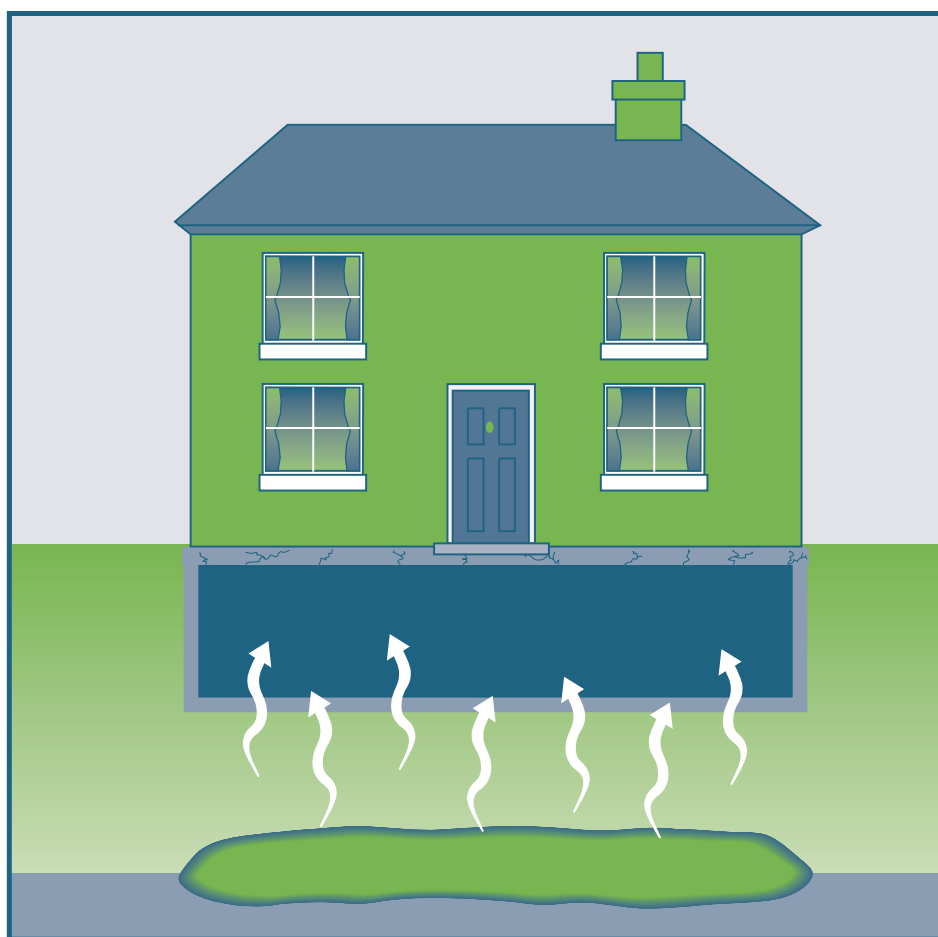




Technical and Regulatory Guidance

Vapor Intrusion Pathway: A Practical Guideline



January 2007

Prepared by
The Interstate Technology & Regulatory Council
Vapor Intrusion Team

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EXECUTIVE SUMMARY

This guideline was developed by the Interstate Technology & Regulatory Council (ITRC) Vapor Intrusion Team and represents the combined effort of more than 100 professionals from state and federal regulatory agencies, consultants, industry, and stakeholders. It is a practical, easy-to-read, how-to guideline for assessing the vapor intrusion pathway. Supplemental information is contained in appendices and in a companion document, *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios* (VI-1A) to assist the practitioner when using the guideline. Due to variations in policy among regulatory agencies, this document does not provide a single prescriptive approach for assessing the vapor intrusion pathway. Rather, the purpose of this guideline is to provide a generalized framework for evaluating the pathway and a description of the various tools available for investigation, data evaluation, and mitigation. The guideline is intended to be used in conjunction with any applicable federal or state vapor intrusion policy or guidance.

The ITRC *Vapor Intrusion Pathway* guidance series consists of two documents—this *Practical Guideline* and its supplement, *Investigative Approaches for Typical Scenarios*. This document, *A Practical Guideline*, consists of four chapters:

1. An overview of vapor intrusion
2. Preliminary screening of sites
3. Site investigation
4. Mitigation

Chapter 1 provides basic information on the vapor intrusion pathway. Although the document is written for the environmental professional who has some general knowledge of vapor intrusion, it is still important to discuss the essential key points that must be understood to investigate and mitigate the pathway. Thus, Chapter 1 touches on conceptual site models, multiple lines of evidence, background contamination, preferential pathways, and community outreach.

The framework of the document presents a 13-step approach that leads the investigator from Step 1 (Is there an acute exposure?) to Step 13 (Is mitigation warranted?), using a lines-of-evidence approach. The first seven steps (Chapter 2) apply to the screening of sites based upon preexisting conditions and data. The user is prompted to consider whether adequate data are available for screening, whether volatile and toxic compounds are present in the subsurface near buildings, and whether concentrations of these compounds exceed any applicable screening levels. Discussions on issues applicable to the preliminary screening process, such as development of screening levels and building design considerations, are included as appendices.

Unless the vapor intrusion pathway is determined to be incomplete during the preliminary screening steps, six steps follow that describe the vapor intrusion investigative process (see Chapter 3). The process begins with selection of an investigation strategy and development of a work plan, followed by execution of the work plan, and ending with an evaluation of the need for mitigation. Chapter 3 is augmented by detailed appendices (e.g., Appendix D. Toolbox), which

give a comprehensive treatment of the investigatory methods used for vapor intrusion assessments. Methods include groundwater sampling, active and passive soil gas sampling, subslab soil gas sampling, indoor air sampling, and supplemental tools such as flux chambers and forensics. Summary tables, charts, and checklists facilitate the use of the methods described in the toolbox.

Chapter 4 provides a comprehensive treatment of mitigation strategies. This chapter begins with an overview of three general approaches to addressing vapor intrusion—site remediation, institutional controls, and building mitigation. While the chapter focuses on building mitigation, it does include discussions on the differences between site remediation and building mitigation. The chapter also provides a description of eight building mitigation approaches, each including technology selection, design and installation considerations, operation, maintenance, performance monitoring, and mitigation system closure. Summary tables comparing the various options and costs are included.

Appendices include checklists for conceptual site models and reviewing soil gas data, a discussion of building types, a toolbox of investigative methods, quality assurance considerations, guidance for development of screening levels, an indoor air survey form, and a discussion of community stakeholder concerns. An extensive reference list is also included.

To illustrate how to use this *Practical Guideline* document, the Vapor Intrusion Team has also prepared a companion document. *Investigative Approaches for Typical Scenarios* describes applicable approaches for evaluating the vapor intrusion pathway under the following scenarios:

1. An active service station in a residential neighborhood
2. A dry cleaner in a strip mall adjacent to a neighborhood
3. A large industrial facility with a groundwater plume under several hundred receptors
4. A vacant lot with proposed brownfield development over a groundwater plume
5. A vacant large commercial building with warehouse space and office space
6. An apartment building with a parking garage over contamination

The scenarios follow the step-by-step approach described in the guidance document, focus on the decision process and alternatives chosen, identify key issues about each scenario, highlight lessons learned during process, and describe the next steps to be followed.

The ITRC *Vapor Intrusion Pathway* guidance series provides the reader with a logical, flexible framework, the variety of tools and remedial approaches, and the practical rationale for developing an investigative strategy when assessing vapor intrusion. Working within the regulatory framework, this difficult and ever-evolving pathway can be properly evaluated and the risks associated with indoor air contamination from vapor intrusion effectively mitigated.

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1. STRATEGIC OVERVIEW

This section provides a brief overview of the vapor intrusion pathway—the typical model and special factors that influence soil gas movement, the phased approach to investigation and remediation, the interpretation of the data, multiple lines of evidence, and interaction with the local community through a site-specific outreach program. Regulatory issues are identified, and key considerations are summarized for assessing the vapor intrusion pathway.

1.1 Introduction

Degradation of indoor air quality causes more apprehension and anxiety among building occupants than are typically associated with other environmental problems. In a residential community, these concerns over vapor intrusion are often magnified. Regulators commonly encounter a series of questions from concerned occupants such as the following:

Vapor intrusion is the migration of volatile chemicals from the subsurface into overlying buildings (USEPA 2002b). Volatile chemicals may include volatile organic compounds, select semivolatile organic compounds, and some inorganic analytes, such as elemental mercury and hydrogen sulfide. Methane should be considered where it is appropriate.

- Is the air that our children breathe safe, not only in our houses, but outside and in our local school or day care?
- What effect will this contamination have on our property values?

These concerns often become “hot button” issues, at times driving the strategy that regulators will take in addressing the vapor intrusion pathway. Public education and community outreach are crucial to how people react to a potential finding of vapor intrusion.

Why has vapor intrusion become such a significant environmental issue for regulators, industry leaders, and concerned residents alike? For more than a decade, environmental scientists and risk assessors viewed contaminated groundwater as a threat principally to the drinking water supply. As long as individuals didn’t drink the water, the risk of exposure to the contamination was believed eliminated. It wasn’t until investigative work of the Massachusetts Department of Environmental Protection (MassDEP) in the 1990s that regulators began to understand the significance of vapor intrusion. State and federal regulators are now in the process of examining older remedial decisions involving groundwater contamination to assess whether the vapor intrusion pathway warrants reopening closed cases. A multidisciplinary team can best evaluate and discuss the occurrence and potential impacts of the vapor intrusion pathway.

In addition, most other exposure pathways are assessed using “exterior” investigative tools to characterize and delineate contamination. While the actions to characterize and remediate contaminated groundwater or sediments may be apparent to the community, they typically are not invasive to the personal lives of individuals. Vapor intrusion, on the other hand, may involve the collection of environmental samples inside or immediately outside a structure. Thus, the process of investigating the vapor intrusion pathway often directly affects occupants.

