subslab (mg/m^3)	Q_s Foundation airflow (L/min)
Cyclohexane	Depressurized	1.1	800	34.8
Methyl-cyclohexane	Depressurized	3.4	1,700	37.4

With the value of Q_s = 34.8 L/min entered in the BioVapor model, a significant aerobic depth below the building foundation is estimated, with an overall decrease (not increase) in indoor air concentrations.

The above discrepancy may have occurred because the model is steady-state, and the imposed pressure change on the building and subsurface soil did not continue for a long enough time period for the transient change in concentrations to approach steady state in the soil layer below the building. Note there is discussion of apparent inconsistencies in the flux and concentration measurements in Patterson and Davis (2009).

With increased airflow through the building foundation, additional surface air is drawn under the building, and O_2 levels should increase under the building. The longest time constant, and therefore limiting time period, in this system is in the diffusion-limited transfer of O_2 into soils at depth below the building. A simple estimate of the transient period for O_2 diffusion through soil, neglecting phases other than vapor, and neglecting O_2 consumption, is:

With σ = 3.3 m (the foundation to source separation distance), D_{eff} = 0.000149 m^2/min (effective diffusion coefficient for O_2), and the air-filled soil fraction, θ_a = 0.39 cm^3/cm^3, this yields t = 11630 minutes (8 days).

Once this 8-day (approximately) time period has elapsed, the transient change in the soil profile of O_2 and hydrocarbon should reach a new quasi-steady state, and the model is expected to better agree with concentration measurements. The experimental building depressurization test lasted for a period of a few hours, not 8 days (personal communication, Patterson to DeVaull).

A relevant study of transient O_2 movement below a building foundation has also been reported (Lundegard, Johnson, and Dahlen 2008). The Lundegard data is also consistent with diffusion-limited transfer of O_2 into soils at depth below the building, in the time period after the purging soil vapors below the building with nitrogen and monitoring the return of O_2.

APPENDIX J. VAPOR INTRUSION CONTROL

This appendix explains how to perform the following tasks:

- Determine and select remediation technologies or a mitigation system that is most appropriate for the site situation to minimize the vapors from entering a structure based on site information.
- Identify performance and closure considerations and strategies for a given mitigation system or remediation technology.

Vapor control for VOCs can include environmental remediation, building mitigation measures, and institutional controls (ICs) to reduce or prevent VI from occurring. The management of vapors may be required at sites when the results of the site investigation phase indicate that indoor air concentrations of volatile compounds exceed mitigation screening levels in existing buildings or are likely to exceed screening levels in future buildings.

Environmental remediation refers to an action that reduces the threat by removing concentration or mass from the media that is affected, while mitigation generally refers to actions that prevent or minimize exposure from the affected media. When either action is required, a remedy or combination of remedies can be selected, implemented, operated, maintained, and monitored to control VI until the source of the vapors is eliminated.

ICs can take many forms, including restrictive covenants, zoning modifications, excavation prohibitions, and groundwater advisories. At undeveloped sites, or at sites where land use may change in the future, ICs may be necessary to ensure that the VI pathway is effectively addressed in the future. ICs can include mechanisms to require the preemptive installation of a vapor control technology or require further assessment. This practice avoids some of the difficulties associated with attempting to predict the potential for VI prior to building construction (because soil gas concentrations and distributions might change due to construction of the building).

Vapor control strategies, whether implemented as part of an ongoing environmental remediation or as part of a building specific mitigation, can be implemented as part of an emergency response action or to address longer-term exposure issues. The descriptions and details provided here focus mainly on the chronic exposure concerns and the investigation and design of an appropriate response. Though some of the technologies discussed below may be similar for emergency situations where the immediate and short-term health and safety of the building occupants is the primary concern, further consideration should determine whether the approach is an appropriate response action.

This appendix provides updates on the remedial and vapor control technologies originally identified in ITRC guidance *Vapor Intrusion Pathway: A Practical Guideline* (ITRC 2007) and has also been expanded to include new and additional technologies that may be appropriate for sites with PVI.

J.1 Vapor Control Technologies

As identified above, vapor control technologies can include:

- environmental remediation
- ICs
- building mitigation measures

When actions are required, a remedy, IC, or combination of remedies can be selected, implemented, operated, maintained, and monitored to control VI until the source of the vapors is eliminated. In most cases, site-wide remedies and ICs are long-term solutions to VI, while building mitigation measures are short-term or interim remedies, implemented until the long-term or site-wide remedy is complete.

Interim actions typically are used to control or abate ongoing risk to human health or the environment in advance of final remedy selection. At some point during the course of an investigation, it may be determined that an interim remedial action is necessary due to the time necessary to complete the building vapor control design. For PVI, the interim response action may be the final response action or it may be a technology that can be effectively and rapidly implemented.

Reasons for taking an interim action may include the need for the following measures:

- Take quick action to protect human health and the environment from an imminent threat in the short term, while a final remedial solution is being developed.
- Institute temporary measures to stabilize the site, prevent further migration or degradation, or both.

J.1.1 Remediation to Reduce or Eliminate Vapors

Site-wide remedies address the source contributing to vapors found in buildings, such as contaminated soil and groundwater, rather than controlling the entry of vapors into buildings. However, site-wide remedies may be sufficient in situations where the vapor concentrations in buildings are very low or where source remediation can be conducted very quickly.

Remediation of soil and groundwater contamination may include remedial technologies to reduce contaminant concentrations in site soils and soil gas, such as soil vapor extraction, or technologies that reduce concentrations in the groundwater, such as in situ bioremediation or multiphase extraction. For a remedial action to be protective for VI, exposures to vapors must be reduced and controlled until concentrations in the soil or groundwater reach acceptable levels. In general, source removal and soil vapor extraction site-wide remedies are likely to have the greatest potential to reduce or eliminate soil gas migration in the short term and, thus, preempt the need for interim control (such as institutional or building control) remedies. In cases where VI has been identified as an issue, the VI pathway must be effectively controlled in all potentially affected and inhabited structures.

Sites that may use a remedial technology to address a VI issue can be generally categorized into three groups:

1. A site that has a remedial technology being implemented that is also capable of addressing the source of vapors at the site (for instance, for a source under or next to the structure, SVE can provide source removal as well as vapor control into the building).
2. A site that has a preferential pathway (such as vapors entering the building via a sewer trench) that is causing the vapors to migrate towards and into a structure and a remedial technology is used to address a specific route of entry.
3. A site at which the potential VI sources are to be remediated or addressed in a short enough time that mitigation is not warranted (for example, source removal through dig and haul) and no emergency response is required.

Although site-wide remedies are not the focus of this document, numerous resources are available from ITRC and USEPA to provide assistance with selecting technologies and approaches associated with source control. These resources include (but are not limited to):

- *Technical and Regulatory Guidance for In Situ Chemical Oxidation of Contaminated Soil and Groundwater* (ITRC 2005b)
- *Evaluating LNAPL Remedial Technologies for Achieving Project Goals* (ITRC 2009)
- USEPA CLU-IN: *Technologies: Remediation* (USEPA 2013g)
- *USEPA Institutional Controls* (USEPA 2013k)
- *Road Map to Understanding Innovative Technology Options for Brownfields Investigation and Cleanup* (USEPA 2005a)

J.1.2 Institutional Control Remedies

ICs are non-engineered instruments, such as administrative and legal controls, that help minimize the potential for human exposure to contamination and protect the integrity of the remedy. ICs typically play an important role in site remedies because they reduce exposure to contamination by limiting land or resource use, providing notifications to owner and a regulatory agency, and guiding human behavior at a site.

However, there are significant drawbacks to ICs that include:

- ICs can be difficult to implement and enforce over time.
- Some states or parties may not have adequate statutory authority to implement ICs.
- An IC also may not be immediately apparent and be difficult to identify, especially for those that establish building type, occupancy, or even prohibited activities on all or even a portion of the property.
- An IC may limit or prevent future development activities.

In the event that site-wide remedies are not immediately effective in reducing or eliminating the potential for VI, or at undeveloped sites or at sites where land use may change in the future, ICs may be necessary to ensure that the VI pathway is effectively addressed. In most states, ICs can be put in place on either an interim or permanent basis to protect human health while the longer-term, site-wide remedies are being developed and implemented.

At undeveloped sites, or at sites where land use may change in the future, ICs may also be necessary to ensure that the VI pathway is effectively addressed in the future. Institutional controls at undeveloped sites caninclude mechanisms to require the preemptive installation of VI controls, such as subslab venting or depressurization systems, in new buildings. This approach avoids some of the difficulties associated with attempting to predict the potential for VI prior to building construction (because soil gas concentrations and distributions might change due to construction of the building). Installation and operation of fans, however, might not be required unless post-construction testing or other evaluations indicated a need.

ICs, like site-wide media remedies, are not the focus of this document. There are several guidance documents available that discuss the implementation of effective and reliable ICs and address the use of ICs as part of environmental remediation. The USEPA provides several documents on ICs (USEPA 2013n)

J.1.3 Mitigation Using Building Control Technologies

Building control technologies are typically required at VI sites (in both existing and new buildings) until long-term, site-wide remedies reduce soil and groundwater concentrations to acceptable levels. The following sections discuss various VI building control technologies, factors affecting technology selection, and common design and installation issues.

Several effective vapor control technologies may prevent the migration of vapors into a building and each have their advantages and disadvantages. One of the main considerations when evaluating each technology, however, is the long-term performance. CVOCs persist on site without active remediation of affected soil and groundwater. For these sites, the vapor control technology selected must operate over the long term or perhaps permanently. The exception to this practice is at VI sites with compounds associated with petroleum releases from underground storage tanks, where biodegradation can occur.

Table J-1 provides a summary of common building control technologies implemented for VI, which can be used as part of a remedial action. This table also provides a typical range of installed costs. However, because of various site conditions that affect the overall installation costs and material required, costs should be evaluated based on actual conditions (which may include additional costs associated withlead paint and asbestos abatement).

Table J-1. Summary of mitigation methods

Technology	Typical applications	Challenges	Range of installation costs (per ft^2)$^{(1)}$
Active system			
Subslab depressurization (SSD)	Most structures; sumps, drain tiles, aer-	Low permeability and wet soils may limit performance, oth-	\$2–\$10/ft^2; residential systems typically in the \$2-4/ft^2

Table J-1. Summary of mitigation methods (continued)

Technology	Typical applications	Challenges	Range of installation costs (per ft^2)(1)
	ated floors, and block wall foundations may also be depressurized if present	erwise, highly effective systems; may require a discharge permit	range
Subslab ventilation (SSV) or Crawl space venting	New and existing structures relies more on influencing air flow over depressurization	Low permeability and wet soils may limit performance, otherwise, highly effective systems; may require a discharge permit	\$2–\$10/ft^2; residential systems typically in the \$2-4/ft^2 range
Submembrane depressurization (SMD)	Existing structures, crawl spaces	Sealing to foundation wall, pipe penetrations; membranes may be damaged by occupants or trades people accessing crawl space	\$1–\$6/ft^2; residential systems typically in the \$1.50–\$2/ft^2 range
Subslab pressurization (SSP)	Same as SSD; most applicable to highly permeable soils	Higher energy costs (not included) and less effective than SSD; potential for short-circuiting through cracks	\$1–\$5/ft^2
Building pressurization	Commercial structures that are specifically designed	Requires regular air balancing and maintenance; may not maintain positive pressure when building is unoccupied and may have high O&M costs	\$1–\$15/ft^2; heavily dependent on size and complexity of structure
Passive barrier			
Asphalt/latex membrane	Typically limited to new construction prior to flooring being installed and crawl spaces; retrofitting a building is possible with the installation of an additional protective barrier	Preventing tears and holes in the liner during installation; may not suffice as a stand-alone technology; must be chemically compatible with the COC	\$3–\$7/ft^2 for the system which includes liner costs of \$2–\$6/ft^2 and a passive venting system cost of \$0.75–\$2/ft^2 *see Note (2)
Thermoplastic liner	Typically limited to new construction prior to flooring being installed and crawl spaces; retrofitting a building is possible with the installation of an additional protective barrier	Preventing tears and holes in the liner during installation; may require seaming and taping; addressing subsurface penetrations; may not suffice as a stand-alone technology; limited vapor resistance testing available; may not suffice as a stand-alone technology	\$2–\$7/ft^2 for the system which includes liner costs of \$0.50–\$5/ft^2 and a passive venting system cost of \$0.75–\$2/ft^2 *see Note (2)
Epoxy floor sealant system	Retrofitting an existing structural slab in which a spray or roll is applied to seal floor	Existing surface preparations (oil and grease free, level, competent); ensuring total or complete coverage; preventing	\$1–\$7/ft^2 cost varies on the amount of surface preparations and leveling required. System may also

Table J-1. Summary of mitigation methods (continued)

Technology	Typical applications	Challenges	Range of installation costs (per ft²)(1)
	surfaces	tears, holes by building use; surface wearability and durability depending on application; may require subsurface venting as well as venting during placement	additional costs of a passive venting system cost ($0.75–$2/ft²)
Passive Venting			
Subslab venting; perforated pipe/low-profile vent and gravel layer	New construction; existing construction would require additional surface protection	Relies on advective flow of air due to wind and heat stack effects; does not continuously operate; air flows and suction typically far less than achieved by active systems; limited regulatory acceptance	$0.75–$5/ft² plus the additional cost of an engineered base consisting of sand or gravel
Aerated flooring	New construction, complete floor replacement, or floor overlays	Relies on advective flow of air due to wind and heat stack effects to increase the oxygen; fans may require to achieve additional air flows and suctions; may not be effective for CVI	New construction, $2–$2.75 /ft² *see Note (2)
Other			
Indoor air treatment	For marginal or low impacts, immediate response actions to address vapor (short term), and expected short time frames for a completed remedial action	Typically generates a waste disposal stream; effective capture of air contaminants may be difficult; energy-intensive, with significant O&M burden	Costs are highly variable dependent upon the building layout, the number of rooms, contaminant, concentration and overall size in addition to the type of technology employed. $15,000–$25,000 per application is typical for treatment of a single 2,000 ft² area.
Sealing the building envelope		May not be effective over the long term	$2.50–$6/ft²; cost varies depending on surface preparations

Notes:
(1) Costs for many of these technologies may be outside the ranges listed above due to many factors (such as regional contractor rates, regulatory review, access issues, and O&M).
(2) Estimated costs do not include the cost of any required additional protective barriers or construction overlays ($2–$4 /ft²) not anticipated through normal construction practices.

J.1.3.1 Passive Barriers

Passive barriers are materials or structures installed below or above a building foundation to physically block or limit the entry of vapors into a building. Passive barriers ideally cause soil gas that would otherwise enter the building under diffusion or pressure gradients to migrate beyond the building footprint. In reality, it may be difficult to completely prevent, or even substantially prevent, the entry of vapors into a building by passive barriers alone. Therefore, passive barriers are generally used in conjunction with passive venting. Any design of a passive barrier, however, should allow the venting system to be supplemented or upgraded to an active system or allow other measures to address inadequate performance. Many states require the use of either passive or active venting to enhance the efficiency of the barrier.

Design Considerations

Prior to the installation of any passive barrier or other mitigation components, the design must address how the construction materials may affect the necessary performance monitoring requirements.

Most passive barriers consist of spray-on asphalt latex membranes, epoxy floor sealants, or low-permeability thermoplastic membranes. The design of a passive barrier should be supported by vapor diffusion coefficients, which assist in evaluating the liner's effectiveness for the site contaminants present. In new structures, barriers are typically installed after the utilities are in place and below the lowest level (prior to the floor slab being installed). In existing structures, membranes can be used to retard the intrusion of vapors in crawl spaces or over dirt floors; however, in most circumstances their use requires the installation of an additional protective layer, which will increase the installation costs of the liner.

Passive barrier designs should include QA/QC plans to address the potential of damage to the membranes during installation, subsequent concrete pours, and building construction activities. It is also important that all future site activities include protocols for minimizing damage until a protective barrier (if necessary) has been installed. The QA/QC should also require thorough inspection of liner seals along all edges and at penetrations, observation during concrete pouring, and detailed procedures for testing the efficacy of the passive barrier after the slab is placed and (for example, pressure tests, smoke tests, and post-construction indoor air tests).

Damage to Passive Barriers

To be effective, passive barriers must provide a complete barrier to vapor intrusion for the compounds of interest. Even small imperfections in the barriers (such as those due to holes, tears, or incomplete seals at the footings or pipe penetrations) may provide a significant migration route for soil gas. Even thicker (10–20 mil) membranes may be damaged during construction, particularly if placed below concrete slabs. The potential for punctures may be reduced by using thicker membranes. As a result some agencies have identified minimum liner thickness (EPA 2008a; Illinois 2013).

Refer to ASTM Standard E 1643-11 for more information regarding the use of water vapor barriers, although this standards is not sufficient to address the chemicals associated with VI and should not replace chemical specific diffusion testing. It is key when designing a passive barrier that the performance methods are identified and agreed upon by all parties. Section J.3 provides additional design considerations for a passive barrier system.

Asphalt Latex Membrane

Most asphalt latex membranes are seamless, spray-applied, water-based membranes containing no VOCs, which provide a deterrent against VI. The membrane is typically installed prior to pouring the concrete slab and below-grade vertical walls in order to fully encapsulate the building footprint. The membrane is typically sprayed onto a carrier geosynthetic (geotextile or thermoplastic membrane).