For example, the Redfield site in Colorado was one of the first major sites to bring the vapor intrusion issue to the attention of the U.S. Environmental Protection Agency (USEPA) and the nation in the late 1990s. Relatively low concentrations of 1,1-dichloroethene (1,1-DCE) in groundwater were found to have impacted indoor air in a large number of homes overlying the solvent plume. Indoor air testing was required in almost 800 homes and apartments at the Redfield site, leading to mitigation of almost 400 residential buildings. Subsequent monitoring of both mitigated and unmitigated homes has continued over the past eight years, resulting in more than 7000 indoor air tests to date in the site vicinity. The essential interaction with residents in this neighborhood is extensive and ongoing.

Finally, vapor intrusion is a significant issue to building occupants due to the personal public health concerns related to the degradation of indoor air quality. While a health officer can provide bottled water for occupants to drink when potable water has been contaminated, what can be done when contaminants from vapor intrusion are found in the air of their buildings?

1.2 Conceptual Model for Vapor Intrusion

Vapor intrusion is typically conceptualized as shown Figure 1-1. Chemicals volatilize from impacted soil and/or groundwater beneath a building and diffuse toward regions of lower chemical concentration (e.g., the atmosphere, conduits, basements). Soil gas can flow into a building due to a number of factors, including barometric pressure changes, wind load, thermal currents, or depressurization from building exhaust fans. The rate of movement of the vapors into the building is a difficult value to quantify and depends on soil type, chemical properties, building design and condition, and the pressure differential. Upon entry into a structure, soil gas mixes with the existing air through the natural or mechanical ventilation of the building. While Figure 1-1 schematically depicts houses and commercial/industrial buildings, other structures (e.g., apartments, schools) also can be of concern. This guidance is generally applicable to all building scenarios.

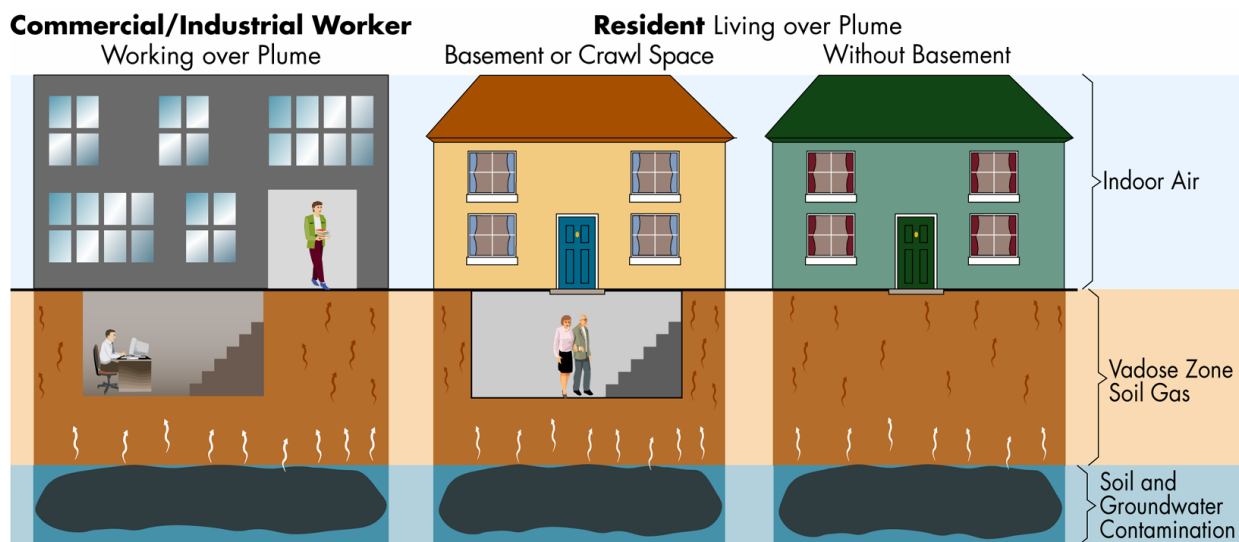


Figure 1-1. Typical conceptual model of vapor intrusion.

Both diffusion and advection are mechanisms of transport of subsurface soil gas into the indoor air environment. Diffusion is the mechanism by which soil gas moves from high concentration to low concentration due to a concentration gradient. Advection is the transport mechanism by which soil gas moves due to differences in pressure. These pressure differences can be generated by atmospheric pressure changes, temperature changes creating natural convection in the soil, or forced pressure changes due to building ventilation systems. Advective transport is likely to be the most significant in the region very close to a basement or a foundation, and soil gas velocities decrease rapidly with increasing distance from the structure (USEPA 2004b). Once soil gases enter the “building zone of influence,” they are generally swept into the building through foundation cracks by advection due to the indoor-outdoor building pressure differential. The reach of the “building zone of influence” on soil gas flow is usually less than a few feet, vertically and horizontally.

A good source of information on the conceptual model and the migration of soil gas in the subsurface can be found in the New Jersey Department of Environmental Protection (NJDEP) *Vapor Intrusion Guidance* (2005b). For additional references, see the Vapor Intrusion Resources and Links page on the Interstate Technology & Regulatory Council (ITRC) Web site (www.itrcweb.org/vaporintrusion).

1.3 Defining the Pathway

To define the vapor intrusion pathway as a complete exposure pathway, a source, migration route, and receptor must be identified (Figure 1-2). Specifically, this assessment entails the identification of all known or suspected vapor sources of contamination; consideration of the contaminant migration routes (mobility) including an evaluation of methods and manner of access, and identification of those likely to be affected by the contaminants (receptors).

The physical source of the contamination should be determined. The initial or primary sources (e.g., a leaking tank or a surface spill) or secondary sources (e.g., contaminated soil gas, soil, or groundwater) may assist in the vapor intrusion investigation. Factors in identifying likely sources include the following:

- product type, chemical composition, and location of contamination
- contaminated media
- constituents of interest present in each medium
- distribution and concentrations of contaminants in each medium

The type and location of the release can be determined by evaluating previous industrial processes employed at a site and historical site use information. The historical data can indicate chemicals used and storage locations. Also, preliminary sampling may yield analytical results that would clarify the type and location of release.

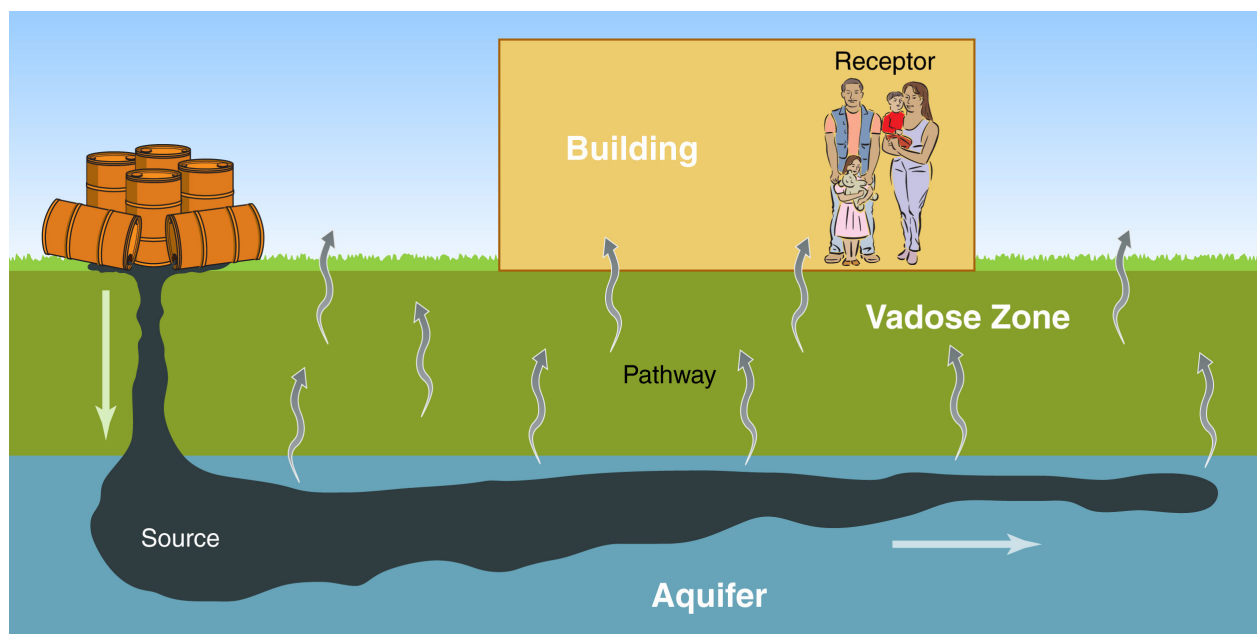


Figure 1-2 Potential source, migration route, and receptor for vapor intrusion.

The movement of contaminants from the source to the receptor is a complicated process in the vapor intrusion pathway. Building depressurization may cause soil gas from soil and/or groundwater contamination to be drawn into buildings through holes and cracks in the foundation. Heating systems, basements, and strong winds promote vapor intrusion into buildings by reducing the internal air pressure and creating a vacuum effect that enhances advective flow from underlying soils and/or groundwater into buildings (“the stack effect”).

Receptors are the people that may be exposed to the site related contaminants. Typical receptors include adults and children exposed in a residential setting, adults exposed in an occupational environment, and adults and children exposed in a nonresidential setting. Other site-specific exposure scenarios (e.g., schools, day care facilities) may be identified.

Identification of possible receptors can be determined using the locality of the facility data, land use data, and demographics. Specific considerations might include the following:

- future site use and surrounding area use
- utilities in the area
- zoning criteria (commercial, industrial, residential, and industrial) and zoning exceptions (e.g., commercial zones that allow residential, multifamily residential, second-story residential)—some industrial zones allow a caretaker to live on the site; other commercial zones allow unique uses, such as day care facilities
- land use constraints
- site vicinity and conditional uses typically allowed

1.4 General Framework for Vapor Intrusion Investigations

For the vapor intrusion pathway to be complete, there must be three components—a source of volatile compounds in the subsurface environment (groundwater and/or soil), inhabited buildings or the potential for future inhabited buildings, and a migration route to connect them (as discussed above). Once the pathway is identified, a “phased” approach is recommended to evaluate whether exposures present significant risk to the receptors, as defined by the regulatory agencies. Where there are obvious signs of vapor intrusion, such as odors or explosive hazards, these potential acute risks should be addressed immediately. For probable chronic exposure, the site may be evaluated on either a generic or site-specific basis in a timely manner. However, there may be precluding factors that limit the use of a generic screen (e.g., wet basements, sumps).

This section presents a general framework for evaluating vapor intrusion from subsurface media contamination that builds on the premise of conservative but flexible guidance, within the confines of the regulatory agency. Ultimately, the intent is to be able to differentiate sites where the pathway presents or does not present an unacceptable risk, while erring on the side of caution when there is uncertainty.

Some key principles that guide this framework are summarized below, with further detail in Chapters 2 and 3:

- implementation of a community outreach program that provides timely information to concerned citizens and property owners
- use of a phased approach that allows for the collection and use of both generic and site-specific information/data
- development of an accurate conceptual site model (CSM) that is representative of site conditions to assist with the investigative strategy and ensure proper use of the data
- application of an iterative process (i.e., starts with available data and collects additional data only to meet the needs of making informed decisions)
- allowance for a site-specific evaluation using modeling, soil gas sampling, indoor air sampling, or mitigation at any point in the process
- evaluation of multiple lines of evidence that result in decisions based on professional judgment
- consideration of current and future site use
- use of screening levels based on the appropriate exposure scenario (e.g., residential, nonresidential, occupational) consistent with the regulatory agency

1.5 Lines of Evidence

Attribution of chemicals in indoor air to vapor intrusion can become a relatively complex and difficult task. It is important to use multiple lines of evidence to reach decisions based on professional judgment. The following are some lines of evidence, listed in no particular order:

- soil gas spatial concentrations, including subslab and exterior (some distance outside the perimeter of the foundations) soil gas data with some level of vertical profiling, if appropriate (see Appendix D)
- groundwater spatial data, with vertical profiling, if appropriate (see Appendix D)
- background, internal and external, sources (see Section 1.6.1)
- building construction and current conditions (see Appendix C)
- subslab (or crawl-space) soil gas data
- indoor air data (see Section 3.7.3)
- concurrent outdoor air data (see Section 3.7.3)
- constituent ratios (see Section 3.7.3)

Other lines of evidence may be available depending on the site-specific circumstances. Conversely, regulatory frameworks of individual states may limit the ability to use some or all of these lines.

In addition to using a phased approach, 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. It should be noted there will likely be some uncertainty associated with such an assessment, regardless of the number of lines of evidence considered. Decisions should be made in consultation with the regulatory agency and based on what professional judgment deems to be reasonable and logical for the specific site.

Soil Gas and Soil Vapor

In many vapor intrusion guidance documents, “soil gas” and “soil vapor” are used interchangeably. In this document, “soil gas” refers to the gaseous elements and compounds in the small spaces between particles of soil. Once the gaseous elements or compounds migrate into a structure, they are referred to as “vapor.”

It is important to point out there may be multiple sources of chemicals affecting the overall quality of the indoor air that may not be associated with the investigated chemical release, confounding the interpretation of indoor air sample results. These other sources may be from building materials, heating/cooling energy sources, residual volatile components of stored items, household activities (cooking/cleaning), and consumer products used in the building or background contaminants from ambient outdoor air (Locus Technologies 2006). Thus, indoor air sampling is generally recommended only after identifying the buildings most likely to be impacted to limit the difficult task of evaluating the data and avoiding false positive results.

1.6 Special Factors Influencing Vapor Intrusion Assessments

Numerous conditions may be important considerations either in addition to or instead of the typical conceptual model. Several are described briefly in the subsections below.

1.6.1 Background Air Concentrations

Indoor air quality often contains measurable concentrations of volatile and semivolatile compounds from household activities, consumer products, building materials, and outdoor air sources. In some cases, these background contributions exceed health-based target

concentrations, especially for benzene, where background indoor air quality often represents an incremental cancer risk greater than 10^{-5} (one in one hundred thousand) for a residential scenario. It is generally advisable to obtain outdoor ambient air samples when collecting indoor air samples. In this way, outdoor air quality can act as a baseline, to which interior and subsurface sources are additive. In many cases, the site-specific chemicals of concern (COCs) may be limited to a few chemicals, which may not be present at significant background levels, so it may be possible to conduct indoor air monitoring for a target list of analytes and avoid complications associated with background contributions. Otherwise, a 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. Several studies (NJDEP, MassDEP, New York State Department of Health [NYSDOH]) of indoor air quality at homes unaffected by subsurface contamination are currently being conducted to provide a statistical basis for assessing background air quality. Data from such studies should prove to be valuable as one line of evidence, although personal preferences and consumer products will vary between properties. Information on New York State's background database studies can be found at www.health.state.ny.us/nysdoh/gas/svi_guidance/svi_appendc.htm.

Prior to indoor air sampling, efforts should be made to address sources of background contamination. Some background sources will occur on a fairly constant basis and are difficult to eliminate (e.g., off-gassing from furniture and treated wood surfaces, volatiles released from long-term stored chemicals or fuels). However, other sources are intermittent and have the potential to skew the data (e.g., cigarette smoke, off-gassing from dry cleaning, exhaust from attached garages). Even a simple activity like a hot shower can strip volatiles from the water, producing a spike in the concentrations of trihalomethanes. It is appropriate to conduct a building walkthrough in advance of any interior sampling events to identify potential background sources, eliminate them, and educate the occupants on those activities that should be avoided immediately before and during the sample collection. A sample building survey form can be found in Appendix G.

1.6.2 Biodegradation

Many hydrocarbons (notably petroleum-based hydrocarbons) are readily degraded to carbon dioxide (CO_2) in the presence of oxygen (O_2) by ubiquitous soil microbes. Oxygen is supplied from the atmosphere by vapor diffusion and barometric pumping and as a dissolved solute in infiltrating rainwater. Aerobic degradation is a rapid process and frequently occurs in a relatively thin (a few feet thick) zone where the concentrations of O_2 and hydrocarbons are most ideal for microbial processes. The bioattenuation of hydrocarbons can potentially reduce soil gas concentrations and vapor intrusion by several orders of magnitude.

Like petroleum hydrocarbons, chlorinated solvents also can be biodegraded, but the process tends to occur under anaerobic conditions and is slower than aerobic degradation of petroleum hydrocarbons like benzene, toluene, ethylbenzene, and xylenes (BTEX). In both cases, degradation occurs via oxidation-reduction reactions that are used by the microbes as an energy source.

For vapor intrusion studies, the importance of biodegradation of chlorinated solvents is that additional compounds of interest are created, with obvious implications for selecting target compounds. These daughter compounds may be considered worse than the parent compound because of increased carcinogenicity.

1.6.3 Preferential Pathways

Spatially, the permeability of subsurface materials can be highly variable. Conditions such as fractured geologic media and gravel lenses or channels may allow an atypical preferential soil gas flow through high-permeability pathways (in some cases opposite to the groundwater flow). If such a migration route connects a source directly to a building or allows higher levels of groundwater contamination to migrate under a building, vapor intrusion may be exacerbated.

Most buildings have subsurface utility penetrations, so their presence alone is not considered “preferential.” For this guidance (consistent with the vapor intrusion pathway in general and the Johnson and Ettinger [J&E] model specifically), some increased component of soil gas flow into the building is usually required to consider the pathway to be preferential. Anthropogenic preferential pathways include building sumps or drainage pits (that can serve as conduits for soil gas to enter buildings) or subsurface utility conduits or drains (that intersect vapor sources or soil gas migration routes and a building foundation). Natural preferential pathways include vertically fractured bedrock where the fractures are interconnected and in direct contact with the building foundation and the vapor contaminant source. Interestingly, the Georgia Environmental Protection Division had a case where rodent tracks or tunnels up to a building foundation allowed vapors to migrate into a basement.

Elevator Shafts

Elevators may constitute a vertical preferential pathway into a building since they may be constructed with subbasement perforations to allow water to drain. Elevators may also allow vapor impact on unexpected floors due to vertical migration up the shaft.

In addition, investigators must consider that preferential pathways may not be apparent based on external building inspections. According to Henry Schuver (USEPA), some communities with unexpectedly high concentrations of indoor contaminants were observed during indoor surveys to have uncapped pipes through the basement floor connected to “dry wells” designed to dispose of fluids through openings surrounded by very permeable fill materials. Thus, they served as preferential pathways by allowing an unexpected amount of vapor to migrate into the structures.

Another example is waste lines without functioning vapor traps. Petroleum compounds often biodegrade before causing vapor intrusion problems. However, one community had elevated petroleum-related concentrations in indoor air traced back to homes connected to sewer lines without vapor traps. These untrapped sewer lines formed a preferential pathway for contaminant vapors that had entered the sewer lines from openings elsewhere along the lines. It is important to note that reports of sewer odors are typically found with vapor traps that have dried out or are no longer operating properly.

The possibility of these conditions highlights the importance of an interior inspection of potentially impacted buildings before the screening process is finalized.

1.6.4 Undeveloped Land

Assessing the potential for vapor intrusion in a future building upon land that is currently vacant poses unique challenges. Some of the investigative tools of the vapor intrusion pathway (e.g., subslab soil gas or indoor air samples) are not possible when there is no slab or structure present on the property. Alternative approaches are required in these circumstances.

Future-use exposure scenarios may involve the evaluation of municipal zoning criteria (commercial, residential) and zoning exceptions (e.g., commercial zones that allow residential, multifamily residential, second-story residential). Other considerations include commercial zones that allow day care facilities and industrial zones that allow on-site caretaker residence.

The use of institutional controls (e.g., deed restrictions, environmental covenants) may be appropriate to ensure that future use of an affected property is protective of human health through the vapor intrusion pathway. Institutional controls could include land use restrictions, future building design requirements to address the potential for vapor intrusion, notification requirements for land owners/developers, or stipulations for further investigation of the vapor intrusion pathway during evaluation of specific future use scenarios.

When institutional controls are not appropriate (or not permitted by the regulatory agency), investigators must delve deeper into their “toolbox” to assess vapor intrusion at undeveloped lands. In the end, it may be preferable to incorporate a vapor barrier and/or subslab venting system into the building design as a proactive approach.