Thickness measurements during the QA/QC process are critical to ensure proper performance of the installed membrane. The curing processes for these membranes highly depend on temperature, humidity, and convective air exchange rate surrounding the membrane. Care must be taken during the curing process to protect the membrane from punctures and damages. The potential for punctures may be reduced by using cushioning materials (geotextile or thermoplastic membrane) above the membrane and sand or fine-rounded gravel (pea gravel) below.

Key Elements of Asphalt Latex Membrane Systems

- *Do not expect complete elimination of vapors.*
- *Select barriers that have sufficiently low permeability for the COC.*
- *Include thorough quality control procedures to minimize barrier damage.*
- *Test barrier integrity and performance after installation.*
- *Have contingencies to enhance passive barriers if they prove inadequate.*

Table J-2. Asphalt latex membrane – Advantages and disadvantages

Advantages	Disadvantages
Low to moderate capital cost	Even small holes can render the membrane ineffective
Spray application should securely bond to most surfaces; eliminates mechanical fastening	Likely not effective without venting
Chemically resistant and adheres to the underside of the slab in case of soil settlement.	Limited applications for existing structures that do not have subslab venting.

Figure J-1 Spray-applied membrane.

Source: Land Science Technologies, a division of REGENESIS.

The grade of latex (polychloroprene or styrene butadiene rubber) varies from manufacturer to manufacturer and the compatibility with the COCs and the potential for the product to off-gas should be assessed on a case-by-case basis.

Epoxy Floor Sealants

The epoxy floor sealant system is a vapor mitigation system that uses a chemically-resistant coating with a 100% solid epoxy blend. The system is designed to protect existing structures from VI without the need for additional concrete protection. Typical epoxy floor sealant systems can range between 10 to 60 mil and can be installed directly on top of an existing concrete slab. The epoxy floor sealant system is relatively new but appears to be effective, especially when used in conjunction with a passive venting system.

Key Elements of Epoxy Floor Sealant System

- *Can be used on existing structures without additional concrete protection.*
- *Poor surface preparations can cause the membrane to peel or flake off.*
- *Forms a chemically-resistant barrier.*
- *Depending on wear and use, additional applications may be necessary in the future.*

Table J-3. Epoxy floor sealants – Advantages and disadvantages

Advantages	Disadvantages
Can be applied to existing structures	Extensive surface preparations required for proper adhesion
Highly resistant to solvents, acids and caustics	Susceptible to peeling and flaking off
	Low tensile strength can result in cracks; small holes, bubbles or cracks can render the barrier ineffective

Epoxy floor sealant systems often require stringent surface preparation to ensure proper membrane-to-concrete adhesion. Any variation from the manufacturer’s specifications such as oil/grease, stains, moisture wicks, and other prior coats on concrete surfaces may cause the membrane to peel or flake off after installation.

Thermoplastic Liner

A thermoplastic is a type of plastic made from polymer resins that become a homogenized liquid when heated and a solid when cooled. Though not a common application, when applied as a liner, a thermoplastic can be used as a passive barrier that can provide relevant resistive and diffusive properties to protect against COCs. Many of these liners, however, can be easily damaged during normal construction activities, even when cushioned by sand (ASTM E-1643- 11).

Key Elements of Passive Barrier Systems

- *Do not expect complete elimination of vapors.*
- *Select barriers that are thick enough to withstand normal construction abuse.*
- *Include thorough quality control procedures to minimize barrier damage.*
- *Inspect barrier seals at all edges, penetrations, and seams.*
- *Test barrier integrity and performance after installation.*
- *Have contingencies to enhance passive barriers if they prove inadequate.*

Table J-4. Thermoplastic liner – Advantages and disadvantages

Advantages	Disadvantages
Low to moderate capital cost	Even small holes can render ineffective
No mechanical parts	Likely not effective without venting
Encapsulates the building footprint	Limited applications for existing structures that do not have subslab venting.

The potential for punctures may be reduced by using thicker membranes (for example, 60 to 100 mil HDPE or similar materials) and by using cushioning materials above or below the membrane, such as geotextiles, sand, or fine rounded gravel (pea gravel). No specific criteria, however, have been developed for thermoplastic liners, and some degree of imperfection (such as punctures or incomplete seals at seams and edges) should be expected in virtually all applications. In addition, ensure the chemical capability of the liner material with the COCs because of the potential for high concentrations of certain chemicals to adversely affect the membrane as well as the seams.

J.1.3.2 Subslab Venting System

SSV systems or passive subslab venting involves the placement of a venting layer below the floor slab to allow soil gas to move laterally beyond the building footprint under natural diffusion gradients (resulting from the buildup of soil gas below the building) or pressure (thermal or wind-created) gradients. Generally, passive venting is only feasible in new construction because of the need to install an engineered base layer beneath the lowest flooring layer. There are several venting systems that can be assembled and installed, including perforated pipe and low-profile vents.

Key Elements of SSV

- *Generally not practicable for existing structures (except crawl spaces).*
- *Do not expect complete elimination of vapors.*
- *Should be combined with sound passive barrier.*
- *Venting layer must be highly permeable, with distributed collection pipe system.*
- *Allow for addition of fan if necessary to meet performance objectives.*
- *Test system integrity and performance after installation.*

Passive subslab venting systems generally result in less depressurization and lower air flow exchange rates than active depressurization systems with fans (USEPA 1993). As a result, passive venting systems require more permeable venting media, more suction pits for a given building area, more distributed collection pipes, and tighter passive barriers than active venting systems. In addition, passive venting systems are typically not installed as stand-alone systems and require sealing or barriers such as those identified above in Section J.1.3.1. In addition, consistent depressurization of the venting layer should not be expected from most systems.

Figure J-2. Passive sump mitigation system.

Source: Kansas Dept. of Health and Environment

Table J-5. Passive venting – Advantages and disadvantages

Advantages	Disadvantages
Often applied when VI is possible, but has not occurred	Not as effective as active venting systems
Can be modified to an active venting system if designed accordingly	Ambient temperatures and winds can adversely affect the success of this technique
More applicable to new than existing buildings	Not suitable for existing structures unless very modest concentration reductions required; active upgrades likely for new structures when large reductions in concentrations required (e.g., greater than about 90%)
Lack of long-term costs from O&M as compared to active systems	

Some jurisdictions may not allow the use of passive venting systems for VI mitigation, and may prefer to go directly to active designs or use in combination with a passive barrier (see Section J.1.3.1). For new construction sites, however, where VI only has the potential to occur, it may be reasonable to begin with a passive design (saving the cost of fans and electricity) and upgrade to an active system only if necessary.

Collection and riser pipes are generally a relatively small part of the overall cost. In general, passive venting systems cost more to install than active venting layers, for less reliable and consistent performance, in part due to the reliance on transmissivity of the venting layer and the integrity of the barrier layer in order to function. Nevertheless, passive venting systems, when they perform adequately, lack the long-term O&M costs of active system fans.

J.1.3.3 Subslab (Active) Depressurization

Key Elements of SSD Systems

- *Most widely applied and effective systems for VI control.*
- *Applicable to new and existing construction.*
- *One or two suction pits are adequate in most single-family homes.*
- *Typically combined with venting layer and passive barrier in new construction.*
- *Performance may be limited where subsurface soils have low permeability.*
- *May be combined with drain tile or block wall depressurization.*

SSD is a practical VI mitigation strategy suitable for most existing and new structures, including those with basement slabs or slab-on-grade foundations (USEPA1993). SSD systems function by creating a pressure differential across the slab that favors movement of indoor air into the subsurface. This movement is accomplished by pulling soil gases from beneath the slab and venting them to the atmosphere at a height well above the outdoor breathing zone and away from windows and air supply intakes. In new construction, SSD systems are similar to passive venting systems, except that a fan is used to draw soil gas through the subslab venting layer prior to discharging the soil gas to the atmosphere.

Figure J-3. Active SSD system.

Source: Kansas DHE.

Active mitigation systems, including SSDs, are the most reliable, cost-effective, and efficient technique for controlling VI in the majority of cases, with concentration reductions in the 90 to 99% range expected (USEPA 1993), and 99.5% or greater in carefully designed and installed systems (Folkes 2002a). Subslab depressurization in the range of 0.025 to 0.035 inches H_2O is generally sufficient to maintain downward pressure gradients (USEPA 1993).

Hollow block wall or cinder block foundation walls may act as migration routes for vapor to enter homes, particularly if the holes in the top row of blocks are open. Therefore, mitigation techniques for block wall foundations include sealing the holes at the top, as well as depressurization of the block wall (USEPA 1993). Block wall depressurization is usually combined with subslab depressurization systems.

Table J-6. Subslab depressurization systems – Advantages and disadvantages

Advantages	Disadvantages
Successful track record of performance, 90 to 99% reductions typical, 99.5% or greater reductions possible with well-designed systems	Requires periodic maintenance
Adaptable technology, applicable to a wide variety of site conditions and geology	Wet and low permeability soils retard soil gas movement, thereby limiting the overall suction field
Simple gauges show whether the system is working or not	Building-specific conditions may limit options for suction pit, riser pipe, and fan locations

Advantages	Disadvantages
	Need to assess the potential for back drafting of fireplaces and combustion appliances
	Limited or no performance during power outage or motor failure

Although the fans for houses are low wattage and rarely require separate electrical circuits, the hook-ups are commonly installed by an electrician and usually require inspection before operation. Annual O&M costs for these systems are typically low. Commercial/industrial systems may use larger, more expensive blowers which consume more power. Often these blowers also require a separate 120 or 240 VAC circuit.

J.1.3.4 Submembrane Depressurization

SMD has been demonstrated to be the most effective mitigation method in crawl spaces, where a membrane is used as a surrogate for a slab to allow depressurization of the soil (USEPA 1993). Properly installed SMD systems have resulted in concentration reductions of up to 99.5%, similar to SSD systems (Folkes and Kurz 2002b). For SSD, an impermeable membrane is used to cover the exposed dirt surface of a crawl space while the depressurization system withdraws soil gas from beneath the membrane and prevents soil gas intrusion into the space above. Figure J-2 illustrates the application of this technology.

Key Elements of SMD Systems

- *May be combined with drain tile or block wall depressurization.*
- *Most widely applied and effective systems for homes with crawl spaces.*
- *Applicable to new and existing construction.*
- *Suction field extension may be required for tight soils (e.g., perforated pipe).*
- *Liners should be sealed to foundation walls and footings.*
- *Liners should be protected against damage where access (e.g., to service furnaces or plumbing) is expected.*
- *Performance may be limited by low permeability subsoils.*
- *May be combined with SSD, drain tile, or block wall systems.*

The membrane must be well-sealed along all edges of the foundation wall or footings, and to any pipe penetrations through the membrane, with enough slack to prevent tearing of the membrane under stress. Because many homes have furnaces or utilities in the crawl space, it may be necessary to place pads or other protective materials over the liner to allow access to the crawl space without damaging the membrane. Membranes can easily be damaged or lose their seal at the edges; therefore, periodic inspection of membranes (or other performance testing) is needed for SMDs.

Annual O&M costs for these systems are similar to that for SSD, though postmitigation monitoring, inspection, and repair costs may be higher.

Table J-7. Submembrane depressurization system – Advantages and disadvantages

Advantages	Disadvantages
Similar to SSDs	Similar to SSDs
Applied in situations (e.g., crawl spaces) where SSD is not practicable Can be combined with SSD	Membranes can be easily damaged and must be sealed well at edges to prevent leaks System must be periodically inspected to confirm leaks are not present
	Performance may decrease during power outage or motor failure

J.1.3.5 Subslab Pressurization

SSP systems are similar to SSD systems, except that fans are used to push air into the soil or venting layer below the slab, instead of pulling it out. This method increases the subslab air pressure above ambient levels, forcing soil gas from the subsurface to the sides of the building. USEPA (1993) suggests that this technology is most effective in highly permeable soils, where it may be difficult to pull enough air to depressurize the subslab region by SSD. SSP systems are applicable to both existing and new structures.

Key Elements of SSP

- *Generally only practicable in commercial buildings.*
- *Requires relatively “tight” buildings to limit air flow and energy costs.*
- *Only the bottom floor (e.g., basement) requires pressurization.*
- *May be cost effective if existing HVAC equipment can be used without significant modifications.*
- *Energy costs typically increased due to higher replacement air flow rates.*

Cracks or openings in the slab or foundation walls can cause short-circuiting of the system and air forced below the slab may reenter the building, potentially pulling in some of the vapors that the system intended to keep out. Because indoor air is typically used to force air below the slab, fans should be equipped with a filter to prevent buildup of debris in the vent system. Other researchers (USEPA 1993) have observed that small pits at the discharge end of the vent system have improved performance of SSP systems. This approach, however, presents yet another design challenge associated with implementing this technology at an existing structure.

Table J-8. Subslab pressurization – Advantages and disadvantages

Advantages	Disadvantages
Does not require soil gas to be collected within structure	More energy intensive than SSD

Table J-8. Subslab pressurization – Advantages and disadvantages (continued)

Advantages	Disadvantages
May be more efficient than SSD in highly permeable soils Potential for O_2 to increase in the subsurface and encourage biodegradation when addressing PVI	Cracks or slab openings may result in short-circuiting, leading to vapors inside structure
	May not be appropriate for tight soils
	Performance may decrease during power outage or motor failure

J.1.3.6 Building Pressurization/HVAC Optimization

In some instances, it may be advantageous to positively pressurize the building interior (relative to the subslab), thereby preventing VI (Table J-9). The use of building pressurization typically requires that the building is designed especially to maintain a positive pressure within the envelope. It may be possible to tune the building's existing HVAC system to achieve this positive pressurization; however this approach typically requires the installation of a new system and possible modification to the building structure. Warehouses and manufacturing facilities are not good candidates for positive pressurization.

The HVAC systems of many buildings operate during normal working hours and are shut off during the night and on weekends. In these cases, VI could occur while the systems are off, thus contaminating indoor air. The degree of the effect on indoor air quality during this time, and the length of time the effect persists after the HVAC system is restarted, must therefore be evaluated in determining the effectiveness of this method.

Additionally, make sure that soil gas is not simply deflected to adjacent, unprotected areas (for example, in a strip mall or multiunit commercial facility).

Table J-9. Building pressurization – Advantages and disadvantages

Advantages	Disadvantages
Can be applied equally well to both new and existing structures	Generally more costly than other techniques
May be the most effective technology for preventing VI	Regular maintenance and air balancing needed to maintain consistent, positive pressure
	Not commonly an option for single-family residences
	Performance may decrease during power outage or motor failure

J.1.3.7 Indoor Air Treatment

As an alternative to other forms of VI mitigation, air within the structure can also be directed to air pollution control equipment (such as carbon adsorption systems) to remove toxic air contaminants from the building interior (Table J-10). This technique is not widely practiced, since it encourages the collection of contaminant vapors within the structure and depends on the treatment system's uninterrupted performance to protect receptors.

Key Elements of Indoor Air Treatment

- *Less effective than other VI control methods.*
- *Expensive to install, operate, and maintain.*
- *Typically generates waste (e.g., spent carbon).*

This approach can be an effective mitigation strategy, however, when combined with other techniques to control vapor concentrations in problem rooms, or when building materials have been affected by PHCs. Indoor air treatment is an alternative to whole building pressurization when subsurface depressurization or pressurization methods are not feasible (for example, when high water tables and wet soils are present). Indoor air treatment is generally only applied in existing buildings, since more cost effective systems can generally be installed in new buildings.

Table J-10. Indoor air treatment – Advantages and disadvantages

Advantages	Disadvantages
Results in the physical removal and disposal of the air contaminant, not simple redirection	Less effective than other control methods (when applicable); zone of influence may be very small
Less susceptible to malfunction or leaks than most other technologies	Very maintenance intensive and costly to install and operate
	System leaks, should they occur, may result in higher exposures than no control

Depending on the specific treatment method, there may be an ancillary waste stream, such as spent activated carbon, that requires disposal. In addition, to the extent treatment of air is required, it may be more advantageous to treat the air exhausted from another treatment technique (such as SSD) rather than to treat the indoor air of a structure. This advantage results from the smaller volumetric rate of air that would require treatment from SSD (which is smaller than the volume resulting if the entire indoor space required treatment).

J.1.3.8 Aerated Floor Systems

Aerated floors are concrete slabs with a continuous void space under the slab that can be used for subslab venting or depressurization in lieu of the sand or gravel venting layer commonly associated with traditional mitigation systems. Because the void space has very low resistance to air flow, vacuum levels and air exchange rates in the void space are generally higher and more uniform than in sand or gravel layers.

Aerated floors are typically constructed using proprietary plastic forms that are placed on the subgrade prior to pouring of the concrete slab. As a result, aerated floor systems are most applicable to new construction, although aerated floors can also be placed over existing slabs if a higher finished floor elevation can be accommodated. The total thickness of aerated floors (including both the void space and concrete) typically range from about 4 inches to several feet and are most commonly about 13 to 15 inches. The volume of concrete is similar to, or may be less than, the volume of concrete required for a traditional flat slab with the same load capacity.

Key Elements of Aerated Floor Systems

- *Generally applicable to new structures, but can be designed for existing structures.*
- *Low resistance of void space to air flow results in highly efficient SSV and SSD systems.*
- *Small fans can vent or depressurize relatively large buildings.*
- *Eliminates gravel and liner layers, although caulking of joints and penetrations to radon industry standards is required for optimum performance.*
- *Low cost and "green" technology.*

Table J-11. Aerated floor – Advantages and disadvantages

Advantages	Disadvantages
Void space allows higher air flow rates for SSV and higher and more uniform vacuum levels for SSD than typical sand/gravel venting media	Less applicable to existing buildings, unless replacing the existing floor slab or placement over the existing floor slab is acceptable
Low-cost system due to elimination of gravel layer and liner. Concrete and steel costs may also be reduced. Made from recycled plastic (green product)	Passive venting might not be sufficient when vapor concentrations are high and buildings are negatively pressurized (potentially requiring active venting)
One small (e.g., 20W) fan can typically provide a relatively high and uniform vacuum across 20,000 sf or larger buildings	Many architects, engineers, and contractors are not familiar with aerated floors, although this should change over time

Aerated floors can be designed for SSV or SSD operation (in the former case, air inlets are typically provided to increase air flow rates) and operated in either active and passive venting modes, depending on the degree of venting or depressurization needed to control vapor intrusion. Note that aerated floors are not barrier systems, although the combination of the interlocking plastic forms, concrete, and caulking of joints and utility penetrations (consistent with radon industry standards) reduces the number of vapor entry points similar to barriers. As with all SSV and SSD venting systems, vapor intrusion is controlled primarily by removal and dilution of subslab vapors, depressurization and reversal of air flow direction across the slab, or both.

Figure J-4. Cupolex aerated floor system.

Source: Vapor Mitigation Sciences, LLC.

J.2 Factors for Selecting Vapor Control Technologies

A number of factors that are commonly identified during the course of a VI investigation and in completing a CSM may affect the choice of technology used to mitigate a particular building.

J.2.1 New versus Redevelopment of an Existing Building

More mitigation options are typically available for new buildings than for existing buildings. In general, subsurface features such as passive barriers and venting layers cannot be installed below existing buildings, although depressurization technologies have been shown to work well in existing buildings without the benefit of these features. In addition, the presence of lead paint or asbestos may make more intrusive technologies less cost effective in older, existing buildings. On the other hand, new buildings may incorporate subslab venting layers, collection pipes, and vapor barriers (membranes) to enhance the performance of SSDs. These features may increase the efficiency of depressurization systems and reduce the number of suction points and fans required to achieve desired performance levels.

In some cases, these enhancements may be sufficient to allow effective use of passive mitigation systems, although passive system performance is case specific and should be critically evaluated during system design and verified during postmitigation diagnostic testing (see Section J.3). New buildings can also incorporate foundation features that enhance the collection of subslab soil gas, such as conduits through grade beams and foundation walls (thereby reducing the number of required suction points). New construction may also incorporate design features that reduce the potential for building depressurization and the stack effect, such as limiting openings that allow vertical movement of air from floor to floor, ventilation of crawl spaces, installation of HVAC systems that allow positive pressurization (for commercial buildings), and outside air supply for gas furnaces and water heaters. Some of these features can be retrofitted into existing buildings. Finally, new buildings can incorporate suction points, collection and riser pipes, and other features into the design, thus allowing optimal location of systems without the aesthetic problems often encountered in existing buildings.

If possible, mitigation should occur when the building is constructed, rather than as an add-on after it is constructed. Such decisions may confront property owners wishing to develop property where contaminated shallow groundwater or soil pose a potential threat to indoor air quality via VI. While the owner (hoping that no mitigation is needed) might choose to wait and test indoor air after the building is constructed, it is generally preferable for the owner and responsible parties to agree on building modifications during the design phase. Costs for the mitigation can then be minimized and better integrated with other building features.

J.2.2 Building Size

The building size may have some effect on technology selection and system design, although in many cases larger buildings simply require larger systems, often with greater economies of scale. Larger commercial or industrial buildings, such as warehouses, may be less susceptible to poor indoor air quality resulting from PVI because of their larger building air volume, higher air exchange rates, open bay doors, positive air pressures (depending on HVAC system operation), and thicker floor slabs. These buildings, or portions of these buildings, therefore, may not require mitigation. But office areas with low ceilings and a number of dividing walls may have air exchange rates and volumes that are similar to residential homes. Therefore, when deciding what type of mitigation is best for the building of concern, consider which portions of the building the system must effectively mitigate.

In most cases, large buildings require multiple SSD suction points and either multiple in-line fans or one larger-sized blower. Multiple suction points can be connected to one larger fan or blower on the roof, using interior walls or columns to locate riser pipes. However, joints between slab sections, cracks, and other penetrations through the slab that are located between suction points should be sealed to prevent short-circuiting of the suction field.

Horizontal pipes may allow efficient depressurization and collection of soil gas over large areas below new building slabs. Horizontal pipes may also be drilled below existing large buildings, although the economies of this approach versus multiple suction points should be examined carefully. The potential impact of multiple horizontal drill holes on the foundation integrity of any shallow footings or weight-bearing slabs should also be considered.

J.2.3 Height of Building

The height of a structure can affect the technology selection and system design, especially for structures greater than three stories. Unlike the overall size of a building, which may simply require a larger system, the height of a structure may prevent certain technologies (such as passive venting) to be implemented. Often larger structures require additional engineering considerations for air flow.

J.2.4 Foundation Type and Condition

Foundation types include basements, crawl spaces, slabs-on-grade, pier and beam, and any number of combinations of these basic types. Foundation type only affects design of mitigation systems that function by depressurizing soils below the building. SSD systems can be applied in any situation where a slab overlies soil, while SMD systems can be used in crawl spaces or anywhere that expanses of soil are exposed and future use of the area will not damage the membrane. Some buildings may require more than one vapor control technology.

Subslab features, such as grade beams, footings, and foundation walls may interrupt the development of suction fields below the slab, requiring installation of suction points in each area. In some cases, existing drain pipes and sump systems may be used as suction points—sealed and converted into efficient depressurization systems in existing residential and commercial/industrial buildings. In rare cases, heating and ventilation ducts may be present below the slab, providing a preferential pathway for PVI and short-circuiting subslab depressurization fields. Building-specific designs may be necessary to overcome this situation.

Certain building features, such as elevator shafts and sumps, may enhance the potential for VI unless they are properly sealed to prevent entry of both soil gas and groundwater containing PHCs. Elevator operations may enhance building depressurization and increase the rate of vapor entry into the building. Elevator shafts and other vertical conduits may also increase the movement of petroleum vapors throughout the building.

The foundation condition may also affect mitigation options. Excessive cracks, utility penetrations, or other openings may cause short-circuiting of the depressurization field, thus limiting the areal influence of a particular suction point. Solutions may include sealing of cracks and penetrations, and creating additional suction points for SSD systems. Fieldstone foundation walls may be too permeable for depressurization remedies to be effective without grouting or otherwise sealing the wall. In extreme cases, alternative mitigation strategies may be necessary, such as building pressurization or slab replacement.

The condition of the foundation wall may also affect mitigation techniques. Cinder block foundation walls may provide vapor migration routes through the interconnected voids in the blocks, particularly if the blocks are not sealed at the top of the wall. Mitigation strategies for such conditions include installation of suction points and depressurization of the wall, as well as sealing of the openings at the top of the wall. In some homes, dugout basements may have exposed earthen walls. These walls typically must be covered by membranes or walled off to allow effective operation of depressurization systems. Basements with exposed earth or rock floors may require placement of a concrete slab or false floor with a membrane to allow depressurization.

In some cases, crawl space areas are not accessible for installation of SMDs (Section J.1.3.4). Options may include digging out the crawl space to allow access; installation of outside air vents to enhance natural ventilation of the crawl space (in warmer climates and where freezing of pipes in the crawl space is not a possibility); installation of horizontal soil gas extraction pipes below the crawl space; and positive pressurization of the crawl space to inhibit vapor entry.

J.2.5 Soil Conditions

Foundation soil conditions may affect the design of depressurization systems. Low permeability soils, in the absence of a permeable venting layer below the slab, restrict the extent of suction fields, increasing the number of suction points required below slabs and membranes. In some cases high-vacuum/low-flow fans may be required. Larger voids or suction pits may also be sufficient to improve SSD system operation in tight soils (Folkes and Kurz 2002b).

Depressurization systems are generally effective in permeable soils; however, large venting layers may require low-vacuum/high-flow fans to move enough air through the system. Fan selection and pipe sizing guidance is available (USEPA 1993 and Fowler et al.1990). The mitigation contractor chosen for the project should have experience installing systems in the type of subsurface soils encountered below the buildings of concern. In permeable soils where depressurization is difficult, subslab pressurization may be more effective. In subslab pressurization, air is pumped into a permeable layer or natural soils below the slab to create positive subslab pressures that divert subsurface soil gas around the structure (see Section J.1.3.5 and USEPA 1993).

J.2.6 High-Water Conditions

Saturated soils may prevent effective depressurization of the subslab region by filling soil pores and making them unavailable for vapor transport. In cases where soils are damp but there is no continuing supply of water, air flow generated by an SSD system may dry the soils out sufficiently to allow effective depressurization. In cases where high water tables are controlled by drain tile or French drain systems, depressurization of the air space in the drain tile may be sufficient to control VI (see Section J.1.3.3). These systems can be retrofitted with larger pipes to accommodate water and air flow.

If high water table conditions are episodic, which could be due to water infiltrating the ground after precipitation, then risk assessments may indicate that occasional loss of petroleum vapor control (due to loss of depressurization) does not result in a significant increase in long-term risk. Therefore, the SSD would only need to operate during low water table periods, when depressurization would be feasible. Alternatively, the SSD system can be augmented by a fan that either ventilates or pressurizes the basement with outside air whenever the sump pump kicks on, provided that flooding only occurs during warmer weather. If dewatering is not practicable, then basement or crawl space pressurization may be the most cost-effective method of petroleum vapor control. Pressurization, however, does not prevent direct partitioning of volatile compounds into the basement or crawl space air if water is entering the building. In these cases, it may be necessary to depressurize the basement or crawl space or to install a false floor above a slab or earth floor and create a thin venting layer that can be depressurized.

J.2.7 Presence of Sumps, Floor, and Footing Drains

Sumps, footing, and other types of drains affect the design of the system. These features can directly affect the radius of influence. In addition, their presence may also provide a preferential pathway for vapors entering into a structure. A site-specific evaluation is required to addressing these features.

J.2.8 Contaminants of Concern

The COCs may affect mitigation system design in at least three ways. First, potentially combustible vapors (that may approach combustible concentrations) require intrinsically safe blowers and monitoring or alarm systems. Second, certain vapors may cause degradation of membranes, pipes, or the solvents used to join pipes. Third, the COC action levels, if any, affect the degree of concentration reduction required inside the building. Reductions of 80% or less may be possible with passive systems, while higher reductions generally require active depressurization or pressurization systems (USEPA 1993). Standard radon SSD and SMD systems generally perform well when reductions of up to 95% are required, while more rigorous attention to installation details, enlarged suction pits, and increased numbers of suction points and fans may be required for higher reductions (Folkes and Kurz 2002b).

J.2.9 Identified Concentrations Levels

The level of contamination present can affect the design of the vapor mitigation strategy. For example, passive barriers may require the use of products that are designed with higher diffusive rates and installed with additional passive vents. For active systems, the higher level of concentrations may also cause products to degrade a faster rate than designed.

In addition, some contaminants can be combustible if specific conditions exist. For compounds such as PHCs and methane, if the contaminant is found in concentrations between the lower explosive limit and the upper explosive limit, then an ignition source, such as an electrical spark, could cause a fire. Therefore, for sites that contain compounds near or within the explosive limits, the use of intrinsically safe equipment should be considered.

Explosive concentration ranges depend on the specific petroleum COC and should be considered when implementing a vapor control technology, especially for active venting layers and subslab pressurization (see Section J.1.3). Note that if concentrations in the subslab are above the upper explosive limit, an active venting or pressurization system could create explosive conditions as air is introduced under the building. Reducing the subslab concentrations from above the upper explosive limit to below the lower explosive limit under the building is not recommended, because the mixing of fresh air and petroleum vapors is neither instantaneous nor complete and may leave pockets of combustible gas.

Methane generation by anaerobic biodegradation should also be considered. The lower explosive limit of methane is 5%; therefore, small amounts of methane can create explosive conditions.

J.2.10 Location of Vapor Source and the Conceptual Site Model

The location of the vapor source plays a key role in the design of a mitigation system. If the source is located adjacent to the structure, then vapor control technologies may be implemented using features that prevent further on-site migration. On-site sources or sources located directly beneath a structure, however, require vapor control directly beneath a structure. A CSM that identifies the location of the vapor source can assist in identifying potential strategies based on the location of the vapor source.

J.3 Design Considerations and Installation of Building Controls

The following sections discuss the general approach to design of building controls, pre- and post-diagnostic testing, and other design issues, including access, owner preferences, lead-based paint and asbestos, and back-drafting potential. As with factors that determine which mitigation method is used, there are design considerations and installation limitations that are common to the mitigation of all vapors.

J.3.1 Design Approach and Level of Detail Necessary to Complete Design

Design of VI controls for new buildings should consider all of the factors discussed in the previous section. VI control requirements should be integrated into the overall building design process as soon as possible, since varying the locations of elevator shafts, basements, and even the building itself might help reduce the risk of VI. Foundations can be designed to enhance, rather than inhibit, suction field extension below slabs. Similarly, building pressurization systems can be optimized by designing tighter bottom floors and installing HVAC systems capable of creating and maintaining positive pressures during all seasons. VI control designs should include system layout drawings, minimum material specifications, installation procedures, construction quality control procedures, and post-installation testing procedures.

Design of VI mitigation systems in existing buildings should begin with a visual inspection of the building. For existing residential homes where SSD systems are applicable and the mitigation contractor is familiar with the houses in the area, this inspection is likely the only step required before installation (USEPA 1993; Folkes 2002a). For larger commercial buildings, or if subsurface or building characteristics indicate that an SSD system may not work well, pre-mitigation diagnostic testing may be required (see Section J.3).

For most existing residential homes, it is usually sufficient to install a relatively standard system without building-specific designs or pre-mitigation diagnostic tests, relying on the mitigation contractor’s experience in the area (USEPA 1993). While this “standard design” approach allows systems to be installed more quickly (which may be important at larger sites with many homes requiring mitigation), some form of postmitigation testing is required to verify that the standard design is adequate. Experience at the Redfield Site in Colorado indicated that only about 10% of homes requiring a 95% or less reduction in concentration needed adjustments after installation of a standard SSD system, and in most cases these adjustments were modest and inexpensive (Folkes 2002a).

For larger, more complex buildings or when visual inspections indicate SSD systems may not function well, it may be appropriate to conduct detailed diagnostic tests prior to mitigation and to prepare building-specific designs. Commercial building owners may only provide access if they can review the mitigation design before it is installed. Some states may also require approval of building-specific designs before installation. Designs may also be needed in order to apply for pre-installation permits or to provide the public opportunity for pre-implementation review and comment. Note that little guidance is available on the design and installation of mitigation systems for larger commercial buildings.

Both the standard design and custom design approaches are effective, but the best approach depends on site-specific circumstances, priorities, and to some extent, the preferences of the regulatory agency and the building owner. A summary of the advantages and disadvantages of each approach is shown in Table J-12.

Table J-12. Mitigation design approach considerations

Approach	Advantages	Disadvantages
Detailed diagnostic testing and design followed by installation and testing	• Post-installation adjustments less likely to be required • May be a more effective approach for unique building types or unusual conditions • May be more effective when a high degree of reduction is required (e.g., >95%) • May be required if multiple reviewers/stakeholders must agree on the specifics of the design before it is installed	• Higher initial design and testing costs • More site visits required for design and initial installation • Likely to be more expensive for multiple residential mitigations; more time is required to install systems via this approach if there are a large number of homes to be similarly mitigated
Standard system installation based on experience and inspection, followed by testing and adjustments, if needed	• Lower initial design and installation costs • Fewer visits required to install system, less disruption to occupants • Many systems can be installed per time period (although some may require adjustments) • Standard design can be adjusted over life of project based on per-	• System adjustments may be required in more homes (most likely a minority of homes, if based on prior experience and standard design adjusted as necessary over life of project) • Costs for system adjustments may result in higher total costs than if these adjustments had been initially installed, although making such adjustments may be less expensive than detailed diagnostic testing • Additional postmitigation tests may be necessary to demonstrate adjusted sys-

Table J-12. Mitigation design approach considerations (continued)

Approach	Advantages	Disadvantages
	formance of first group of systems • Most appropriate for homes and when installers (and regulatory reviewers) have prior experience with similar homes in the same area	tems working adequately

J.3.2 Need for Discharge Permits and Emission Controls

The need for air permits and exhaust gas controls for subsurface mitigation systems should be determined on a site-by-site basis, in compliance with applicable federal, state, or local air quality control regulations. Many states have a permitting program to implement the requirements of the federal Clean Air Act, as well as state-specific regulations. Typical permits include a Permit to Construct or a Permit to Operate. In some states, subsurface mitigation systems may be exempt from permitting requirements. Even exempt systems, however, may have a filing requirement. Filing may consist of a description of the emission source, the data necessary to estimate VOC emission, and information to determine whether the equipment is operating in compliance with local, state, and federal laws and regulations. As a part of permit maintenance, the state may require that VOC emissions be determined by USEPA, local state test methods, or both.