1.7 Community Concerns

Vapor intrusion investigators must be trained to deal with community concerns. Informing residents or business owners that chemicals may have entered their buildings is a delicate situation. Usually, people are just learning that the groundwater and/or soil near their properties have been contaminated by releases from a local company or individual. Communities may be skeptical or unsure of what will happen next. How will the vapors affect their health or that of their co-workers and families? It is important to learn from experiences of other investigators who have overcome similar challenges with impacted communities.

Communication is an essential component of any community outreach program. For example, it is generally not a good idea for building occupants to learn about a vapor intrusion investigation for the first time when someone knocks on their door asking permission to drill holes in their floors or inquire about their personal activities (e.g., smoking, dry-cleaning clothes).

Redfield, Colorado Site

To facilitate public education and communication with the residents, investigators went door to door providing information packets and discussed the program directly with each resident when requesting access for testing. Testing personnel were selected, in part, for their ability to communicate and work well with the residents. Consider situations regarding language barriers and residents. Other community relation efforts included frequent public meetings, periodic mailing of project newsletters, articles published in local community newsletters, door-to-door surveys, and development of a project Web site (www.redfieldsite.org) posting fact sheets and the most recent results of groundwater and indoor air testing.

To be successful, agencies conducting or overseeing vapor intrusion (VI) investigations need to develop a strong community outreach program to educate and reassure the local community about vapor intrusion in a meaningful, sensitive, and effective manner. Unlike any other contaminant pathway, vapor intrusion merits effective education of the affected community regarding the risk of soil gas migrating from the subsurface as well as background sources typically found in the building.

Community Advisory Groups (CAGs) may assist in this process. CAGs are generally small groups of residents who meet regularly with agencies and responsible parties. They provide an opportunity for the public to gradually gain an understanding of the complexities of vapor studies. In such settings, initial adversarial relationships usually break down, and community members often come up with constructive advice.

1.8 Remediation

Some vapor intrusion investigations will indicate that actions (remedies or mitigations) should be taken to reduce the amount of vapor intrusion into a building. “Remediation” commonly refers to an action that reduces the level of contamination in the environmental medium (e.g., groundwater) that is acting as the source of the indoor air vapors. “Mitigation,” on the other hand, is generally applied to actions that prevent or minimize exposure. While the two terms are used interchangeably in this industry, the differences should be understood by the investigator. When an action is needed, a remedy or combination of remedies should be selected, implemented, operated, maintained, and monitored to properly respond to the vapor intrusion problem and bring the site to closure.

Chapter 4 of this document covers sitewide remediation, institutional controls, and building controls. Of these, building control remedies are discussed in the most detail because they include those active mitigation methods most commonly implemented at structures impacted by vapor intrusion.

1.9 Regulatory Considerations/Drivers

As indicated by the ITRC Vapor Intrusion Survey (ITRC 2004b), existing policies, regulations, and guidance regarding the methods for evaluation of the vapor intrusion pathway vary widely among jurisdictional agencies. Prior to developing a site-specific approach for the evaluation of the vapor intrusion pathway, consideration should be given to applicable local, state, and federal policies, regulatory requirements, and available guidance. Regulatory policies may offer specific approaches and screening levels for the evaluation of the vapor intrusion pathway. Coordination of vapor intrusion investigations with the appropriate jurisdictional agencies early in the planning process may allow for a more focused vapor intrusion assessment and ensure that regulatory compliance criteria are met.

Stay Ahead of the Curve

A review of the developing science relating to the vapor intrusion pathway should be conducted on a regular basis. As the state-of-the-practice for evaluating the vapor intrusion pathway develops, additional guidance, investigative tools, and case study information will be available at the ITRC Vapor Intrusion Web page (www.itrcweb.org/vaporintrusion).

The agency with oversight responsibility will offer regulatory guidance that is applicable for a given investigation. In an ideal world, the best technical approach for any given situation is defined in the applicable regulatory guidance. In reality, vapor intrusion is an evolving science with many variables. Thus, investigators must be prepared to justify their technical approach.

Since various states express a wide range of comfort about the data types that are acceptable for screening a site from further consideration, this guidance is not prescriptive as to what data types present an appropriate methodology for screening purposes. Rather, this guidance is intended to assist the investigator in understanding the factors and methodologies that may be used to assess the vapor intrusion pathway. To refine the approach, the investigator is encouraged to consult the individual state's guidance on the subject of vapor intrusion. Check the ITRC's Vapor Intrusion Web site (www.itrcweb.org/vaporintrusion) for updated links on VI guidance documents and related information from the various states, federal government, industry and other interested parties.

2. PRELIMINARY SCREENING PHASE

The initial step in assessing the vapor intrusion pathway is developing a conceptual site model based on all available data. Once prepared, the CSM becomes a primary developmental method used by investigators when conducting a preliminary screening of a contaminated site. This chapter provides a fundamental seven-step approach to assessing the vapor intrusion pathway through this early phase of data evaluation. (The remaining six steps of the total 13-step vapor intrusion assessment are discussed in Chapter 3, Site Investigation Phase.) The role of generic screening levels and the importance of groundwater data usability are discussed as they relate to the preliminary screening phase.

As noted in Chapter 1, evaluating the potential for vapor intrusion at a site of concern should be approached as a sequential process extending from the evaluation of initially available data through the determination of no further action or mitigation. This section is intended to help the investigator evaluate existing data and make decisions regarding the need to proceed to the investigative phase to collect additional data. Given that regulator-defined screening levels are often close to background levels for many compounds and that spatial/temporal variability and sampling bias are often present, the ultimate risk management decisions should be based upon multiple lines of evidence rather than upon a single line of evidence (Section 1.5).

An appropriate initial screening process will ensure that those sites most likely to pose unacceptable risk from vapor intrusion are retained for more detailed evaluation. It is also expected that some sites will be removed from further evaluation if it is demonstrated that

- the exposure pathway is and will remain incomplete,
- the COCs are not deemed sufficiently volatile (as defined by the regulatory agency) to pose a hazard, or
- the concentrations of the volatile chemicals fall below generic screening levels.

2.1 Developing a Conceptual Site Model

The goal for developing a CSM in the assessment of the vapor intrusion pathway is to assemble a three-dimensional concept of the site that is as comprehensive as possible. This is based on available, reliable data describing the sources of the contamination, the release/transport mechanisms, the possible subsurface migration routes, and the potential receptors, as well as historical uses of the site, cleanup concerns expressed by the community, and future land use plans. All the important features relevant to characterization of a site should be included in a CSM, and any irrelevant ones excluded. The CSM should present both a narrative and a visual representation of the actual or predicted relationships between the contaminants at the site and receptors (building occupants), as well as reflect any relevant background levels. Appendix B is a CSM checklist to assist in preparing this important component of the vapor intrusion assessment.

A CSM typically contains information on soils, geology, hydrogeology, the relative amount of heterogeneity, groundwater quality data, regional groundwater flow direction, well records, boring logs, and surficial features suggestive of whether the area is in a groundwater recharge or discharge area (e.g., ground cover, surface water bodies). Sources to check for this data are county soil surveys; state or federal water supply or geologic reports/maps; U.S. Geological Survey (USGS) topographic maps; geographic information systems; and federal, state, and local government or quasi-government agency records.

A preliminary CSM documents current site conditions, such as site geology, hydrogeology, and volatile organic compound (VOC) distribution and composition relevant to soil gas migration, and should be supported by maps, cross sections, and site diagrams. A narrative description should clearly distinguish what aspects are known or determined and what assumptions have been made in its development. The CSM should provide all interested parties with a conceptual understanding of the potential for exposure to compounds of concern at a site. It is an essential tool to aid management decisions associated with the site and also serves as a valuable communication tool both internally with the site team and externally with the community.

Sources of CSM Information

- “Conceptual Site Model Checklist” (Appendix B)
- *Vapor Intrusion Guidance* (NJDEP October 2005b)
- *Collecting and Interpreting Soil Gas Samples from the Vadose Zone: A Practical Strategy for Assessing the Subsurface Vapor-to-Indoor Air Migration Pathway at Petroleum Hydrocarbon Sites* (API 2005)

The CSM is a dynamic tool to be updated as new information becomes available, and therefore it should be amended, as appropriate, after each stage of investigation. It is especially important that the site be reasonably well characterized for the purposes of sampling plan development. The updated CSM should then contain the following information:

- Types of volatile COCs (e.g., chlorinated solvents, gasoline, jet fuel, diesel) currently or previously stored or handled at the site
- COCs and their concentrations in soil and groundwater—the future use of the data and the regulatory requirements that will be applied to the data are used to determine the appropriate laboratory analytical methods

- Potential sources and source areas of vapors (e.g., soil; groundwater; nonaqueous-phase liquid [NAPL])
- Geology and hydrogeology in the area of the site
- Approximate location of vapor sources in the subsurface and the distances (lateral and vertical) between the sources and the building
- Current subsurface soil gas-to-indoor air migration routes (e.g., utility conduits, sewers, diffusion through vadose zone soils, see Figure 2-1)
- Construction features of existing buildings (e.g., size, age, presence of foundation cracks, entry points for utilities, and number of distinct enclosed units)
- Potential future uses for undeveloped lands based on municipal zoning laws

Appendix D of the USEPA draft vapor intrusion guidance (USEPA 2002b) explains the relationship of the CSM to the USEPA data quality objective (DQO) process.

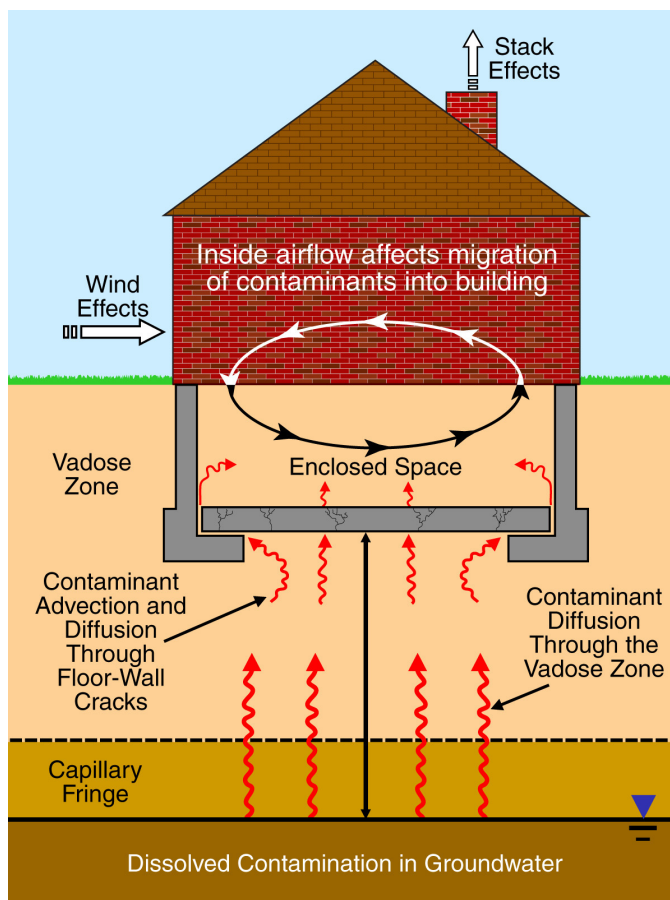


Figure 2-1. CSM illustrating vapor intrusion from groundwater contamination.

2.2 Preliminary Screening Steps

The preliminary screening process presented below comprises seven specific steps to initially assess a contaminated site. Even after the preliminary screening phase is completed, the investigator is advised that data collected in subsequent rounds of investigation may necessitate revisiting these screening steps. Thus, the iterative process discussed earlier in the document is reflected even in the preliminary stages. Refer to the preliminary screening flowchart (Figure 2-2) for additional guidance.

- Step 1: Does the site represent an acute exposure concern?
- Step 2: Are there sufficient characterization data to evaluate this pathway?
- Step 3: Are any of the site COCs both volatile and toxic?
- Step 4: Are buildings located in close proximity to volatile chemicals in soil, soil gas, or groundwater?
- Step 5: Identify the appropriate occupant exposure scenarios and generic screening levels for this site.
- Step 6: Do the data exceed the appropriate generic screening levels?
- Step 7: Does an exceedance of the generic screening level warrant further investigation?

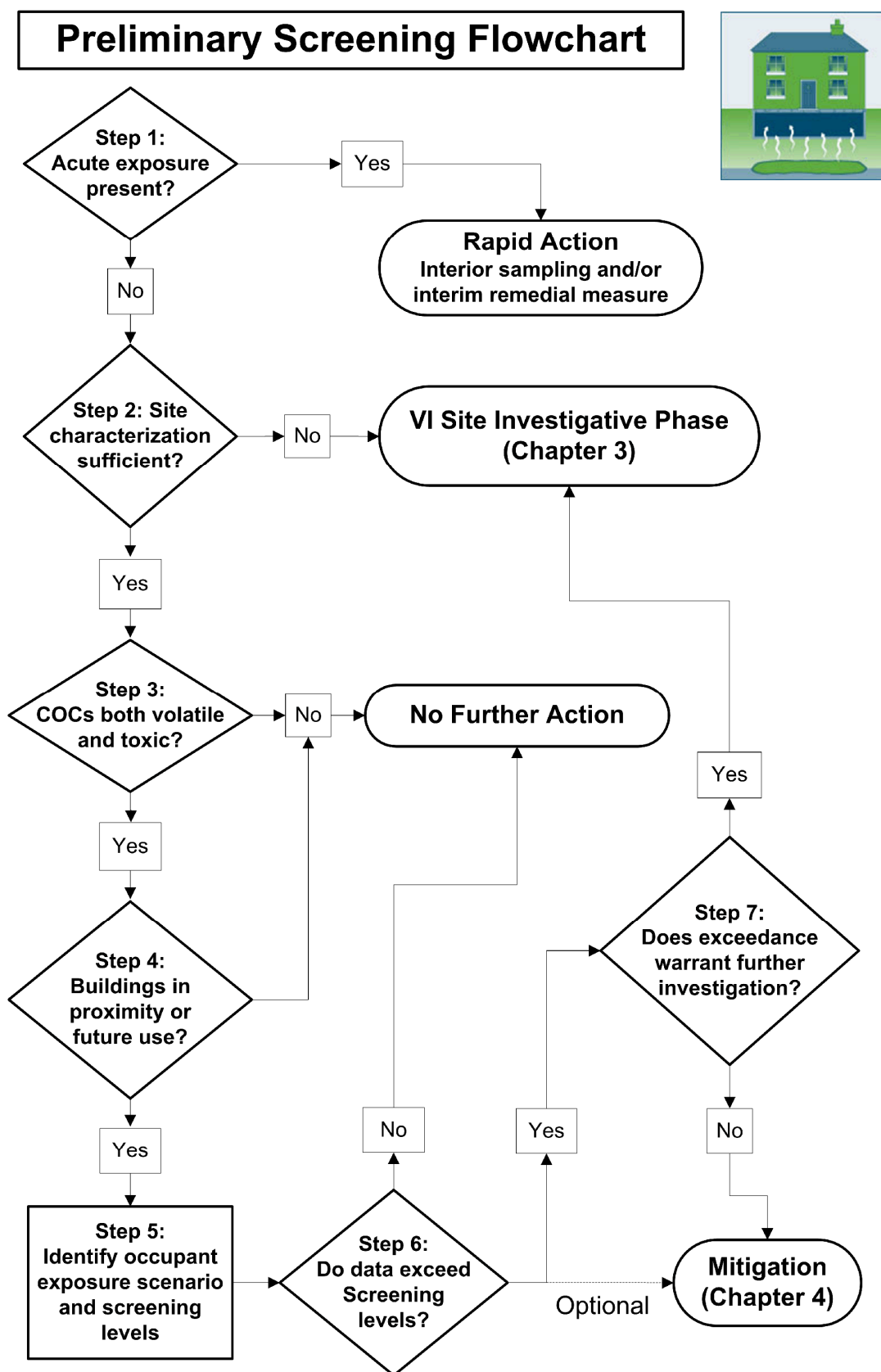


Figure 2-2. Decision-making process for VI preliminary screening.

2.3 Step 1: Does the Site Represent an Acute Exposure Concern?

When an acute or emergency hazard resulting from vapor intrusion is suspected, the initial priority should be the immediate safety of the building occupants. Unless the indicators are unambiguous in nature (odors, physiological symptoms, etc.), it is unlikely that a significant decision such as evacuation could be made without interior measurements (subslab soil gas and/or indoor air samples). The judgment to conduct an interior investigation should be made on a site-specific basis. Each regulatory agency has its own preferences as to when subslab soil gas and indoor air sampling is warranted.

If the prompt collection of interior samples is warranted, several sampling techniques may be employed to make an acute/emergency decision. An investigator may choose to use a photoionization detector (PID), combustible gas indicator (CGI), or similar field screening device to determine whether volatile gases are present at substantial levels that could indicate an immediate hazard. Other investigative methods may be preferable to obtain more accurate determinations of VOC concentrations.

Conversely, it may be determined an interim remedial measure (IRM) would either remove the receptors from acute exposure (e.g., evacuation of the affected buildings) or disrupt the migration route (e.g., subslab depressurization or similar remedial systems).

Whichever option is selected, it must be made on a case-by-case basis, using the agencies' best judgment, and must be done rapidly. In general, vapor concentrations of this magnitude are not common.

As part of the iterative process for the vapor intrusion pathway, the investigator must always consider the potential for acute exposure when evaluating data from any subsequent investigative phases.

2.4 Step 2: Are There Sufficient Characterization Data to Evaluate this Pathway?

Preliminary screening for the vapor intrusion pathway is conducted in the context of the available data. Most contaminated sites fail to have sufficient data at this preliminary stage to conclusively eliminate the vapor intrusion pathway. Alternately, the data may not meet the quality assurance/quality control (QA/QC) level required by the regulatory agency. The investigator must determine whether adequate investigation has been conducted to identify all COCs and at their highest concentrations likely present (worst-case pathway or receptor) at the site.

If there are insufficient data to eliminate a site, then additional investigation is warranted. Thus, characterization is called for when the VI pathway may be present or inadequate results are available to make that determination. Supplemental investigation may or may not involve actual media sampling. Chapter 3 provides additional information on the investigative process of site characterization.

Investigate Source

In general, if there are no contaminants of concern at the source (e.g., soil gas at the groundwater table below a building), there may be no need for further characterization. So check the source first!

2.5 Step 3: Are Any of the Site Chemicals of Concern Both Volatile and Toxic?

A vapor intrusion assessment typically begins with collecting information about the release. Site assessment reports, interviews with site owners and operators, spill reports from federal and state environmental agencies, and state fire marshal records may contain information and maps about sources. The COCs are typically those compounds that have been used at a site or released into the environment. The project manager should remain cognizant that some volatile chemicals may naturally degrade into other compounds (e.g., trichloroethene [TCE] can break down to vinyl chloride), so the suite of chemicals that are of potential concern may be more extensive than just the compounds released at the site.

Defining “Volatiles”

Regulatory agencies have different ways to define volatile chemicals for the VI pathway.

- The USEPA (2002b) defines volatiles as chemicals with a Henry's law constant greater than 10^{-5} atm m³ mol⁻¹ at room temperature.
- NJDEP (2005b) considers a chemical to be volatile if its Henry's law constant is greater than 10^{-5} atm m³ mol⁻¹ and its vapor pressure is greater than 1 mm Hg at room temperature.

For the most part, only compounds of sufficient volatility and toxicity are a concern for the vapor intrusion pathway. Table 1 of USEPA's draft VI guidance (2002b) lists some of the more common chemicals of sufficient volatility and toxicity. If other volatile chemicals are present at the site, Appendix D of the draft guidance presents an approach to evaluate these chemicals.

In addition, there may be other potentially explosive or toxic chemicals (e.g., methane and hydrogen sulfide) that can represent a subsurface soil gas threat and should be investigated. If the COCs do not meet these criteria, further consideration of the vapor intrusion pathway is not warranted. Otherwise, the investigator moves onto the next step in the preliminary screening phase.