J.3.3 Preferences of the Owner or Tenant

While the investigator and regulatory agency may be primarily concerned with the performance, cost effectiveness, and reliability of any mitigation system, the tenant in the building mitigated must live (or work) with the system and the owner of the building must maintain the value of the investment. The tenant and owner preferences for mitigation design features, therefore, should be taken into account.

Owners, tenants, and other parties (including contractors and architects) in the building process often have strong opinions about the aesthetic effects and inconvenience experienced. For example, if the mitigation contractor is considering an attic location for a fan, owners and tenants should be asked about the current and near-future use of that space. When there are multiple appropriate mitigation options available, the responsible party should be prepared to present the options that explain the advantages and disadvantages associated with each and also to describe why the preferred alternative should be the option installed.

J.3.4 Design and Installation Considerations for SSDs

When necessary, pre-mitigation tests can be conducted in existing buildings to measure the potential extent of the suction field for SSD systems. These tests, which are often referred to as “communication” or “suction field extension” tests, indicate whether SSD systems are viable, and aid in the selection of suction pit locations and fan size. The tests may also indicate whether any conditions (soil or building) exist that might preempt the use of active depressurization systems. The test typically involves applying suction to a centrally-located hole drilled through the floor slab (using a small portable vacuum or a portable radon fan) and observing the movement of smoke downward into construction joints or small holes drilled at locations surrounding, but distal to, the suction point. Digital micromanometers or other types of small differential pressure monitoring devices can also be used to assess the extent to which the suction system can achieve sufficient vacuum. Diagnostics should include testing under stressed conditions, such as during operation of furnaces and vent fans that tend to depressurize the building. In most cases, suction field extension tests are the only pre-mitigation diagnostic testing necessary prior to design and installation of SSD systems (USEPA 1993).

Suction field extension tests may also be conducted during installation of SSD systems, rather than prior to installation, using the first suction point to apply a vacuum and determine whether additional suction points (and larger fans) are required.

In many cases, mitigation contractors have sufficient experience with soil conditions and building types to accurately judge the size and locations of mitigation components. If many mitigation systems must be installed as quickly as possible, then it may be more expedient to install standard systems, test these systems as they are being installed and, when necessary, enhance or modify the systems to meet performance criteria (see Section J.4).

J.3.5 Design and Installation Considerations for Barrier Systems

The passive VI mitigation system described in this section generally consists of a vapor barrier membrane that has been combined with a passive venting system. Unlike most active vapor control or mitigation systems, a passive barrier must demonstrate resistive properties against the COCs. Therefore chemical exposure and diffusion testing are pertinent when selecting the appropriate passive barrier. Other critical elements that must be incorporated into the design are protective barriers and a passive venting system.

New construction provides an opportunity to install a passive mitigation system, since the system can be easily incorporated into the design process. In most new construction design using passive barriers, the protective layer consists of the placement of cement and other flooring material planned as part of the building design. However, if a structure will be retrofitted with a liner on top of existing flooring, depending on the barrier used, an additional protective layer may be installed (except when using some of the newer epoxy floor sealant systems).

Passive venting is a critical component of any passive mitigation system and prevents the diffusion of contamination across the barrier. Therefore, it is common practice (and a requirement in most states) to incorporate relatively inexpensive ventilation piping and wind-driven ventilators. The design of the venting system should also allow for the conversion of the passive system to an active system if needed. The actual design and layout of the piping system should be based on soil types as well the expected concentrations of vapors expected. The piping sizes and locations should be sufficient to remove any vapors generated by the source material.

To aid the in the design and the selection of an appropriate liner, the diffusion coefficient of a passive barrier can be incorporated into a J&E model to assess the design performance. One method includes using a three-phase model, which allows permeabilities to be entered from different horizons. To account for the barrier, the diffusion coefficient for the contaminant is substituted in place of one the soil layers. The three phase model is available from the USEPA Waste and Cleanup Risk Assessment website (USEPA 2005c).

A mitigation system barrier can also be considered when other mitigation methods are difficult to implement, such as for low permeability soils or shallow groundwater beneath the floor slab. In these cases, it is difficult to obtain adequate vacuum fields for active mitigation systems. Installation specifications for barriers should follow the manufacturer's guidelines. It is also critical that a construction QA/QC plan be developed and followed during installation to ensure that the installation meets the design specifications, because most passive barriers will be inaccessible upon completion of the building. Most construction QA/QCs include visual inspection, thickness testing, smoke testing, detailed records of the amount of material used, and photographic evidence. Geomembrane barriers that are dual-track welded should be channel pressure tested. Spray-applied membranes should be allowed to cure sufficiently (typically overnight), then thickness tested with a blunt-nosed thickness gauge or by cutting specimens every 500 ft^2.

If the performance of the passive barrier will be evaluated using the collection of samples above the liner, then sampling ports should also be incorporated into the design so that contamination both above and below the liner can be compared.

J.3.6 Pre-Mitigation Diagnostic Tests

When necessary, pre-mitigation tests can be conducted in existing buildings to measure the potential extent of the suction field for SSD systems. These tests, which are often referred to as "communication" or "suction field extension" tests, indicate whether SSD systems are viable and aid in the selection of suction pit locations and fan size. The tests may also indicate whether any conditions (soil or building) exist that might preempt the use of active depressurization systems. Tests typically involve applying suction to a centrally-located hole drilled through the floor slab (using a shop vac or a portable radon fan) and observing the movement of smoke downward into construction joints or small holes drilled at locations surrounding, but distal to, the suction point. Digital micromanometers or other types of small differential pressure monitoring devices can also be used to assess the extent to which the suction system can achieve sufficient vacuum. Diagnostics should include testing under stressed conditions, such as during operation of furnaces and vent fans that tend to depressurize the building. In most cases, suction field extension tests are the only pre-mitigation diagnostic testing necessary prior to design and installation of SSD systems (USEPA 1993).

Suction field extension tests may also be conducted during installation of SSD systems, rather than prior to installation, using the first suction point to apply a vacuum and determine whether additional suction points (and larger fans) are required.

In many cases, mitigation contractors have sufficient experience with soil conditions and building types to accurately judge the size and locations of mitigation components. If many mitigation systems must be installed as quickly as possible, it may be more expedient to install standard systems, test these systems as they are being installed and, when necessary, enhance or modify the systems to meet performance criteria (see Section J.4).

J.3.7 Access and Scheduling Limitations for Installation and Assessment

Whether the structure to be mitigated is a commercial or institutional structure, or a private residence, arranging for access to the property can prove difficult. Commercial building tenants may not want construction activities disrupting business operations, and some homeowners may resist granting access to their home for a variety of reasons, including privacy issues. Scheduling indoor tests may also be difficult, since access is required for both placing canisters and picking them up 24 hours later. Homeowners often want to schedule tests before or after work. To address these concerns, it is best to develop and execute an access agreement between the property owner and the investigating/mitigating entity.

J.3.8 Presence of Lead-based Paint or Asbestos

Depending on the age of the structure being investigated, other environmental hazards such as lead-based paint or asbestos may be present and can potentially delay mitigation activities. Generally, structures built before 1990 may pose a hazard with respect to lead-based paint, while asbestos may be present in buildings built before 1980.

The presence of one or more of these materials may delay construction activities within the structure until the hazard is adequately addressed or the appropriate safeguards are in place. Addressing these hazards adds to the cost of mitigation and may negatively affect the overall project schedule.

J.3.9 HVAC Issues, Including Altering Building Pressures

When one or more ventilation techniques are used to address VI, these systems affect the overall balance of air flow within the structure. If the ventilation equipment and combustion devices within a structure (such as furnaces, wood stoves, clothes dryers, and water heaters) are not properly balanced, then exhaust gases from the combustion units may collect within the structure. This situation is often referred to as “back-drafting” or “spillage.”

In buildings with natural draft combustion equipment, a back-draft test may be indicated prior to installation of mitigation systems involving active ventilation (such as SSD). If back-drafting is occurring, it should be corrected prior to installation to avoid safety hazards.

Most residential mitigation activities using pressurization and ventilation techniques add little to the potential for overall building depressurization. Typically, SSD fans operate at low flow rates and induce a minimum pressure differential across the slab. SSD systems should be installed by experienced contractors familiar with the potential for and prevention of back-drafting of combustion equipment (for example, water heaters or furnaces).

Although typically required by building codes in newer homes, older homes may not have cold (outside) air-supply vents for gas furnaces or water heaters, resulting in greater negative pressures when furnaces turn on and greater potential for both back-drafting and VI. In some cases, providing cold-air vents alone may mitigate minor VI problems and, in all cases, should enhance the performance of SSD systems. Although not currently required of radon contractors, USEPA has recommended (USEPA 1993) that procedures be undertaken to investigate the possibility of back-drafting.

J.3.10 Vent Risers

Depending upon the size of the building and the number of system fans/pumps needed, system piping limitations for delivery or extraction of air must be considered. Vent risers should be in a location that can be properly secured for protection against damage and should terminate at a minimum of two feet above the roof of the structure, while also a minimum of 10 feet away from any window or air intake into the building. The diameter of the vent riser should be appropriate for the capacity of the system and meet any local building or fire codes.

Other things to consider for venting include overall height of the structure (see Section J.2.3), the ability to access the riser for sampling, seasonal heating and cooling effects and their effects on pressure differentials, moisture issues, rain and debris guards, and contaminant compatibility. In addition, all vent risers should be clearly marked and designated as being part of a vapor mitigation system.

J.3.11 Reliability of the System

Because the reduction goals must be met consistently over long periods of time, reliability is an important criterion for selecting vapor control technologies. While most of these technologies are considered mature and have been used extensively for other applications such as radon or moisture control, confirm system reliability with the vendor or consulting engineer.

J.3.12 Methane for Petroleum Hydrocarbons

An aerobic biodegradation zone (see Figure 2-1) is typically present along the perimeter of the PHC plumes in groundwater and soil gas. Within this bioactive zone, natural microbial activity can degrade many PHCs into nontoxic end products such as carbon dioxide, water, and methane. If PHC concentrations are high enough, available oxygen may be depleted, which in turn limits aerobic biodegradation. When oxygen is limited, anaerobic biodegradation of LNAPL or other organic sources can produce methane. Significant anaerobic biodegradation and methane generation can occur in some situations within anoxic zones of the plume interior and adjacent to the LNAPL source. Methane readily biodegrades under aerobic conditions and, when present, creates an additional oxygen demand. Methane also creates an explosion hazard if it accumulates within confined spaces (such as utility vaults and passages, basements, or garages) in high concentrations and there is sufficient oxygen and a source of ignition.

Methane may be more significant at sites where large volumes of ethanol-blended gasoline (and higher ethanol content fuels) have been released into the subsurface. As the ethanol content increases, so does the potential for creating methane. Methane production can increase soil gas volume and pressures and result in advective soil gas flow toward receptors. Petroleum vapors may also migrate with the methane. In addition, aerobic biodegradation of methane may deplete oxygen that otherwise could be used for biodegradation of the PHC contaminants. Moreover, in situations where intrusion of methane into confined spaces results in the accumulation of very high concentrations, there can be a risk of explosion.

J.3.13 Consideration of Intrinsically Safe Equipment

Intrinsically safe equipment is defined as “equipment and wiring which is incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a specific hazardous atmospheric mixture in its most easily ignited concentration" (ANSI 2003). This condition is achieved by limiting the power available to (and used or generated by) the electrical equipment in the hazardous area to a level below that which will ignite the hazardous atmosphere.

When methane or other contaminants that may obtain or reach explosive conditions are present, ensure that the electrical components are intrinsically safe. Although methane generated by degradation of PHCs is not under pressure and is unlikely to produce an explosive environment, there is the potential for an active mitigation system to pull in methane, which can come into direct contact with the electrical components.

J.4 Performance Criteria

Performance criteria provide benchmarks for measuring whether the vapor control technology is meeting objectives and provide a reasonable indication of whether the system is operating as specified. The primary performance metric for a vapor control technology is acceptable levels of contaminants in indoor air; however, indoor air samples may be avoided in some situations through the collection and assessment of indirect performance indicators. Environmental professionals, however, may need to determine percent reduction in measured contaminant concentrations in indoor air resulting from the engineered system or barrier in order to assess the systems effectiveness.

Performance criteria for a vapor control technology should be include a specified time frame that depends in part on the risk to the occupants. In addition, it is critical that the performance criteria undergo constant evaluation to determine whether they are meeting the overall project objectives. Note that often more than one performance criteria may be applicable for a specific type or design of a mitigation system.

J.4.1 Indoor Air

Indoor air sampling for the COCs is generally the most direct method to determine whether exposures have been controlled by the mitigation system. Because of the possibility of significant background sources for PHCs, indoor air sampling should be paired with ambient air sampling, as well as with updated chemical inventories. Indoor air samples should be collected from the lowest potentially occupied space. In situations where there are separate types of mitigation systems (such as rooms over crawl spaces with membranes, versus rooms over a concrete slab with an SSD) samples should be collected over each area. For large buildings, with multiple air handling systems, samples should be collected from each distinct HVAC zone.

In buildings, COCs may not be distributed uniformly in space and time. Thus, the sampling plan must consider the locations, number, and frequency of samples. Sample placement and duration are frequently selected to meet risk-assessment-related requirements. Durations over which to collect an air sample are established by the local or state agency (for example, 24 hours for residential scenarios). The air within relatively open zones (such as auditoriums, reception areas, and living spaces of residential buildings) that have nearly uniform temperatures can be expected to have contaminants well mixed within the zone. Measured variations within such zones are often comparable to the observed variations of duplicate measurements. Short-term spatial variations are usually small compared to temporal variations on daily and seasonal scales. When a complex building is being evaluated, it is typically represented by a conceptual model consisting of a group of interacting zones. Parts of the building with separate air-handling systems or built using different construction methods are considered as independent zones.

J.4.2 Subslab Measurements

During mitigation, subslab measurements during the operation of a vapor control technology can provide direct and indirect information on whether they system is effective in preventing VI.

J.4.2.1 Subslab Samples

The collection of subslab samples is not always performed; however, when it is collected, the data can be valuable for several purposes. Decreasing concentrations can indicate that a stepped mitigation approach may be considered (to prevent constant fan operation) or indicate that vapor concentrations have decreased due to a remedial action or through biodegradation and VI is no longer an issue.

Evaluations typically require multiple sampling events to account for expected sampling variability. Detailed instructions for installation of subslab sampling probes are provided in several documents (for example, USEPA 2006a, NYSDOH 2006b, NJDEP 2005, and MADEP 2002a).

J.4.2.2 CO_2, CH_4, O_2

CO_2, CH_4, and O_2 are key parameters typically monitored to document that biodegradation is occurring. Generally when O_2 is present at concentrations at 5% or greater, aerobic conditions are known to exist, and the microorganisms consume all available PHCs. This aerobic biodegradation can occur relatively quickly, with degradation half lives as short as hours or days under some conditions (DeVaull 2007). Some PHCs can also biodegrade under anaerobic conditions; however, this process is less important and generally much slower than aerobic biodegradation. Documenting the levels of CO_2, CH_4, and O_2 can provide evidence that site conditions prevent PVI from occurring.

J.4.2.3 Pressure Differentials

For subslab depressurization systems or for HVAC systems designed to create positive building pressures, performance can be verified by measuring pressure differentials across the slab (typically with a micromanometer). In some situations, the pressure differential across the basement walls is also critical. Pressure differential readings should be collected at a sufficient distance from a subslab depressurization suction point to reflect the pressure field extension to distal portions of the slab. Where subslab obstructions are present, differential pressure measurements should be taken on either side of such obstructions. Locations for pressure measurements should extend to the extremes of the slab.

A micromanometer should be used to measure pressure differentials at measurement points (NYSDOH 2006b). If the pressure field extension cannot be quantified with a micromanometer, then the performance of the mitigation system may be in question. Typical measurements should be collected as 5 to 10 second averages. Guidelines for adequate subslab differential pressure vary by state, with values of 0.004 inches of water column considered acceptable in some states (New York and New Jersey), while ASTM and Massachusetts recommend a minimum value of 0.01 inches water column. In order to achieve the highest reliability, the micromanometer should undergo annual calibration.

J.4.3 Smoke and Tracer Gas Testing

Smoke testing is a qualitative method of tracer testing that can be used to detect leaks or preferential migration pathways, or to test airflow patterns of an SSD. A smoke tube or smoke stick, which emits a visible stream of smoke, can be used to test for leakage through pipe joints and slab-wall junctions. In general, leak testing of pipe joints is more effective if smoke is injected into the pipe under pressure. Smoke testing for membrane applications can be used to test for leaks at the seams and seals of membranes. This testing can also be used at cracks and joints in a slab and at suction points in SSD systems.