2.6 Step 4: Are Buildings Located in Close Proximity to Volatile Chemicals in Soil, Soil Gas, or Groundwater?

Preliminary screening Step 4 is useful in establishing potential vapor intrusion impact areas around releases. Often, significant contaminant concentrations are found only in relatively close proximity to the original source. USEPA guidance establishes an area within 100 feet vertically or laterally from a volatile concentration of regulatory concern as a potential impact area (USEPA 2002b). Some states have established buffers of 30 feet. Others states, such as New Jersey (NJDEP 2005b), established different distance criteria based on the contaminant type (petroleum versus chlorinated hydrocarbons). Recent work (Lowell and Eklund 2004) suggests that even for sites with the presence of pure petroleum product and contamination a couple of meters below the surface, VOC emissions will tend to be insignificant at lateral distances of about 100 feet transgradient to groundwater flow from a source. Hydrocarbons probably will not migrate as far laterally if oxygen is present. Check with your local regulatory agency as to the applicable distance criterion.

Distance Criterion

USEPA (2002b) suggests that buildings within 100 feet of a contamination plume or source should be evaluated for vapor intrusion unless a significant conduit (preferential pathway) exists, in which case, the area to evaluate should extend to some unspecified distance. States have developed their own distance criterion. Check with the local regulatory agency before evaluating the existing data.

At this step, the investigator is assumed to have sufficient information to map the subsurface contaminated soil gas distribution. Otherwise, the site has not been properly characterized (Step 2).

The length of time between the release date and the time of soil gas collection will affect the magnitude of the contaminant concentrations at a location away from a release point. The time required for soil gas to reach near-steady concentrations at any point increases with the square of the distance from the source. Soil gas concentrations measured near a source will in most cases be representative of near-steady conditions. Near-surface concentrations or soil gas concentrations measured several meters away from a source may or may not be representative of near-steady conditions. Additional information can be found in API Publication 4674 (1998).

Answering the Step 4 question requires a judgment call based on confidence in the accuracy of the data and the CSM versus the potential risk to the receptors. Investigators should consider the likely level of heterogeneity and whether or not the applicable distance criteria is conservative, given the site-specific conditions.

Finally, consider the future use of the area under investigation. While the property may be undeveloped at this time, potential developments may expose future occupants to unacceptable risk based on vapor intrusion.

2.7 Step 5: Identify the Appropriate Occupant Exposure Scenarios and Generic Screening Levels for the Site

An evaluation of the vapor intrusion pathway requires consideration of the use of the buildings in proximity of contaminated media (e.g., groundwater, soil, soil gas). For sites that have measurable sources of volatile chemicals and a viable migration route to the building, the ultimate risk decisions may depend on the use of the buildings under current conditions. Future use of current buildings and undeveloped parcels may also need to be considered in light of the probable future exposure patterns.

For preliminary screening purposes, an evaluation of building occupancy scenarios should be conducted. Occupancy scenarios include evaluating building use (e.g., residential, commercial, industrial, schools and day care) as well as potentially exposed populations (e.g., children or adults).

The approach in the USEPA draft VI guidance (2002b) is designed primarily to ensure protection of the public in residential settings but may be adjusted to evaluate nonresidential human exposures which occur in commercial, industrial, and recreational settings. Most state agencies are now making that distinction in their screening levels. According to the Vapor Intrusion Survey (ITRC 2004b), of those states that have developed vapor intrusion screening levels, 69% differentiate between residential and nonresidential values.

It is important to note that exposure to the “general public” in public buildings is usually not the most significant risk driver if there are any full-time workers in the building. USEPA’s draft VI

guidance may be interpreted to recommend that people exposed in occupational settings should be evaluated under Occupational Safety and Health Administration (OSHA) using occupational standards rather than by current risk-based screening approaches. This position appears to be going through a reconsideration based on recent draft revisions to the USEPA VI guidance.

Many state agencies now require that occupational exposure be based on risk-based screening values and not OSHA standards when the COCs are not used in the building being investigated. Again, check with your state agency for guidance in this area. In all cases, consider the potential future use of the building, not just the current function.

2.8 Step 6: Do the Data Exceed the Appropriate Generic Screening Levels?

Existing data can be compared to generic screening levels for an initial evaluation to determine whether the pathway is complete and whether there is a potential for risk associated with the inhalation of vapors from subsurface media contamination. The generic screening levels are typically conservative, non-site-specific values. Refer to Appendix H for more information on screening levels.

USEPA included a series of groundwater, soil gas, and indoor air generic screening levels as part of its draft VI guidance (2002b). These values are still being used by the federal government and many state agencies pending revisions in the USEPA guidance document. In addition, numerous state agencies have developed their own generic screening or remediation levels for the vapor intrusion pathway.

At this stage, if the data do not exceed the applicable screening levels, no further action would be warranted (assuming proper characterization has been completed per Step 2). However, an exceedance of a generic screening level generally requires the investigator to move on to Step 7. The one exception may be the option to move directly to mitigation or long-term monitoring.

It should be noted that some state agencies allow modeling of site conditions as part of the preliminary screening to prepare site-specific screening levels.

2.9 Step 7: Does an Exceedance of the Generic Screening Level Warrant Further Investigation?

Exceedance of the applicable screening levels does not automatically mean that a remedial action is appropriate. A determination will have to be made whether additional data are necessary as part of the investigative phase (Chapter 3). Refer to the Preliminary Screening Flowchart (Figure 2-2) for further guidance.

For many regulatory agencies, an exceedance of the state's vapor intrusion criteria simply identifies the need for further investigation (especially at the preliminary screening phase). In fact, 73% of the state agencies surveyed by ITRC in January 2006 acknowledged their criteria as "screening" rather than "action" levels.

If there is enough information to confirm VI at a concentration that adversely impacts human health (possible acute exposure), the investigator moves onto the Mitigation Phase (Chapter 4). Otherwise, further characterization is required as part of the Site Investigation Phase (Chapter 3). Of course, the investigator may elect to be proactive and move directly to the mitigation phase at any point in the process, irrespective of the information collected to date.

2.10 Data Usability for Preliminary Screening

In moving from preliminary screening to the investigative phase, it should be clear that the following questions have been answered:

- Have adequate groundwater, soil, soil gas data been collected from the applicable locations?
- Do the results meet the minimum data quality requirements of the DQOs established for the site or of the regulatory agency?

The data usability of the groundwater, soil, soil gas, and/or indoor air results is a critical consideration when making a determination on the vapor intrusion pathway.

3. SITE INVESTIGATION PHASE

This chapter continues the 13-step approach to assessing the vapor intrusion pathway with the site investigation phase. During this phase the majority of the field data are collected according to investigative strategies and work plans developed following early data evaluation.

3.1 Investigative Process

When the preliminary screening phase (Chapter 2) fails to eliminate a site from further consideration of the vapor intrusion pathway, additional evaluation may be conducted during the site investigation phase.

Before conducting a site-specific investigation and evaluation of the vapor intrusion pathway, the investigator must first decide on the general approach (i.e., the information needed and acceptable for determining whether or not the pathway is complete at a specific building or site). Different investigation approaches are available based on the environmental medium being investigated. These distinctive investigation methodologies may be followed in a progressive or phased manner.

As indicated in Table 3-1, each investigative approach has uncertainties, resulting in the potential for false positives (due to conservative assumptions) or the risk of false negatives (if less conservative assumptions are used). Specific investigation tools for each of these media and the advantages and disadvantages of each approach are discussed in more detail in Appendix D. It is common to use several investigative approaches during an investigation. The data gathered from several approaches in the decision-making process is considered as using multiple lines of evidence.

Table 3-1. General approaches for vapor intrusion investigations

Media Investigated	Evaluation Method	Principal Issues
Groundwater	Attenuation factor or modeling based on site-specific conditions used to predict indoor air concentration	Imprecision of attenuation factors or modeling requires very conservative assumptions. Henry's law must be corrected for the aquifer temperature.
Soil gas	Attenuation factor or modeling based on site-specific conditions used to predict indoor air concentration	Fewer pathway assumptions required than groundwater, but the accuracy and representativeness of measurements may be an issue
Subslab soil gas	Attenuation factor estimated or measured (e.g., using radon) to predict indoor air concentration	Fewest pathway assumptions required, but intrusive and attenuation factors may still be conservative for many buildings.
Indoor air	Indoor air concentrations directly measured	Intrusive, and background sources may confound data interpretation. Seasonal variations are also an issue.

Many investigators and state agencies prefer to begin the investigation process outdoors (i.e., exterior groundwater or soil gas measurements) in the hope that vapor intrusion can be ruled out without having to test indoors (subslab and/or indoor air samples). An exterior assessment also allows the properties most likely affected to be identified prior to interior sampling. This approach results in less inconvenience to building occupants and avoids the complexities of potential background sources of COCs. For example, if conservative attenuation factors or modeling fail to eliminate vapor intrusion based on exterior data, then interior sampling would be the next step in the areas identified as having the highest soil gas concentrations. Alternatively, preemptive mitigation or other risk management decisions could be based on the results of any of the steps prior to interior testing.

Other investigators and some states prefer going directly to interior testing, combining indoor air and subslab soil gas sampling, or just conducting indoor air sampling. The usual reason given for adopting this approach is concern over the reliability of exterior measurements or assumptions/models used to predict indoor air concentrations versus taking direct indoor air measurements. Perhaps the most reliable approach is to base the investigation and determination of pathway completeness on site-specific conditions and multiple lines of evidence with offsetting strengths and weaknesses.

3.2 Common Vapor Intrusion Scenarios

Innumerable variations of vapor intrusion scenarios are possible, based on the multitude of COCs and sources, geologic and groundwater conditions, and potentially impacted properties and buildings. Differences in these conditions could lead to numerous investigation issues, constraints, and options, all of which impact the investigation work plan and its implementation. While it's impossible to describe each and every scenario that could result from varying circumstances, experience has shown that a few situations tend to occur more frequently than others. Therefore, *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios*

(VI-1A, ITRC 2007), developed as a supplement to this guidance document, describes six different hypothetical, yet common vapor intrusion scenarios and the investigation approaches that might be followed. Key decision points and alternatives that may be chosen during that stage of the investigative process are identified in the scenarios.

Vapor intrusion investigations can be very complex, and the scenarios are tools in themselves. The main theme of each of the scenarios is to highlight the decision process and the reasoning behind the decision, the selection of a specific tool versus an alternative investigative strategy, and how the tool was used in the hypothetical scenario. Review of the hypothetical case histories presented in the scenarios supplement may help users better understand the nuances of various investigative procedures, particularly for a site similar to one of the six scenarios.

Typical VI Scenarios

The supplement to this document, *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios*, discusses the following VI scenarios:

1. Gas station in residential neighborhood
2. Dry cleaner in strip mall located adjacent to neighborhood
3. Large industrial facility with long plume under several hundred buildings
4. Vacant lot with proposed brownfield development over groundwater plume
5. Vacant large commercial building with warehouse space and office space
6. Apartment building with parking garage over groundwater plume

3.3 Site Investigation Phase

For many contaminated sites, assessing vapor intrusion involves collecting additional data to make a determination on the completeness of the pathway. In the Preliminary Screening Flowchart (Figure 2-2), the decision points at Step 2 and Step 7 may lead the investigator to the site investigation phase. In both cases, further investigation is warranted due to insufficient data to properly characterize the site or delineate COCs. The site investigation process presented below continues the progressive approach to assessing a site for the vapor intrusion pathway. It comprises six specific steps to complete the evaluation of a contaminated site:

- Step 8: Choose an investigative strategy.
- Step 9: Design a vapor intrusion investigative work plan.
- Step 10: Implement the vapor intrusion investigation work plan.
- Step 11: Evaluate the data.
- Step 12: Is additional investigation warranted?
- Step 13: Is mitigation warranted?

Each of the site investigation steps (see Figure 3-1) is discussed in greater detail below.

3.4 Step 8: Choose an Investigative Strategy

Before the process can begin, investigators must decide on the technical approach that they believe is acceptable for assessing the vapor intrusion pathway and making risk-management decisions (Step 8). This decision dictates the media to be investigated and the tools that are available. Of course, investigators may have preferences for or against specific tools or evaluation procedures available for each media, as discussed later in this section.

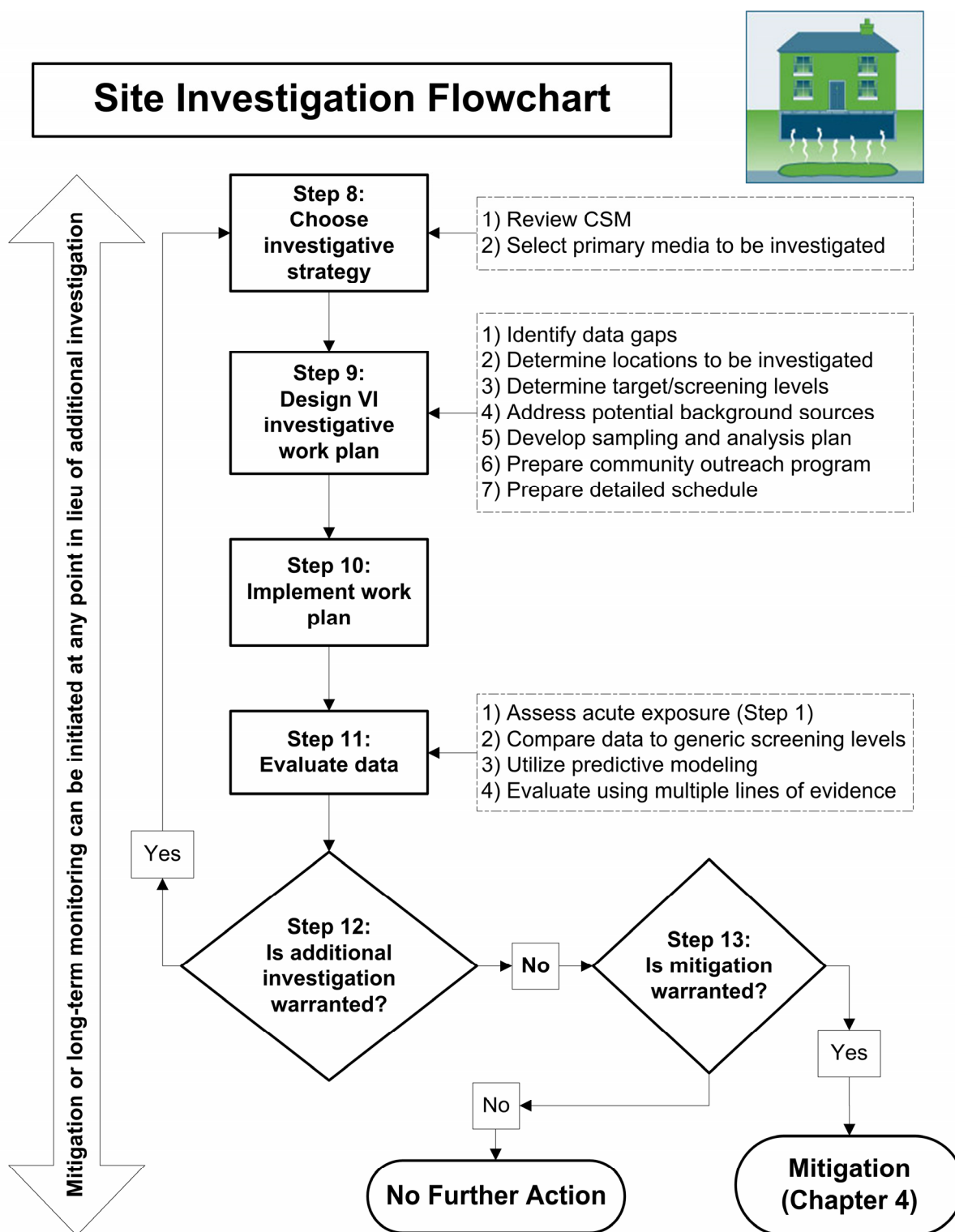


Figure 3-1. Decision-making process for VI site investigation.

The best method for a given application depends on various site-specific factors; therefore, no specific recommendations will be provided here. It should also be noted that strategic approaches

can be altered during the investigative phase. For example, the procedures used to determine whether the worst-case building in a group of buildings is impacted may not be the same as those used to determine whether neighboring buildings are also impacted. Thus, the investigative approach used for one site may not be the best for the next site or even the next structure or neighborhood at the same site. Section 3.5.10 discusses in more detail the delineation of the nature and extent of vapor intrusion contaminants.

The investigative processes available for vapor intrusion sites are split into two broad categories—exterior and interior measurements. Supplemental data are used to enhance these two categories. Typically, investigations start with exterior measurements and then move to interior measurements to further evaluate the pathway. The choice of one of these two categories reflects the investigative strategy (Step 8) and should be based on the stage of the investigation and the guidance or policies of the regulatory agency. Appendix D further explains each of the following investigative strategies in greater detail.

3.4.1 Exterior Measurements

Groundwater

Groundwater contaminant plumes migrating under or near buildings may be a source of vapor intrusion. Because of the distance interval between groundwater monitoring wells, it is often necessary during the early stages of a site investigation to estimate the contaminant concentrations at locations that are closer to the building(s) of potential concern. While the concentrations between monitoring wells may be interpolated based on the distance between the wells, it is generally safer to use the higher concentration found in the nearby wells initially to estimate the contaminant levels that may partition into the soil pore space, possibly leading to vapor intrusion. Since water concentrations at the top of the water table are the potential source of vapor partitioning, understanding the well construction and how groundwater samples were collected can be beneficial in making more accurate determinations. The vertical profile of concentrations and water table fluctuations may be necessary data for assessing the potential for off-gassing.

Soil

Soil matrix data are less than ideal for evaluating vapor intrusion risk because of the uncertainty associated with using partitioning equations to calculate soil gas concentrations and the potential loss of VOCs during sample collection. Numerous studies have identified sampling biases, and USEPA (1993a) has determined that the scale of the biases can be as large as several orders of magnitude. Scientific studies have failed to show a good correlation between soil and soil gas sampling and analysis on a consistent basis. Consequently, soil data should be used as a screening or secondary line of evidence in vapor intrusion assessments. Soil data may be available from previous investigations and therefore assist in the development of a CSM (e.g., source location and distribution).

Soil Gas

Measurement of soil gas is a common approach around the country for evaluating the vapor intrusion pathway. Soil gas data are reflective of subsurface properties and allow for real-time results. Risk-based screening levels for soil gas are usually higher than indoor air screening levels. Drawbacks to this method include the lack of knowledge of the proper attenuation factor to apply when interpreting soil gas data; debate over the number, location, and method of sample collection; and uncertainty over temporal and/or spatial variations in soil gas concentrations. Soil gas data are recommended over other data, specifically soil matrix and groundwater data, because soil gas data represent a direct measurement of the contaminant that can potentially migrate into indoor air.

Two methods are available to measure soil gas contamination in the unsaturated zone, active and passive soil gas sampling. More details of the soil gas measurement methods can be found in Appendix D.

Soil gas samples can be further differentiated by the location of the samples. Near-slab soil gas samples are collected outside a structure but within a short distance (usually 10 feet) of the building's foundation. Soil gas samples collected 10 feet or more from the perimeter of the building are generally referred to as "exterior" samples. Finally, subslab soil gas samples are collected from below the building foundation or slab. This interior measurement is discussed below.

3.4.2 Interior Measurements

Subslab

Subslab soil gas sampling is the preferred approach of many regulatory agencies for investigating vapor intrusion, primarily because of the proximity of the sample location to the receptor and the elimination of background interferences (when proper sampling methods are employed). Subslab soil gas sampling involves collecting soil gas from the space immediately under a slab or basement. It is distinct from shallow (e.g., 5 feet below ground surface [bgs]) soil gas samples that are collected outside and either next to (near slab) or some distance (exterior) from a slab.