The reliability of smoke testing for small leaks has been questioned. Quantitative methods have been recommended in place of smoke testing, such as tracer testing and differential pressure instruments. The concept of using a tracer gas to verify the integrity of a subslab membrane is similar to that for leak testing a subslab or soil gas sample port. When using a tracer gas to detect leaks in a membrane, the tracer gas is typically injected under the membrane, and the atmosphere above the membrane is monitored for the tracer gas by sweeping a detector probe across the entire membrane area. Tracer gases typically used include helium or sulfur hexafluoride. Helium and sulfur hexafluoride specific detectors are readily available; however, be mindful of the response time for the detector being used and adjust the rate at which the detector probe is swept across the membrane accordingly. Depending on the construction methods used and how the membrane is attached to the foundation, tracer gas detections may occur around the perimeter of the membrane.

J.4.4 Passive Barriers

The use of passive barriers often requires unique performance criteria that are either met or evaluated during the design and monitored during the installation. In order to effectively design a passive barrier, a manufacturer must be able to provide testing that documents the effective diffusivity for the COC. The effective diffusivity based on the estimated or expected concentrations establishes the thickness requirements necessary to limit the flux of contaminants into a structure. As part of this procedure, the installation documentation is critical to ensure that the design specifications are met. Testing procedures, such as pressure differential and smoke testing, often assist in evaluating the installation.

J.4.5 Other Methods

There may be other diagnostic tools or testing procedures that may be used to document that the installed vapor control technology is functioning as intended. The method used should be appropriate and establish that the data quality objectives are being met.

J.5 Operation, Maintenance, and Monitoring

Before or shortly after mitigation systems are installed, a building or site-specific operation, maintenance, and inspection/monitoring (OM&M) plan should be prepared. Regular monitoring and maintenance intervals should be considered. The plan should identify what must be done following startup of the and what must be done on an ongoing basis for the life of the system, as well as provide a schedule for conducting these activities. The activities conducted immediately following start up should help to determine whether the system was installed properly and is operating as designed. The ongoing activities conducted should confirm that the system is still operational and that system components have not failed due to age or fouling. System performance criteria (such as a certain observable vacuum at a given location) should be evaluated during the initial and ongoing OM&M activities to confirm that criteria are being met. If multiple systems are installed (such as at a VI site with many homes), a standard OM&M plan can be prepared to cover all of the systems, with house-specific drawings and details contained in an appendix. Consult the manufacturer for specific details of system OM&M.

ASTM (2005) also requires that the average lifetime of the devices be taken into account and that the monitoring frequency should be a function of the time frame for possible failure of the engineering control (more frequent for an active system, less frequent for a passive system) and the relative effect of such a failure on a potential receptor (more frequent for immediate impact, less frequent for a delayed impact). Design specifications may include a monitoring frequency that varies over the operating period of the engineering control or a provision to evaluate and modify the monitoring frequency based on data or information obtained during monitoring and maintenance. For example, it may be acceptable to reduce sampling frequency once performance objectives for indoor air quality are met (preferably during the heating season). Likewise, decreased inspection/maintenance frequency may be acceptable once efficient system operation has been demonstrated for a year (NJDEP 2005). ASTM also suggests triggers for unscheduled inspections such as floods, earthquakes, and building modifications.

The average lifetime of the device, as well as any expected or required maintenance intervals should be available from the manufacturer. Additional information on operation and maintenance of venting systems may be found in Section 4.4 of NYSDOH (2006b).

J.5.1 Indoor Air Testing

Indoor air testing for COCs is often part of a long-term performance monitoring program, although long-term indoor air monitoring may not be warranted for every system installed. In addition to monitoring for COCs, monitoring for the presence of methane using a combustible gas detector should also be conducted because of the increased risk for the presence of methane at PHC sites. Once proper operation of the system has been confirmed by performance criteria (see Section J.4), indoor air testing may only be warranted in instances where the system design is complex, or the construction problematic. In situations where the pre-mitigation levels were high, however, more frequent monitoring may be necessary. Long-term indoor air testing could also be considered for a portion (such as 10%) of systems as a quality assurance check on installation. If, during inspections, the inspector believes that the building foundation or components of the mitigation system itself have been modified by the owner/tenant since the last inspection, indoor air or suction field extension testing should be considered to ensure that performance expectations are being realized.

J.5.2 OM&M Considerations for Specific Mitigation Methods

All mitigation systems should be inspected periodically. Visual inspections should be performed to confirm the integrity of system components. Routine inspections should also include an evaluation of any significant changes made to the building (for example, remodeled basement, new floor penetrations, or a new furnace) that would affect the design of the mitigation system or the environment in which it is operated.

J.5.3 Passive Venting/Passive Barriers

If present, inlets and discharges should be inspected and cleared of any debris. A smoke test can be performed to confirm the flow of air into the system. Passive barriers should be inspected and repaired any time that the floor is breached due to construction or deterioration.

J.5.4 SSD, SSV, SMD, SSP, and Aerated Floor Systems

If present, inlets and discharges should be inspected and cleared of any debris. Inspections should include confirmation that original suction levels are being maintained (by checking manometer readings). Crawl space membranes should look like they are being sucked down against the soil, particularly near suction points. Suction field extension testing may be warranted if manometer readings indicate reduced suction levels or indoor air tests show increasing trends. Fans generally do not require routine maintenance; however, fans should be replaced as necessary throughout the operating life of the system.

J.5.5 Building Pressurization

Building pressurization involves the design or modification of HVAC systems to maintain a positive pressure inside the building. During inspection it should be confirmed that the settings for these systems are set to maintain positive pressure. If indoor and outdoor pressure sensors are parts of the building control system, then it should be confirmed that the inside pressure is greater than the outside pressure.

J.5.6 Indoor Air Treatment

Indoor air treatment involves the installation of an air purifying technology that uses a media to filter or purify the indoor air. The media should be replaced based on manufacturer recommendations and based on indoor air concentrations. The spent filters and used media may have specialized disposal requirements (based on state or local regulations) that should be followed.

J.5.7 Sealing the Building Envelope and Epoxy Floor Coatings

Sealing of the building envelope and application of epoxy floor coatings involve applying a film of material on the surface or around openings in the building envelope. During inspection, the integrity of the material should be assessed. For epoxy floor coatings, high-traffic areas should be inspected for wear.

J.5.8 Discharge Permits and Emission Controls

Any monitoring necessary for permit should be completed and submitted to the appropriate authority. It may be necessary to modify or update the system to meet any limits or requirement based on the monitoring performed.

J.5.9 Warning Devices and System Labeling

According to ASTM (2003a): “All active radon mitigation systems shall include a mechanism to monitor system performance (air flow or pressure) and provide a visual or audible indication of system degradation and failure.” This requirement should be equally applicable to VI systems for other contaminants. ASTM further states “the mechanism shall be simple to read or interpret and be located where it is easily seen or heard. The monitoring device shall be capable of having its calibration quickly verified on site.” The Wisconsin guidance provides a detailed discussion of the circumstances and contaminants for which odor can provide a warning for VI problems (pages 7–9, WIDOH 2003)

Fixed gas detectors have been widely used for such acutely hazardous air pollutants as CO and methane in residential and industrial applications. Fixed detectors using infrared (IR) or photoionization (PID) devices are also available for VOCs (Skinner and Avenell 2005). Government websites that provide information about the selection and installation of gas detectors of various types include:

- Chapter 3 of the *OSHA Technical Manual* (OSHA 1999)
- Chapter 13, Appendix A of *ES&H Manual* by Lawrence Berkeley National Laboratory (LBNL 2013)

The New York and New Jersey VI documents also recommend durable pressure monitoring devices and alarms (NYSDOH 2006b; NJDEP 2013a). These devices may indicate operational parameters (such as on/off or pressure indicators) or hazardous gas buildup (such as percent LEL indicators). System failure warning devices or alarms should be installed on the active mitigation systems (for depressurization systems), and appropriate responses to these alarms should be understood by building occupants. Monitoring devices and alarms should be placed in readily visible, frequently-trafficked locations within the structure. The proper operation of warning devices should be confirmed on installation and monitored regularly.

Permanent placards should be placed on the system to describe its purpose, its operational requirements, and what to do if the system does not operate as designed (for example, a phone number to call). These placards should be placed near the monitoring/alarm part of the system, as well as near the fan or other active parts of the system. The placard should also explain how to read and interpret the monitoring instruments or warning devices provided.

J.5.10 Post-Mitigation Diagnostic Tests and System Modifications

Post-mitigation diagnostic tests are generally recommended to ensure that mitigation systems are meeting performance objectives and criteria. Some states have required indoor air tests shortly after mitigation systems are installed to ensure that action levels are being achieved. The number and timing of required tests varies, from a minimum of one or two (Montana 2011; MADEP 2002a) to long-term indoor air testing programs (CDPHE 2004). When only two postmitigation indoor air tests are performed, at least one of the tests is generally performed during cooler months. Post-mitigation indoor air tests should not be conducted immediately after the system has been installed because time is required for vapors that have already entered the structure to dissipate. Some state guidance documents suggest that indoor air sampling not be conducted for at least 30 to 45 days after installation and, preferably, during the heating season, although experience at sites in Colorado suggests that indoor testing may be conducted within two weeks of system installation (unless extenuating circumstances suggest waiting for a longer period of time).

When assessing system performance at new construction sites, monitoring of VOCs should account for the initial off-gassing of new building materials and furniture (NYSDOH 2006b). This initial off-gassing may require a longer delay for sampling after system startup than would be typical for an existing building.

In some cases, no indoor air testing is required and postmitigation suction field testing is considered sufficient to demonstrate SSD performance, assuming downward pressure gradients are measured or observed at all points over the slab. Postmitigation suction field extension testing can be conducted immediately after system installation, or after a short period of operation.

When long-term indoor air testing is used to monitor mitigation system performance, other forms of diagnostic testing are generally not necessary (except when action levels are not being achieved). On the other hand, when no indoor air testing is performed, perhaps due to concerns about background sources of contamination, more rigorous suction field testing is warranted.

If post-installation diagnostic tests indicate an inadequate suction field, a number of system modifications or enhancements have been shown to be effective (Folkes and Kurz 2002b), including:

- improving sealing of cracks, construction joints, loose membrane seals, and other penetrations in slabs or membranes that may be short-circuiting the system (as indicated by smoke tests)
- enlarging suction pits below floor slabs
- extending suction points further under membranes, using a pipe tee, perforated pipe, or nonwoven geotextiles
- adding additional suction points, with or without the addition of fans
- increasing fan size

J.6 System Shutdown and Closure

At most sites, long-term cleanup efforts eventually reduce volatile compound concentrations in soil or groundwater to levels that no longer require mitigation. At this point, vapor mitigation systems can be turned off or removed, depending on the preferences of the building owners and obligations of responsible parties. Likewise, ICs could presumably be retired. This practice is termed “closure.” This section generally refers to active systems used to prevent VI, not passive systems, although passive system piping could be removed if accessible. If there is nothing to turn off or take away, then closure is primarily an administrative task.

Regulatory personnel and responsible parties should consider early in the project how to determine when vapor mitigation is no longer required, as this decision affects the type of data to be collected during the operating period of the mitigation system. For example, the decision to stop mitigation could be based on indoor air confirmation tests, which would be conducted after temporarily shutting down the system. The number, location, and frequency of confirmation tests may be the same as those used to identify VI impacts; however, a smaller number of confirmation tests might be justified by an improved understanding of site conditions. As is the case with postmitigation monitoring, background indoor and outdoor air sources can complicate the evaluation of indoor air confirmation testing results. In any case, the decision to no longer require vapor mitigation in a building will likely be based first on groundwater, soil, and soil gas concentrations, which may indicate that the vapor source has been effectively eliminated. Just as it is difficult to predict VI effects in any particular building based only on media concentrations, it may also be difficult to predict when subsurface media concentrations have become low enough to curtail VI mitigation.

The selection of the media concentration that triggers closure (confirmation) testing is largely a matter of site-specific considerations. The length of time that the media must remain below these levels will also be a site-specific decision, based on a judgment of whether the media has been permanently remediated and how many environmental measurements over time are needed to demonstrate remediation. If there is documentation that the source of the contaminated vapors has been completely removed (for example, excavation of soils to below detection or conservative VI-based screening levels), then limited (or no) confirmation testing may be warranted. Although the time required for soil gas fluxes to diminish after source removal varies from site to site, evaluations by Johnson et al. (2002) indicate that soil gas concentrations (and, therefore, indoor air concentrations due to VI) will likely decrease in a relatively short period of time. When significant residual phase may be trapped in fractures or sorbed in low permeability bedrock, however, soil gas concentrations may decline much more slowly.

Mitigation systems must be shut down before confirmation tests can be conducted. Indoor air testing of mitigated buildings while the system is in operation do not indicate whether vapor mitigation is still required. One option may be to turn off the mitigation system for a few weeks, and then sample indoor air to determine whether the system is still currently needed. This approach is only recommended if the lines of evidence indicate that short-term exposures to conservatively-estimated indoor air concentrations (from VI) are not likely to result in unacceptable health effects, and if this approach is acceptable to the building occupants and owners. In the case of PHCs, indoor background sources are likely to confound the results of indoor air testing alone, and subslab or soil vapor may provide the most reliable indicators of VI potential.

Alternatively, subslab soil gas samples cab be collected as a surrogate for indoor air tests. Collecting soil gas from immediately beneath the slab will reduce (but not eliminate) the potential impacts of indoor or background sources on measured COC concentrations.

The decision to close vapor mitigation systems may be made on a building-by-building basis or, in some cases, it may be made by only testing “worst case” buildings at the site (or in certain areas of a larger site). If the mitigation systems at these “worst case” buildings can be closed, then there may be high confidence in the hypothesis that if these buildings are no longer at risk, other buildings at the site will not be at risk either. Closure decisions for the entire area may then be based on the results of confirmation tests for this subset of buildings.

Finally, even if regulators decide that systems may be turned off, some building owners may choose to continue operation of their mitigation systems to provide radon control or as a preemptive measure to control VI resulting from any sources that might occur in the future. Regulatory agencies may wish to promote the continued operation of vapor mitigation systems by building owners for radon control. The responsible party that originally installed and operated the vapor mitigation system, however, would probably not be held responsible for the system under the applicable regulatory program once controls were no longer required.

APPENDIX K. COMMUNITY ENGAGEMENT FACT SHEETS FOR FREQUENTLY ASKED QUESTIONS

The fact sheets listed below offer responses to frequently asked questions (FAQs) to support effective community engagement communications. The following FAQ Fact Sheets are provided:

PVI FAQ Fact Sheet 1: What is Petroleum Vapor Intrusion?

PVI FAQ Fact Sheet 2: What to Expect in a Petroleum Vapor Intrusion Investigation

PVI FAQ Fact Sheet 3: How to Fix a Petroleum Vapor Intrusion Problem

PVI FAQ Fact Sheet 4: Is a Petroleum Vapor Intrusion Problem Ever Over?

These fact sheets are useful for various aspects of project communications, including:

- as handouts for public meetings and public availability sessions
- as a tool for interacting directly with homeowners prior to sampling events
- as a tool for communicating with individuals and homeowners whose properties (or nearby properties) are undergoing PVI remediation
- for creating site-specific or user-specific FAQ sheets

APPENDIX L. INDOOR AIR BACKGROUND DATA

For environmental investigations, the term "background" generally refers to levels of contaminants that are either present due to naturally-occurring phenomena or those otherwise present in the absence of a release of that substance to environmental media (USEPA 2002c). For this appendix, “background” refers to indoor air levels of contaminants that are present in the absence of a release to the environment or in the absence of a complete PVI pathway. These VOCs may be present as a result of consumer products; hobbies; indoor or adjacent storage of VOC sources (USEPA 1992); residential heating fuels; household or building materials (Otto et al. 1990; USEPA 1998); and other sources (USEPA 1987; Brown et al. 1994).

Since background levels in indoor air may confound vapor intrusion investigations, the role of indoor air background has received attention from regulators and the regulated community and requires careful consideration (EPRI 2005; USEPA 2011). VOCs such as BTEX require particular attention, since these compounds are common to personal indoor air (Gordon et al. 1999; Clayton et al. 1999; Kinney et al. 2002;Sexton et al. 2004) and outdoor ambient air sources (USEPA 1988b; USEPA 2000).

BTEX levels have been identified in new (finished but unoccupied) prefabricated and site-built houses (Hodgson et al. 2000), and higher background levels of VOCs have been observed in homes with attached garages (Kurtz and Folkes 2004; Graham et al. 2004). Such VOCs are also commonly found in commercial buildings (Daisey et al. 1994; Girman et al. 1999). Indoor air background levels of BTEX VOCs have been identified at statistically higher levels than those collected at soil vapor intrusion investigations at MGP sites (EPRI 2007). Accordingly, investigators should pay careful attention to indoor air background sources at PVI sites. In the event that indoor air background levels have confounded a PVI investigation, forensic analysis may be required to assess the relative contribution from subsurface and background sources, possibly requiring multiple lines of evidence and multiple methods of interpretation (Plantz et al. 2008). Other site investigation methods detailed in Chapter 4 may be used prior or in addition to indoor air sampling if there is a concern that indoor air background sources will confound a PVI investigation.

For a general discussion of background sources, see Section 1.6.1 of the ITRC VI guidance document (ITRC 2007). For a more detailed discussion of indoor air sampling and background issues (including other sources) seeSection 3.5.4 and Section 3.7.3 of the ITRC VI guidance document.

In addition to the references included in Section 5of the ITRC VI guidance and those named above, the following studies have been performed regarding background concentrations:

- *Typical Indoor Air Concentrations of Volatile Organic Compounds in Non-Smoking Montana Residences Not Impacted by Vapor Intrusion* (MTDEQ 2012)
- *Total Volatile Organic Concentrations in 2700 Personal, Indoor, and Outdoor Air Samples collected in the US EPA Team Studies* (USEPA 1991b)

- *Air and Energy Engineering Research Laboratory. Indoor Air Quality Data Base for Organic Compounds* (USEPA 1992).
- *The use of indoor air measurements to evaluate intrusion of subsurface VOC vapors into buildings* (Hers et al. 2001).
- *Comparison of Personal, Indoor, and Outdoor Exposures to Hazardous Air Pollutants in Three Urban Communities* (Sexton et al. 2004)
- *Residential Typical Indoor Air Concentrations Technical Update* (MADEP 2008).
- *2008* (NYSDOH 2003)
- *Soil Vapor Intrusion Guidance, Appendix C. Study of Volatile Organic Compounds in Air of Fuel Oil Heated Homes, 1997-2003* (NYSDOH 2006c)
- *Availability of Documented Background Indoor and Outdoor Air Concentrations and/or Statistics* (Truesdale 2003)
- *http://iavi.rti.org/attachments/Resources/IAVIdb_12-10-03_background.pdf* (Rago, McCafferty, and Lingle 2007)
- *Indoor air VOC concentrations in suburban and rural New Jersey* (Weisel, Alimokhtari, and Sanders 2008)

APPENDIX M. FATE AND TRANSPORT OF PETROLEUM VAPORS

The following fate and transport mechanisms explain the behavior of PHC vapors and describe how this behavior affects the PVI pathway:

- partitioning of PHC vapors from contaminated soil, groundwater, or LNAPL into soil gas
- diffusion of PHC vapors in soil gas from the source toward the ground surface
- biodegradation in an aerobic biodegradation zone
- advection into a building
- mixing of vapors with building indoor air

An understanding these properties can help to explain the distribution of vapors at a site, evaluate multiple lines of evidence to determine completion of the PVI pathway, and refine the CSM. These processes are described in this appendix, with further discussion in Appendix C, Chemistry of Petroleum.

M.1 Phase Partitioning

PHCs are present in the subsurface partition between the solid, liquid, and gas phases. Partitioning equations are used to calculate the relationship of chemical concentrations in these different phases. The common partitioning equations used are Henry's law (which relates water and vapor concentrations), Raoult's law (which relates LNAPL and vapor concentrations), and linear sorption isotherms (which relate sorbed and aqueous concentrations). Partitioning calculations can be used to estimate the gas-phase concentration from a bulk soil or groundwater concentration. Note, however, that uncertainties and broad assumptions are associated with these calculations and related models that estimate soil gas concentrations from soil or groundwater data (McHugh and McAlary 2009). If partitioning information is needed, direct sampling of soil gas is generally recommended to avoid concerns associated with the partitioning equations.

Phase Partitioning

The separation of fuel constituents into soil, water, and air-filled soil porosity. Phase partitioning is most easily and accurately determined by direct sampling.

The composition of PHC vapors in the subsurface depends on both the original chemistry of the fuel and the effects of weathering. Weathering occurs primarily from three processes: volatilization, dissolution into water, and biodegradation, all of which significantly change the composition and reduce the mass of vapors potentially reaching receptors (Potter and Simmons 1998). Lower molecular weight constituents and those with higher vapor pressures preferentially volatilize from the source, thereby reducing the concentrations of these components in the source. Additionally, more soluble constituents, such as aromatic hydrocarbons (which include BTEX), preferentially partition into water and reduce the source concentrations of these constituents. Biodegradation is further discussed in Section 2.2.1. All PHC vapors may possibly be consumed by bacteria in the soil under optimal conditions.

M.2 Diffusion

Diffusion is the movement of a chemical from an area of higher concentration to lower concentration. Diffusion is typically the dominant transport mechanism for vapors in the vadose zone.

Diffusion

The dominant transport mechanism of vapors in the vadose zone, defined by movement of vapors from areas of higher concentrations to lower concentration.

The diffusive mass flux of a vapor in the soil is described by Fick's law. Diffusion occurs in both the aqueous and gas phases. The diffusive mass flux is directly proportional to the soil vapor concentration gradient; therefore, higher soil vapor concentrations result in higher flux. Additionally, an effective diffusion coefficient is used to integrate tortuosity of porous media and the diffusivity of the gas phase and soil moisture.

In addition to the concentration gradient, the degree of water saturation also affects the rate of the diffusive mass flux through the vadose zone. Diffusion coefficients in water are typically about four orders of magnitude lower than the diffusion coefficients in air, so as the soil becomes increasingly saturated, vapor flux decreases. Therefore, the capillary fringe (a thin layer of highly saturated soil in the vadose zone) can often reduce the overall vapor diffusive flux from groundwater to ground surface. Conversely, dry soils provide numerous air-filled pore spaces that allow for appreciable rates of diffusive transport.

The site-specific stratigraphy can also significantly affect the upward diffusion of contaminant vapors from the source and the downward diffusion of O_2 from the atmosphere due to changes in soil permeability and soil moisture content. Under dry conditions, diffusive transport can be similar for soils with a broad range of textures and grain sizes. Additionally, work presented by Carr (Carr, Levy, and Horneman 2010) illustrates how layers of saturated fine-grained soils are associated with significant reductions in the concentration of chlorinated vapors.

M.3 Biodegradation

A notable feature of aerobic biodegradation of PHCs in soils is the short acclimation time for this process, which can be measured in hours and days (Turner et al. 2014). The acclimation time is the time required for the microbial community to start consuming PHCs after the initial introduction of these chemicals. This short acclimation time indicates that PHC biodegradation is a common physiological trait of soil microorganisms.

Biodegradation Rates

The rate of biodegradation typically exceeds diffusive transport rates for PHC vapors.

Biodegradation is the breakdown of organic chemicals, including PHCs, by microorganisms. This process generally happens concurrently with and limits the diffusion of vapors through the vadose zone. Microorganisms that biodegrade PHCs are ubiquitous in most subsurface soils. Although PHCs can be biodegraded in the absence of O_2, the most rapid rates of biodegradation typically occur under aerobic conditions. The vadose zone above an area contaminated by a petroleum release is normally an aerobic environment in which oxygen can be readily replenished from the atmosphere. PHC vapors are typically, but not always, fully biodegraded in the vadose zone because rates of PHC vapor biodegradation usually exceed the rates of petroleum transport via diffusion.

M.3.1 Environmental Effects on Biodegradation

Despite the general reliability of aerobic biodegradation in reducing PVI, several environmental factors can slow this process. The most significant factor is the availability of O_2, which is a necessary electron acceptor and enzyme reactant in the aerobic biodegradation of PHCs. Low permeability soils (for instance, those with low porosity or high moisture content) may limit the recharge of O_2. Large building foundations (25 feet or more from the center to the edge of the slab) may also restrict recharge of O_2 (MIDEQ 2012; CRC CARE 2013; Knight and Davis 2013). Furthermore, O_2 concentrations may also be limited by its consumption because of biodegradation itself in areas of high PHC concentrations, such as near LNAPL sources. In the vadose zone, O_2 present at greater than 1% supports aerobic biodegradation (Abreu and Johnson 2006). Note that a number of state regulations and guidance documents use O_2 levels greater than 2–4% by volume to confirm that conditions are suitable to support aerobic biodegradation.

In the absence of O_2, anaerobic microorganisms can use other electron acceptors to support PHC biodegradation. Anaerobic biodegradation of PHCs is typically slower than aerobic biodegradation, and the rates of biodegradation in the presence and absence of O_2 can differ substantially.

Acclimation of Microorganisms

Microbial communities start consuming PHCs within hours or days.

Another factor limiting biodegradation is that microbial processes depend on moisture, so appreciable biodegradation rates occur only in the presence of moisture. In most vadose zone soil profiles, sufficient moisture, nutrients, and O_2 are present and do not limit microbial PHC biodegradation. However, in more extreme circumstances (such as arid environments), insufficient moisture or limited nutrients can potentially limit PHC biodegradation, even if sufficient O_2 is available.

M.3.2 Generation of Methane and Effects on Biodegradation

Cold climates do not necessarily decrease the potential for biodegradation. Although biological processes generally slow in colder temperatures, specific PHC-consuming microorganisms thrive in temperatures ranging from 20ºC to 0ºC (Margesin and Schinner 2001). Additionally, O_2 appears to be readily available in the subsurface in cold climates and biodegradation has been observed in arctic soils at subzero temperatures (Hers et al. 2011; Rike et al. 2003).

When PHCs are present at sufficiently high concentrations or in large source areas, O_2 and other electron acceptors may become depleted. PHCs may then be biodegraded through the activities of methanogenic microbial communities. Because methane is not a component of gasoline or other liquid hydrocarbon products, the presence of methane indicates that insufficient O_2 is available for aerobic PHC biodegradation.

Methane Production

Methane is produced when O_2 is depleted in the presence of high PHC concentrations or large source areas, or by breakdown of petroleum products containing ethanol.

The presence of methane can also further affect PHC biodegradation, because methane itself can be readily biodegraded under aerobic conditions. The consumption of O_2 for methane biodegradation can limit the amount of O_2 available for biodegradation of other hydrocarbons. O_2 levels can also be reduced in the presence of ethanol by a similar mechanism, resulting in further methane production. However, the effect of methanogenic degradation of ethanol in this context is limited in fuels containing 10% or less ethanol by volume (Wilson, Weaver, and White 2012b; Wilson et al. 2013).

M.3.3 Effects of PHC Chemical Structure on Biodegradation

The chemical structures of PHCs and their physicochemical properties can also influence their biodegradation. Generally, for PHCs dissolved in the water phase, microorganisms biodegrade n-alkanes (straight-chain alkanes) more rapidly than cyclic and aromatic compounds, and biodegrade shorter chain n-alkanes more slowly than longer chain n-alkanes (Alexander 1977). The structure of the chemical (for example, more branching) and the presence of specific substituents or functional groups (for example the ether group on methyl tert-butyl ether, or MTBE) can also strongly affect biodegradability. Another important factor that affects the biodegradability of a chemical based on its structure is the air-to-water partitioning coefficient. For petroleum chemicals, because the air-to-water partitioning of aromatic compounds is less than n-alkanes, a greater fraction of the aromatic compounds are partitioned into water, are more readily available to be biodegraded, and, therefore, may be more significantly attenuated by microbial biodegradation than n-alkanes (DeVaull 2007).

A summary of the effects of chemical structure on aerobic biodegradation rates is presented in Section 5.3.1.3: First-Order Biodegradation Rate Constants. For more information about the chemistry of petroleum, see Appendix C.

M.4 Advection

Pressure gradients between the building and subsurface can result in advective transport of subslab vapors to indoor air through a variety of potential entry points in the building foundation. Entry points include preferential pathways such as utility penetrations and lines, expansion joints, floor drains, and sumps, as well as structural defects such as cracks in the floor and foundation.

Pressure gradients between the air inside a building and the subsurface can be caused by several processes:

- wind loading on the building
- operation of combustion devices within the building
- HVAC operation
- the stack effect, caused by heating of building air to temperatures greater than outdoor air
- barometric pressure fluctuations
- methane generation due to anaerobic degradation of organic matter or residual PHCs in soil

Typically, pressure differentials between the building and the subsurface are relatively small (a few to a few dozen pascals), so the zone of influence of the pressure fields associated with building-induced advective flow does not penetrate far beneath the base of the building. Pressure gradients can differ as a result of building construction; for example, the stack effect may be more significant for taller buildings. Pressure gradients may also fluctuate for a variety of other reasons, such as HVAC operations, barometric pressure, and open windows.

Mechanical ventilation systems and weather-driven increases in barometric pressure can cause over-pressurization of the building and induce VOC migration from the building downward into the subslab soil. Thus, mixing of subslab soil gas and building air takes place not only inside a building, but also in the fill materials and native soils beneath the lowest floor. Consequently, the presence of a volatile contaminant beneath and inside a building may not be sufficient as a sole line of evidence that subsurface VI is occurring. Absent additional evidence, contamination of internal air and external soil gas from a contaminant source inside the building may be equally plausible.

M.5 Air Mixing within a Building

Intruded vapors can mix and dilute with indoor air. HVAC systems may rapidly distribute intruded vapors throughout the building. Dilution of subslab soil vapor concentrations is characterized by the building ventilation rate, expressed as air exchanges per hour.

APPENDIX N. TEAM CONTACTS

Lilian Abreu
ARCADIS
100 Montgomery St Suite 300
San Francisco, CA 94104
415-432-6928
lilian.abreu@arcadis-us.com

Delonda Alexander
NC Dept. of Environment and Natural Resources
1646 Mail Service Center
Raleigh, NC 27699
919-707-8365
delonda.alexander@ncdenr.gov

Taryn Badal
TestAmerica Inc.
880 Riverside Parkway
West Sacramento, CA 95605
916-201-1598
taryn.badal@testamericainc.com

Arthur Baehr
Pennsylvania Dept. of Environmental Protection
2028 Horace Ave.
Abington, PA 19001
215-370-3278
abaehr@pa.gov

Sam Bailey
Kleinfelder
3880 Lemon Street, 3rd Floor
Riverside, CA 92501
951-801-3681
sbailey@kleinfelder.com

Maple Barnard
Region 8 Denver Federal Facilities
7500 W 33rd Ave,
Denver, CO 80033
303-312-6321
barnard.maple@epa.gov

Deborah Barsotti
AMEC
200 American Metro Boulevard
Hamitlon, NJ 08619
609-631-2902
deborah.barsotti@amec.com

Bruce Bauman
API
1220 L St NW
washington, DC 20005
202-682-8345
bauman@api.org

Lila Beckley
GSI Environmental Inc.
9600 Great Hills Trail Suite 350E
Austin, TX 78759
512-346-4474
lmbeckley@gsi-net.com

Thomas Beckman
ERM
825 W. 8th Ave.
Anchorage, AK 99516
907-264-4451
thomas.beckman@erm.com

Heather Benfield
Tetra Tech
3475 E. Foothill Boulevard, Suite 200
Pasadena, CA 91107
626-470-2415
heather.benfield@tetratech.com

David Benham
GSA
330 Independence Ave
Washington, DC 20201
202-617-1932
davidwbenham@msn.com

David Bennett
Groundwater & Environmental Services, Inc.
1750 Kraft Drive, Suite 2700
Blacksburg, VA 24060
540-239-1400
dbennett@gesonline.com

Bharat Bham
Pennsylvania Dept of Environmental Protection
4530 Bath Pike, Route 512
Bethlehem, PA 18017
610-861-2070
bbham@pa.gov

Natalie Bickham
Conestoga-Rovers & Associates
5551 Corporate Blvd Suite 200
Baton Rouge, LA 70808
225-296-6511
nbickham@craworld.com

Richard (Kirby) Biggs
OSWER/OSRTI/TIFSD/TIIB
6101 Edsall Road #1206
Alexandria, VA 22304
703-823-3081
biggs.kirby@epa.gov

Quinten Bingham
CH2M Hill
215 So State St, Suite 1000
SLC, UT 84111
801-350-5216
quin.bingham@ch2m.com

Todd Blessing
Alaska Department of Environmental Conservation
555 Cordova Street
Anchorage, AK 99501
907-269-7699
todd.blessing@alaska.gov

Eric Blodgett
Barr Engineering Company
4700 West 77th Street, Suite 200
Minneapolis, MN 55435
952-842-3662
eblodgett@barr.com

Thomas Booze
DTSC
8800 Cal Center Dr
Sacramento, CA 95843
916-255-6628
tbooze@dtsc.ca.gov

John Boyer
New Jersey Department of Environmental Protection
401 East State Street, P.O. Box 420
Trenton, NJ 08625
609-984-9751
john.boyer@dep.nj.gov

Joe Branch
GSH
7601 Old Channel Trail
Montague, MI 49437
231-670-6809
joseph_branch@oxy.com

Patrick Brennan
Village of Paw Paw, Mi
32566 E Red Arrow Highway
Paw Paw, MI 49079
269-657-7695
pbrennan635@gmail.com

Kevin Brown
San Francisco Bay Regional Water Quality Control Board
1515 Clay Street, Suite 1400
Oakland, CA 94612
510-622-2358
kebrown@waterboards.ca.gov

Christopher Brown
Delaware DNREC
391 Lukens Drive
New Castle, DE 19720
302-395-2524
christopher.brown@state.de.us

Richard Burns
Conestoga-Rovers & Associates
410 Eagleview Boulevard, Suite 110
Exton, PA 19341
610-321-1800
rburns@craworld.com

Roland T Cain
Biosphere Consultants, LLC
3935 Brownstone
Houston, TX 77053
713-410-7484
biospherellc@yahoo.com

Donna Caldwell
US Navy
6506 Hampton Boulevard, LRA Building A
Norfolk, VA 23508
757-322-4816
donna.caldwell@navy.mil

Frank Camera
NJ DEP
380 Scotch Road, PO Box 420
Trenton, NJ 08625
609-530-2681
frank.camera@dep.nj.gov

J.R. Capasso
City of Trenton
c/o Housing & Economic Development, 319 East State St
Trenton, NJ 08608
609-989-3501
jcapasso@trentonnj.org

Grant Carey
Porewater Solutions
27 Kingsford Cres.
Ottawa, Ontario K2K 1T5
613-270-9458
gcarey@porewater.com

Ricky Cathey
TN Dept of Env & Cons/Division of UST
4th FL/L & C Tower, 401 Church St.
Nashville, TN 37243-1541
615-532-0950
ricky.cathey@tn.gov

Mark Cejas
Cardno ENTRIX
201 N. Calle Cesar Chavez. #203
Santa Barbara, CA 93103
305-342-2250
mark.cejas@cardno.com

Michael Chacon
Pueblo de San Ildefonso
124 Than Povi Po, Bldg. A
Santa Fe, NM 87506
505-455-4122
mchacon@sanipueblo.org

Arnab Chakrabarti
Geosyntec Consultants
1111 Broadway Street, 6th Floor
Oakland, CA 94612
510-285-2755
achakrabarti@geosyntec.com

Jagesh Chandra
512/368 4th Lane Nishatganj Lucknow Up
Lucknow, IN 226007
980-758-4021
jageshchandra@yahoo.com

William R. Chapman
Virginia Department of Environmental Quality
13901 Crown Court
Woodbridge, VA 22193
703-583-3816
randy.chapman@deq.virginia.gov

Rodney Clark
AMEC
1308 Patton Avenue
Asheville, NC 28805
828-252-8130
rodney.clark@amec.com

Peter Collopy
AMEC
9177 Sky Park Court
San Diego, CA 92103
858-514-6418
peter.collopy@amec.com

James Colmer
BB&E
10311 Ray Road
Gaines, MI 48436
248-489-9636
jcolmer@bbande.com

Ed Corack
Tetra Tech
5700 Lake Wright Dr, Suite 309
Norfolk, VA 23502
757-466-4908
ed.corack@tetratech.com

Robin Davis
Utah DEQ
195 North 1950 West
Salt Lake City, UT 84116
801-536-4177
rvdavis@utah.gov

George DeVaull
Shell
3333 Highway Six South, C2024C
Houston, TX 77082
281-544-7430
george.devaull@shell.com

Mike Duffin
Texas Commission on Environmental Quality
TCQ 12 100 Park 35 Circle
Austin, TX 78753
512-239-2378
Michael.Duffin@tceq.texas.gov

Bart Eklund
URS Corporation
PO Box 201088
Austin, TX 78720-1088
512-419-5436
bart.eklund@urs.com

Will Elcoate
Alpha Analytical
8 Walkup Drive
Westboro, MA 01581-1019
508-330-3753
welcoate@alphalab.com

Robert Ettinger
Geosyntec Consultants
924 Anacapa St. #4A
Santa Barbara, CA 93101
805-897-3800
rettinger@geosyntec.com

Brendlyn Faison
EPA Office of Water
1200 Pennsylvia Ave NW, Mail Code 4304T
Washington, DC, DC 20460
202-566-1311
faison.brendlyn@epa.gov

Marco Falconi
ISPRA
Via Vitaliano Brancati 48
Rome, - 61041
00393471204170
marco.falconi@isprambiente.it

Michael Fanizza
ERM
1701 Golf Road Suite 1-1000
Rolling Meadows, IL 60008
847-258-8930
michael.fanizza@erm.com

Tripp Fischer
Brownfield Science & Technology, Inc.
3157 Limestone Road
Cochranville, PA 19330
610-593-5500
tfischer@bstiweb.com

David Folkes
Geosyntec Consultants
7009 S Potomac Street, Suite 300
Centennial, CO 80112
303-790-1340
dfolkes@geosyntec.com

Alyson Fortune
ALS Environmental
15 Park Drive
Littleton, MA 01460
978-501-2735
afortune@caslab.com

Julia Fraser
Colorado DLE of Oil and Public Safety
633 17th Street, Suite 500
Denver, CO 80202
303-318-8504
Julia.Fraser@state.co.us

David Frazier
Arkansas Department of Environmental Quality
5301 Northshore Dr.
North Little Rock, AR 72118
501-682-0982
frazier@adeq.state.ar.us

Aaron Friedrich
ERM
11350 North Meridian Street, Suite 320
Carmel, IN 46032
317-445-6684
aaron.friedrich@erm.com

Valerie Garrett
Missouri Department of Natural Resources
P.O. Box 176, 1730 E. Elm Street
Jefferson City, MO 65102
573-526-3385
valerie.garrett@dnr.mo.gov

Gregory Garvey
Integral Consulting Inc.
200 Harry S. Truman Parkway, Suite 330
Annapolis, MD 21401
215-238-1937
ggarvey@integral-corp.com

Sandra Gaurin
Tetra Tech
1000 The American Rd
Morris Plains, NJ 07950
973-630-8040
sandra.gaurin@tetratech.com

Marc Grant
AMEC
AMEC, 271 Mill Road
Chelmsford, MA 01824
978-392-5330
marc.grant@amec.com

Cindy Greene
State of Tennessee
401 Church Street, 4th Floor, L&C Tower
Nashville, TN 37243-1541
615-532-0988
Cindy.Greene@tn.gov

Daniel Groher
US Army Corps of Engineers
696 Virginia Road
Concord, MA 01742
978-318-8404
daniel.m.groher@usace.army.mil

Haile Habtegiorgis
Golder Associates
220 1755 Springfield Road
Kelowna, BC V1Y 5V5
250-860-8424
haile_habtegiorgis@golder.com

Kevin Hale
NYS DEC
625 Broadway
Albany, NY 12233
518-402-9543
kghale@gw.dec.state.ny.us

Blayne Hartman
Hartman Environmental Geoscience
717 Seabright Lane
Solana Beach, CA 92075
858-204-6170
blayne@hartmaneg.com

Jill Henes
Calscience Environmental Laboratories, Inc.
7440 Lincoln Way
Garden Grove, CA 92841
714-895-5494
jhenes@calscience.com

Ian Hers
Golder Associates
#500-4260 Still Creek Drive
Burnaby, British Columbia V5C6C6
604-298-6623
ihers@golder.com

Geoff Hewitt
ION Science Americas LLC
347 Blush Hill Estates
Waterbury, VT 05676
802-342-0005
geoff.hewitt@ionscienceusa.com

Tom Higgins
Minnesota Pollution Control Agency
520 Lafayette Road North
St. Paul, MN 55155-4194
651-757-2436
tom.higgins@state.mn.us

Jay Hodny
Amplified Geochemical Imaging, LLC
210 Executive Drive, Suite 1
Newark, DE 19702-3335
302-266-2426
hodny@agisurveys.net

Harley Hopkins
ExxonMobil
3225 Gallows Road
Fairfax, VA 22037
703-846-5446
harley.hopkins@exxonmobil.com

Michael Hyman
North Carolina State University
Department of Microbiology, 4545 Thomas Hall
Raleigh, NC 27695
919-515-7814
michael_hyman@ncsu.edu

Glenn Nicholas Iosue PE
Directional Technologies, Inc.
77 North Plains Industrial Road
Wallingford, CT 06492
484-318-9087
giosue@directionaltech.com

Undine Johnson
Georgia Environmental Protection Division
4244 International Parkway, Suite 104
Atlanta, GA 30354
404-362-2594
undine.johnson@dnr.state.ga.us

Deborah Johnston
Corps of Engineers
3745 East Marginal Way S
Seattle, WA 98124
206-316-3969
deborah.j.johnston2@usace.army.mil

Nick Jose
Vapor Protection Services, LLC
6507 Ferguson Street, Suite B1
Indianapolis, IN 46220
317-252-5295
jose@vaporprotection.com

Julie Kabel
AECOM
1000 Elm Street, Suite 802
Manchester, NH 03101
603-263-2145
julie.kabel@aecom.com

Thomas Kettinger
AECOM
1555 N. River Center Drive, Suite 214
Milwaukee, WI 53212
414-944-6181
thomas.kettinger@aecom.com

Flint Kinkade
Viridian Inc
Po Box 3009
Upper Montclair, NJ 07043
973-746-7600
flint@viridianinc.com

Preston Klingseis
Tetra Tech
1881 Campus Commons Drive, Suite 200
Reston, VA 20191
703-390-0701
preston.klingseis@tetratech.com

Ravi Kolhatkar
Chevron
4901 Briarpark, #BP416
Houston, TX 77042
713-954-6082
kolhatrv@chevron.com

Ronald Kotun
Tetra Tech
661 Andersen Drive
Pittsburgh, PA 15220
412-921-8291
ronald.kotun@tetratech.com

Jeffrey Kuhn
Montana Department of Environmental Quality
P.O. Box 200901, 1100 North Last Chance Gulch
Helena, MT 59601
406-841-5055
jkuhn@mt.gov

Tara Kulkarni
Norwich University
193 Dover Road
Montpelier, VT 05602
802-485-2268
tkulkarn@norwich.edu

Jeff Kurtz
EnviroGroup Limited
7009 S. Potomac Street, Suite 300
Centennial, CO 80112
303-790-1340
jkurtz@envirogroup.com

Michael Kwiecinski
Colorado Division of Oil and Public Safety
633 17th Street, Suite 500
Denver, CO 80202-3660
303-318-8512
mike.kwiecinski@state.co.us

Matthew Lahvis
Shell
Westhollow Technology Center, 3333 Hwy 6 South
Houston, TX 77082
281-544-6884
matthew.lahvis@shell.com

Michael Lam
Conestoga-Rovers & Associates
20818 44th Ave West, Suite190
Lynnwood, WA 98036
425-563-6508
mqlam@craworld.com

Lori Landmeyer
SC DHEC
2600 Bull Street
Blythewood, SC 29016
803-896-2965
landmedc@dhec.sc.gov

Nathan Lewis
Kentucky Division of Waste Management/Underground Storage Tank Branch
200 Fair Oaks Lane
Frankfort, KY 40601
502-564-5981
nathan.lewis@ky.gov

James Lingle
EPRI
4927 W. Willow Road
Brown Deer, WI 53223
414-355-5559
jlingle@epri.com

David Lipson
ARCADIS
1687 Cole Boulevard, 2nd Floor
Arvada, CO 80401
303-231-9115
Dave.Lipson@arcadis-us.com

Patricia Locklin
Maine Department of Environmental Protection
17 State House Station
Augusta, ME 04333
207-287-8444
patricia.a.locklin@maine.gov

Dot Lofstrom
Cal/EPA - Dept. of Toxic Substances Control (DTSC)
8800 Cal Center Drive
Sacramento, CA 95826
916-255-6532
Dot.Lofstrom@dtsc.ca.gov

Kevin Long
ENVIRON
13 Del Rio Drive
Yardley, PA 19067
609-951-9048
klong@environcorp.com

Jun Lu
AECOM
3995 Via Oro Ave
Long Beach, CA 90810
562-213-4120
jun.lu@aecom.com

Loren Lund
CH2M Hill
787 E. 1500 N.
Shelley, ID 83274
208-357-5351
Loren.Lund@ch2m.com

Hong Luo
Arizona State University
Arizona State University, ECG-252, PO 5306
Tempe, AZ 85201
480-358-7198
hong.luo@asu.edu

Emma Hong Luo
Chevron
3901 Brairpark Dr
Houston, TX 77042
713-954-6101
emma.hong.luo@chevron.com

Silvia Maberti
ExxonMobil
2800 Decker Dr NW-53
Baytown, TX 77520
281-834-4690
silvia.i.maberti@exxonmobil.com

Jimmy N. Mackey
Community Stakeholder Org.
120 Old Towne Rd.
Okatie, SC 29909
843-645-3952
thesis_fire@yahoo.com

Diana Marquez
Burns & McDonnell Engineering Company, Inc
10809 Haskins Street
Lenexa, KS 66210
816-822-3453
dmarque@burnsmcd.com

Ben Martich
Geosyntec Consultants
110 West 38th, Ste 200A
Anchorage, AK 99503
907-433-0770
bmartich@geosyntec.com

Vanessa McCowan
CH2M Hill
3010-B Papali St
Honolulu, HI, HI 96819
732-429-9827
vanessa.mccowan@ch2m.com

Richard McCoy
Air National Guard
NGB/A7OR, 3501 Fetchet Avenue
Joint Base Andrews, MD 20762-5157
240-612-8541
richard.mccoy@ang.af.mil

Colin McCoy
Tetra Tech
7 W 6th Ave Ste 612
Helena, MT 59601
406-441-3261
colin.mccoy@tetratech.com

Thomas McHugh
GSI Environmental Inc.
2211 Norfolk, #1000
Houston, TX 77098
713-522-6300
temchugh@gsi-net.com

William McKercher
Mississippi Department of Environmental Quality
515 West Amite Street, P.O. Box 2261
Jackson, MS 39225
601-961-5731
Willie_McKercher@deq.state.ms.us

Doug McReynolds
EA Engineering, Science and Technology, Inc.
5427 W Hanover Ave
Dallas, TX 75209
214-415-3876
doug.mcreynolds@gmail.com

Sat Mellacheruvu
Broward County Pollution Prevention, Remediation and Air Quality Division
1 North University Drive, Suite 203
Plantation, FL 33324
954-519-1448
smellacheruvu@broward.org

John Mellow
Licensed Professional Geologist/Environmental Activist
1190 West State Street
Archbald, PA 18403
570-290-0347
mellow5n2@aol.com

John Menatti
Utah Department of Environmental Quality
195 North 1950 West, P.O. Box 144840
Salt Lake City, UT 84114-4840
801-536-4159
jmenatti@utah.gov

Tara Meyers
NAVFAC Engineering and Expeditionary Warfare Center (EXWC)
1000 23rd Ave., EV 33
Port Hueneme, CA 93043
805-982-1614
tara.meyers@navy.mil

Abdellatif "Adam" Mohamed
Arizona Department of Environmental Quality
1110 West Washington Street
Phoenix, AZ 85007
623-695-1397
aam@azdeq.gov

Mary Monahan
WA State Department of Ecology
15 W. Yakima Avenue, Suite 200
Yakima, WA 98902
509-454-7840
mary.monahan@ecy.wa.gov

Robin Mongeon
New Hampshire Department of Environmental Services
29 Hazen Drive
Concord, NH 03302-0095
603-271-7378
Robin.Mongeon@des.nh.gov

Raymond Montero
District Department of the Environment
1200 First Street, NE
Washington, DC 20002
202-535-2294
raymond.montero@dc.gov

William Morris
Vapor Mitigation Sciences, LLC
4475 W. Piute Avenue
Glendale, AZ 85308
785-480-5688
mitigationsciences@gmail.com

Christopher Mulry
Groundwater & Environmental Services, Inc.
1350 Blair Drive, Suite A
Odenton, MD 21113
410-320-1715
cmulry@gesonline.com

Josh Nagashima
State of Hawaii
919 Ala Moana Boulevard, Suite 212
Honolulu, HI 96814
808-586-4226
josh.nagashima@doh.hawaii.gov

Gary Newhart
US EPA - ERT
US EPA - ERT, 4900 Olympic Boulevard
Erlanger, KY 4108
513-569-7661
newhart.gary@epa.gov

Hieu Nguyen
CETCO
2870 Forbs Avenue
Hoffman Estates, IL 60192
714-448-7262
hieu.nguyen@cetco.com

Eric Nichols
Substrata LLC
78 Piscassic Rd
Newfields, NH 03856
603-770-6577
eric@substrata.us.com

Gerold Noyes
VT ANR Dept of Environmental Conservation
1 National Life Dr - Davis 1
Montpelier, VT 05620-3704
802-522-5614
gerold.noyes@state.vt.us

Adebayo Ogundipe
James Madison University
801 Carrier Drive
Harrisonburg, VA 22807
540-568-4964
ogundiaa@jmu.edu

Harry O'Neill
Beacon Environmental Services, Inc.
2203A Commerce Road, Suite 1
Forest Hill, MD 21050
410-838-8780
harry.oneill@beacon-usa.com

Mary Ann Parcher
Groundwater & Environmental Services, Inc.
1750 Kraft Drive, Suite 2700
Blacksburg, VA 24060
540-552-0685
mparcher@gesonline.com

Mukta Patil
Langan Engineering & Environmental
Services
555 Montgomery St, Suite 1300
San Francisco, CA 94111
415-955-5241
mpatil@langan.com

Tony Payne
AECOM
8 Mahuhu Crescent
Auckland, Auckland 10065
555-555-5555
tony.payne@aecom.com

Jessica Penetar
ENVIRON
214 Carnegie Center
Princeton, NJ 08540
609-243-9897
jpenetar@environcorp.com

Jodie Peotter, P.G.
ECCS Nationwide Mobile Laboratories
525 Junction Road, Suite 1900
Madison, WI 53717
608-234-7183
jpeotter@consulttruenorth.com

Gary Perkowitz
St. John-Mittelhauser & Associates, Inc.
1401 Branding Avenue, Suite 315
Downers Grove, IL 60515
630-427-8104
garyp@st-ma.com

Ioana Petrisor
Cardno ENTRIX
25371 Commercentre Drive, Suite 250
Lake Forest, CA 92084
949-273-6311
ioana.petrisor@cardno.com

Mike Pfister
Cal EPA/Department of Toxic Substances Control
1515 tollhouse Road
Clovis, CA 93619
559-297-3958
mpfister@dtsc.ca.gov

Jeffrey Pintenich
Brown and Caldwell
Brown and Caldwell, 501 Great Circle Road, #150
Nashville, TN 37228
615-250-1237
jpintenich@brwncald.com

Robert Pirkle
Microseeps, Inc
220 William Pitt Way
Pittsburgh, PA 15238
412-826-5245
mseepsbobp@aol.com

Robert Pirkle
Microseeps, Inc
220 William Pitt Way
Pittsburgh, PA 15238
412-826-5245
rpirkle@microseeps.com

Gina Plantz
Haley & Aldrich, Inc.
3 Bedford Farms Dr.
Bedford, NH 03110
603-391-3319
gplantz@haleyaldrich.com

Ron Poustchi
NJDEP
401 East State Street, 5th flr, P.O. Box 420
Trenton, NJ 08625-0420
609-292-3115
Ron.Poustchi@dep.state.nj.us

Abhijeet Prasad
Acuity Environmental Solutions
Jatin Das Sarani, Near Jewel Athletic Club,,
Ashrampara, Siliguri
Siliguri, IN 734001
993-318-8647
abhikhushi10@gmail.com

Richard Rago
Haley & Aldrich, Inc.
100 Corporate Place, Suite 105
Rocky Hill, CT 06067
860-290-3115
rrago@haleyaldrich.com

Mohammed Rahman
Illinois Environmental Protection Agency
1021 North Grand Avenue East
Springfield, IL 62794
217-782-9848
mohammed.rahman@illinois.gov

Edward Ralston
ConocoPhillips
76 Broadway
Sacramento, CA 95818
916-558-7633
ed.c.ralston@conocophillips.com

Edward Ralston
Phillips 66
76 Broadway
Sacramento, CA 95818
916-558-7633
ed.c.ralston@p66.com

Francis Ramacciotti
ENVIRON
214 Carnegie Center, Suite 200
Princeton, NJ 08540
609-243-9833
framacciotti@environcorp.com

Catherine Regan
ERM
1 Beacon Street, 5th Floor
Boston, MA 02108
617-646-7859
catherine.regan@erm.com

Andy Rezendes
Alpha Analytical
320 Forbes Blvd.
Mansfield, MA 02048
508-822-9300
andrez@alphalab.com

Todd Ririe
BP
4 Centerpointe Dr
La Palma, CA 90623
714-504-2316
todd.ririe@bp.com

Christopher Saunders
Kleinfelder
200 Queen Street
Melbourne, VIC 3068
045-217-6464
csaunders@kleinfelder.com

Jennifer Shin
ExxonMobil
1545 US 22 East
Annandale, NJ 08801
908-730-1108
jennifer.shin@exxonmobil.com

Mary Siders
Nevada Division of Environmental Protection
901 S. Stewart Street, Suite 4001
Carson City, NV 89701
775-687-9496
msiders@ndep.nv.gov

Deepak Singh
District Department of the Environment
1200 First Street NE, 5th Floor
Washington, DC 20002
202-535-2634
deepak.singh@dc.gov

Russell Sirabian
Battelle
50 Main Street, Suite 1000
White Plains, NY 10804
914-682-2179
sirabianr@battelle.org

Lawrence Sirinek
WV DEP
131 A Peninsula St.
Wheeling, WV 26003
304-238-1220
lawrence.p.sirinek@wv.gov

Carl Skelley
TestAmerica Inc.
14050 Summit Drive, Suite A100
Austin, TX 78728
512-310-5208
carlw.skelley@testamericainc.com

Claudio Sorrentino
Dept. Toxic Substances Control - Cal EPA
8800 Cal Center Drive
Sacramento, CA 95826
916-255-6656
Claudio.Sorrentino@DTSC.ca.gov

Roy Spalding
University of Nebraska
279 Plant Sciences
6200 West Waverly Road
Lincoln, NE 68583-0915
402-472-8214
rspalding1@unl.edu

Lynn Spence
Chevron
4536 Mirador Drive
Pleasanton, CA 94566
925-846-4721
lynnspence@comcast.net

Carl Stay
ERM
700 W. Virginia St., Suite 601
Milwaukee, WI 53204
414-289-9505
carl.stay@erm.com

LeVonne Stone
Fort Ord Environmental Justice Network
P.O. Box 361
Marina, CA 93933
831-277-5241
ejustice@mbay.net

Mark Strong
CH2M Hill
11301 Carmel Commons Blvd, Suite 304
Charlotte, NC 28273
704-543-3289
mstrong@ch2m.com

Arthur Taylor
ERM, Inc.
1277 Treat Blvd, Suite 500
Walnut Creek, CA 94609
925-946-0455
teke.taylor@erm.com

Debra Thoma
SCDHEC
2600 Bull Street
Columbia, SC 29201
803-896-6397
thomadl@dhec.sc.gov

Shannon Thompson
Trihydro Corporation
1537 Riverside Ave
Fort Collins, CO 80524
307-745-7474
sthompson@trihydro.com

Derek Tomlinson
Geosyntec Consultants
1787 Sentry Parkway West, Building 18, Suite 120
Blue Bell, PA 19422
267-464-2800
dtomlinson@geosyntec.com

Alvaro Torres Jr.
Nonprofit org.
Macrdida 204
Lima, Lima 33
51-1-2415606
a.torresenriquez@gmail.com

Laura Trozzolo
AECOM
548 W. Spruce Way
Louisville, CO 80027
970-530-3444
laura.trozzolo@aecom.com

Audrey Van Cleve
Minnesota Pollution Control Agency
520 Lafayette Rd N
St. Paul, MN 55155-4194
651-757-2792
audrey.van.cleve@state.mn.us

Terry Vandell
ConocoPhillips
1000 S. Pine
Ponca City, OK 74604
580-767-6561
terry.d.vandell@conocophillips.com

Terry Vandell
Phillips 66
1000 S. Pine
Ponca City, OK 74601
580-767-6561
Terry.D.Vandell@P66.com

Trish Venable
Naval Facilities Engineering Service Center
NFESC, Code EV33, 1100 23rd Ave.
Port Hueneme, CA 93043
805-982-1411
patricia.venable@navy.mil

Ann Verwiel
AMEC
68 Graceland Drive
San Rafael, CA 94901
415-446-9858
averwiel@comcast.net

Susan von Gonten
New Mexico Environment Department
Petroleum Storage Tank Bureau, 1301 Siler Road, Building B
Santa Fe, NM 87507
505-476-4389
susan.vongonten@state.nm.us

Tom Walker
Office of Underground Storage Tanks
2733 South Crystal Drive
Arlington, VA 22202
703-603-7159
walker.tom@epa.gov

Yi Wang
ZymaX Forensics
600 S Andreasen Drive, Suite B
Escondido, CA 92029
760-781-3338
yi.wang@zymaxusa.com

Fan Wang-Cahill
Parsons
100 M Street, Suite 1200
Washington DC, DC 20003
202-469-6483
fan.wangcahill@parsons.com

Nadine Weinberg
ARCADIS
482 Congress Street, Suite 501
Portland, ME 04101
207-828-0046
nadine.weinberg@arcadis-us.com

Jim Whetzel
Amplified Geochemical Imaging, LLC
210 Executive Drive, Suite 1
Newark, DE 19702
302-266-2421
whetzel@agisurveys.net

Matthew Williams
Michigan Department of Environmental Quality
525 West Allegan Street, DEQ, Superfund, 5th Floor South
Lansing, MI 48909-7926
517-284-5171
WilliamsM13@Michigan.gov

Scott Wilson
Regenesis
1011 Calle Sombra
San Clemente, CA 92009
949-366-8000
swilson@regenesis.com

Elizabeth Winger
Calscience Environmental Laboratories, Inc.
7440 Lincoln Way
Garden Grove, CA 92841
714-895-5494
ewinger@calscience.com

Stacie Wissler
Kleinfelder
5015 Shoreham Place
San Diego, CA 92103
858-320-2000
swissler@kleinfelder.com

Tedd Yargeau
Cal EPA Dept. of Toxic Substances Control
9211 Oakdale Avenue
Chatsworth, CA 91311
818-212-5340
tyargeau@dtsc.ca.gov

Mary Yelken
The Yelken Group, Inc.
6700 Blue Ridge Lane
Lincoln, NE 68516
402-325-9615
myelken@theyelkengroup.com

Keith Ziobron
O'Brien & Gere
8200 Roberts Drive, Suite 450
Atlanta, GA 30350
678-315-9264
keith.ziobron@obg.com

APPENDIX O. ACRONYMS

1,1-DCE	1,1, dichloroethene
AF	attenuation factor
APH	air-phase petroleum hydrocarbon
API	American Petroleum Institute
AST	aboveground storage tank
ATSDR	Agency for Toxic Substances and Disease Registry
bgs	below the ground surface
BTEX	benzene, toluene, ethylbenzene, and xylenes
CAG	community advisory group
CaPAH	carcinogenic polynuclear aromatic hydrocarbons
cc	cubic centimeter
CEP	Community Engagement Plan
CGI	combustible gas indicator
CH_4	methane
CIP	Community Involvement Plan
COC	contaminant of concern
CPSi	cancer potency slope, inhalation
CSIA	compound-specific isotope analysis
CSM	conceptual site model
CVI	chlorinated vapor intrusion
CVOC	chlorinated volatile organic compound
DNAPL	dense nonaqueous phase liquid
DQO	data quality objective
DTSC	California Department of Toxic Substances Control
E&P	oil exploration & production
ECD	electron-capture dissociation
EJ	environmental justice
EPH	extractable petroleum hydrocarbon
FAQ	frequently asked questions
FID	flame ionization detector
GC	gas chromatography
GC/MS	gas chromatography/mass spectrometry
GW	groundwater

HDPE	high density polyethylene
Hg	mercury
HQ	hazard quotient
HVAC	heating, ventilation and air conditioning
IA	indoor air
IC	institutional control
ID	inner diameter
IR	Infrared
IRIS	Integrated Risk Information System
IRM	interim remedial measure
ITRC	Interstate Technology & Regulatory Council
J&E	Johnson & Ettinger model
LNAPL	light nonaqueous phase liquid
MDEQ	Michigan Department of Environmental Quality
MDL	method detection limit
MGP	manufactured gas plant
MIBK	4-methyl-2-pentanone
MLE	multiple lines of evidence
MNA	monitored natural attenuation
MTBE	methyl tertiary-butyl ether
MW	monitoring well
NASA	National Aeronautics and Space Administration
NJDEP	New Jersey Department of Environmental Protection
NYSDEC	New York State Department of Environmental Conservation
OD	outer diameter
OM&M	operation, maintenance and monitoring
OSHA	Occupational Safety and Health Administration
OSWER	USEPA Office of Solid Waste and Emergency Response
OUST	Office of Underground Storage Tanks (USEPA)
PAH	polynuclear aromatic hydrocarbons
PCE	tetrachloroethene (also called perchloroethene)
PCP	pentachlorophenol
PDBS	passive diffusion bag samplers
PEEK	tubing made from polyetheretherketone

PEL	permissible exposure limit
PHC	petroleum hydrocarbon
PIANO	analytical list that includes paraffin, iso-paraffins, aromatics, naphthenes, and olefins
PID	photoionization detector
ppbv	parts per billion by volume
PQL	practical quantitation limit
PVC	polyvinyl chloride
PVI	petroleum vapor intrusion
QA/QC	quality assurance/quality control
RfC	reference concentration
RfD	reference dose
RfDi	reference dose, inhalation
RL	reporting limit
RRT	relative retention time
SCAN	continuous scanning mode
SIM	selective ion monitoring
SMD	submembrane depressurization
SOP	standard operating procedures
SSD	subslab depressurization
SSP	subslab pressurization
SSV	subslab ventilation
SVE	soil vapor extraction
SVOC	semivolatile organic compounds
TAGA	trace atmospheric gas analyzer
TAME	tert-amyl-methyl-ether, an oxygenate
TBA	tert-butyl alcohol, an oxygenate
TBEE	tert-butyl-ethyl ether, an oxygenate
TCA	trichloroethane
TCD	thermal conductivity detector
TCE	trichloroethene
TPH	total petroleum hydrocarbons
URF	unit risk factor
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

UST	underground storage tank
VI	vapor intrusion
VOC	volatile organic compound
$\mu g/m^3$	microgram per cubic meter

APPENDIX P. GLOSSARY

A

aerobic

Pertaining to or caused by the presence of oxygen.

aliphatic

A hydrocarbon compound in which the carbon atoms are in a straight-chain, branched, or cyclic arrangement and are saturated or unsaturated.

alkane

A group of chemicals (also known as paraffins or aliphatic hydrocarbons) for which the carbon atoms are all linked by single covalent bonds.

alkene

A group of chemicals (also known as paraffins or aliphatic hydrocarbons) for which the carbon atoms contain at least one double bond.

anaerobic

Pertaining to or caused by the absence of oxygen.

aromatic

An organic compound that contains one or more benzene or equivalent heterocyclic rings.

attenuation factor

A ratio of the indoor air concentration to soil gas or groundwater concentration; sometimes used to estimate the indoor air concentration from soil gas or groundwater concentration.

B

biodegradation

The breakdown of chemicals by microorganisms.

C

capillary zone (or fringe)

The pore spaces in soil just above the water table that may contain water above the static level from interactive forces between the water and soil.

clean soil

Soil with an acceptable level of contamination to remain conducive to biodegradation of petroleum vapors.

coal tar

A byproduct of pyrolysis of coal, coke, or oil in a closed vessel during the production of manufactured gas containing a small percentage of volatile organics and polycyclic aromatic hydrocarbons.

community engagement

The process of communicating with local residents and other stakeholders to: provide information throughout the investigation and clean-up of a contaminated site; provide opportunities for offering input about site investigation/cleanup plans; and to facilitate the resolution of community issues related to a contaminated site.

concentration gradient

The change of concentration over a certain distance.

conceptual site model

A three-dimensional visualization of site conditions that allows for evaluation of contaminant sources and affected media, migration pathways and potential receptors.

cyclic

A compound that contains a closed ring of atoms.

D

diffusion

Movement of vapors away from areas of higher concentration.

E

environmental justice

The fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies.

F

Fick's law

The principle that diffusive flux goes from areas of high concentration to areas of lower concentration with a magnitude proportional to the concentration gradient.

flux

Flow per unit area.

G

gasolines

Petroleum mixtures characterized by a predominance of branched alkanes with carbon ranges from C3 to C12 and lesser amounts of aromatics, straight-chain alkanes, cycloalkanes, and alkenes of the same carbon range.

H

Henry's law

The principle that the amount of a gas dissolved at equilibrium in a certain quantity of liquid is proportional to the pressure of the gas in contact with the liquid.

heterocyclic

A compound that contains a closed ring of atoms in which one of the ring members is not a carbon atom.

I

indicator compound

A compound chosen for its likely presence in an area of interest that is used to estimate conditions as a whole for the area of interest.

J

Johnson & Ettinger model

A one-dimensional analytical solution to convective and diffusive vapor transport into indoor spaces and provides an estimated attenuation coefficient that relates the vapor concentration in the indoor space to the vapor concentration at the source of contamination.

L

light nonaqueous phase liquid

A liquid that is not soluble and has a lower density than water.

M

methanogenic

Able to produce methane from a limited number of substrates.

middle distillates

Petroleum mixtures characterized by a wider variety of straight, branched, and cyclic alkanes, as well as polycyclic aromatic hydrocarbons and heterocyclic compounds with carbon ranges of approximately C9 to C25.

O

organic carbon partition coefficient

The theoretical ratio of the mass absorbed to soil particles versus dissolved in pore water.

oxygen sink

A process (such as biodegradation) that reduces the amount of oxygen present.

P

petroleum vapor intrusion

The process by which volatile hydrocarbons partition from petroleum-contaminated soils and/or groundwater and migrate through the vadose zone in gaseous form to receptors.

phase partitioning

Separation of fuel into solid, liquid, and gas phases.

preferential pathway

A high-permeability conduit for vapor migration such as a utility penetrations, lines, or drains; building sumps or drainage pits; elevator shafts; fractures in bedrock; or gravel channels.

R

Raoult's law

The principle that the vapor pressure of an ideal solution is directly dependent upon the vapor pressure of each chemical component and mole fraction of each component in the solution.

residual fuels

Petroleum mixtures characterized by complex, polar polycyclic aromatic hydrocarbons and other high molecular weight hydrocarbon compounds with carbon ranges that generally fall between C24 and C40.

risk communication

Actions, words, and other messages, responsive to the concerns and values of the information recipients, intended to help people make more informed decisions about threats to their health and safety.

S

soil pore space
The air- or water-filled space that is between soil particles.

T

tortuosity
The ratio of the diffusivity in free space to the diffusivity in the porous medium.

total petroleum hydrocarbons
The sum total of all compounds composed of hydrogen and carbon in petroleum including all aliphatic and aromatic components.

V

vadose zone
The unsaturated zone of soil in which the pore space is filled with both air and water.

vapor control technologies
Technologies employed to mitigate real or potential impacts from vapor intrusion.

vapor intrusion
The process by which volatile vapors partition from contaminated groundwater or other subsurface sources and migrate upward through vadose zone soils and into overlying buildings.

vertical screening distance
The minimum distance in soil between a petroleum vapor source and building foundation needed to effectively biodegrade hydrocarbons below a level of concern for PVI.

vertical separation distance
The vertical distance from a petroleum vapor source to a building foundation.