Subslab soil gas concentrations, by themselves, do not necessarily indicate the extent to which vapor intrusion is occurring or, if it is occurring, whether vapor intrusion represents a health risk. However, if subslab soil gas concentrations are more than 1,000–10,000 times the target indoor air levels, the probability of unacceptable vapor intrusion is likely sufficient to warrant proactive mitigation without further investigation. Conversely, if the concentrations in the subslab soil gas are not higher than the regulatory soil gas screening levels (if available), there may be no further need for assessment. This principle alone may help to constrain the number of properties subjected to costly indoor air monitoring programs.

Indoor Air

Measuring indoor air is the most direct approach, but may not be the simplest. It is intrusive, and background contaminant sources in the building must be considered. Many commonly used household products contain some of the same target COCs (e.g., tetrachloroethene [PCE] from dry-cleaned clothes, trichloroethane [TCA] from degreasing cleaners). In some areas, especially urban centers, outdoor ambient concentrations (e.g., benzene) may exceed allowable indoor risk based levels, further complicating this approach. When doing indoor air sampling, a household inventory should be performed to find sources of indoor air contaminants. In addition the occupants should be instructed on appropriate actions that should be taken prior to and during the sampling event. Indoor air sampling may still be the method of choice if the COC is not one commonly found in household products or ambient air (e.g., 1,1-DCE, carbon tetrachloride). Agencies may find that residents prefer indoor air sampling over other investigative methods, and the data can be directly compared to screening values rather than having to be predicted or modeled.

Crawl Space

There are several approaches to investigating crawl spaces that involve collecting either air or soil gas samples using both active and passive methods. Typically, crawl-space air samples are collected following protocols similar to those for indoor air samples for a period of up to 24 hours. Ambient air can confound analytical results because of the uncertainty of outdoor air contribution to the crawl space. Soil gas collection can also be performed in the crawl space by inserting the probe rod or sampling tube horizontally through the crawl-space access ports or vertically through the overlying structure. Additionally, flux chambers can be used to determine the surface flux of the contaminant that may be moving into the crawl space. There are little data available to assess the attenuation from crawl space to indoor air.

Ambient

When indoor air sampling is performed as part of a vapor intrusion study, coincident outdoor ambient air samples should also be collected. Ambient air samples are important to characterize site-specific outdoor air contaminants. Depending on building air exchange rates, contaminants from outdoor ambient air may make up a large percentage of indoor air contaminants. Ambient air typically contains numerous VOCs, such as benzene, PCE, and TCE, that often exceed indoor air risk-based screening levels. Some compounds, however, that are not typically found in ambient air (e.g., vinyl chloride or 1,1-DCE) may be a concern for vapor intrusion studies. For residential structures, outdoor air samples should be collected from a representative upwind location, away from wind obstructions such as trees and buildings. The typical intake would be at about 3–5 feet off the ground (at the approximate midpoint of the ground level of the building) and about 5–15 feet away from the building. For commercial structures, outdoor air samples should be collected in representative locations for the intakes of the building heating, ventilating, and air conditioning (HVAC) systems.

Representative samples should be located to minimize bias toward obvious sources of volatile chemicals (e.g., automobiles, lawn mowers, oil storage tanks, gasoline stations, industrial

facilities). Outdoor air samples should be collected and analyzed by the same method as for indoor air samples and generally for the same time periods. Consider collecting basic meteorological data during the sampling event.

3.4.3 Supplemental Data

A number of different supplemental data collection tools may be useful when evaluating the vapor intrusion pathway to further define the site-specific CSM. Some of the available tools are listed below and discussed further in Appendix D:

- emission flux chambers
- determination of slab-specific attenuation using conservative tracers (e.g., naturally occurring radon)
- determination of room ventilation rate using tracers
- indoor/subslab differential pressure measurements
- real-time analyzers
- forensics (e.g., constituent ratios, isotopes)
- meteorological data
- pneumatic testing
- manipulating pressure differentials

3.5 Step 9: Design a Vapor Intrusion Investigative Work Plan

Once the investigative strategy is selected (or established by state policy/guidance), a work plan is developed (Step 9) to assess the vapor intrusion pathway. Key components of any vapor intrusion work plan include updating the CSM, identifying data gaps, addressing background contaminant sources, developing the sampling and analysis plan, formulating a schedule, and preparing a community relations plan.

3.5.1 Conceptual Site Model

As discussed in Section 2.1, the CSM should be considered in the preparation of the vapor intrusion investigative work plan. In addition, any deficiencies in the CSM should be identified as data gaps and incorporated into the work plan. For example, consider whether any geophysical investigative techniques are feasible and whether they would help evaluate site lithology and stratigraphic features prior to additional invasive investigations. Critical components of the CSM include the following:

- the location and nature of the source of COC found in the subsurface
- COC properties, including degradation products, solubility, vapor pressure, diffusivity in air and water, and Henry's law constant
- COC screening levels in indoor air and other media, as applicable
- a basic understanding of lithology and stratigraphic features that influence the occurrence and movement of groundwater, NAPL (if any), and soil gas
- depth to groundwater and groundwater flow directions (including vertical gradients or recharge that might lead to a clean groundwater lens at the water table)

- general nature and extent of COCs in groundwater and/or soil gas
- locations and depths of major underground utilities (particularly storm sewers)
- potential background sources of COC and typical indoor/ambient air concentration ranges
- locations, ownership, and general use of buildings (current and potential future) within the area potentially impacted

Refer to Section 2.1 for more information on CSM development. In addition, Appendix B contains a CSM checklist that should assist investigators in identifying the key components of a CSM.

3.5.2 Data Gaps

The information in the previous section is required to evaluate the potential for vapor intrusion, regardless of the investigation approach, and constitutes a data gap if not known to a reasonably conservative degree. Additional data gaps may exist based on the selected investigative strategy (Step 8). For example, approaches that rely to at least a certain extent on modeling of groundwater concentrations require site-specific information on the geology and nature/extent of COCs in groundwater below the building of concern. On the other hand, strategies that rely primarily on interior measurements for risk management decisions (including background contaminant sources) may require only general information on the nature and extent of groundwater contamination to help guide the sampling program.

3.5.3 Locations to Be Investigated

The specific properties and/or buildings that require investigation should be identified in the work plan. This is a relatively straightforward decision when only one property or building is of concern (e.g., Scenario 1 in ITRC 2007). However, when a large number of off-site buildings are potentially impacted, selection of the property or building for initial investigations can be more challenging (e.g., Scenario 3, ITRC 2007).

Spatial Patterns

It may be discovered that buildings with a specific design feature may be more susceptible to vapor intrusion and warrant closer attention or proactive mitigation. The building does not necessarily need to be located over the most highly contaminated area.

USEPA's draft VI guidance (2002b) suggests selecting the worst-case building(s)—those most likely to be impacted by vapor intrusion—for the initial investigations. The worst-case building, however, is not always readily apparent due to the large number of factors that contribute to vapor intrusion migration, including COC concentrations in groundwater or soil gas, depth to groundwater, soil types, building construction and ventilation, and groundwater flow direction.

In many cases, it may be appropriate to collect additional groundwater and/or soil gas data to narrow down the area with the highest concentrations before selecting individual properties or buildings for site-specific evaluation (e.g., Scenario 3, ITRC 2007). Select several buildings for the initial investigation to account for uncertainty and ensure that the varying factors potentially affecting soil gas migration are addressed. For example, the building overlying groundwater or soil gas with the highest concentrations, as well as the building with the most susceptible

foundation conditions (but not necessarily overlying the highest concentrations) might both be investigated.

At some sites, a statistical approach has been adopted for selecting properties or buildings to begin investigations. Buildings might be selected based on the magnitude of underlying concentrations, with bias toward grid cells overlying higher groundwater concentrations (stratified, systematic sampling approach). This method is most appropriate when concentrations are fairly similar over a broad area and there is little to distinguish the most susceptible building or area. The investigator should work with the community outreach coordinator in these cases since the apparently random nature of properties selected for sampling will raise concerns with the local building occupants.

3.5.4 Background

Background contamination is generally defined by anthropogenic (e.g., soils) or upgradient/upstream sources (e.g., groundwater, surface water). However, background indoor air contamination is everything unrelated to the subsurface soil gas that migrates into a structure. (See Appendix G for important questions to ask during an indoor air sampling program.)

One of the initial steps when conducting an indoor air sampling program is to define which chemicals have been released into the subsurface and which are COCs with regard to the vapor intrusion pathway. These COCs may be both primary chemical constituents and their degradation products. Background indoor air sources of volatile chemicals in residential structures include consumer products, supplies used for personal hobbies, household cleaners, paints, and building supplies. These background sources should be identified and, if practical, removed prior to indoor air sampling. Information on common household products that cause measurable levels of volatile chemicals in indoor air can be found on the National Institutes of Health Household Products Database (<http://householdproducts.nlm.nih.gov/>) and include the following:

- adhesives (automotive, household, craft, plumbing)
- household cleaners
- lubricants
- bonders
- adhesive removers
- antistatic aerosols
- automotive parts cleaners
- paint strippers
- “spot removers” for fabrics
- jewelry polish
- water repellants
- spray paints
- dry-cleaned materials (e.g., clothing containing residual dry-cleaning solvents)

“Background” Structures

In unique circumstances, investigators can determine indoor background air concentrations as one part of a multiple-lines-of-evidence approach in the assessment of vapor intrusion. Using data from structures of similar construction but located outside the contaminant soil gas or groundwater plume, investigators can compare results with buildings impacted by VI. This is particularly useful in reoccupancy scenarios. For example, at a petroleum hydrocarbon site in Colorado, vapor intrusion caused the evacuation of two schools. Indoor air samples were collected in another school located outside of the influence of the contaminated plume. Following mitigation activities, the students were allowed to return to the formerly impacted school when contaminant concentrations in indoor air were in the range of concentrations detected in the unaffected school.

- caulks and sealants
- cosmetics including hair spray, nail polish and nail polish remover, perfume, cologne
- air fresheners and odor eliminators
- insect repellants

As a general rule of thumb, these products should not be used inside the building at least 24–48 hours before and during the indoor air sampling activities, if practical. Investigators should consider the sorptive nature of some materials (e.g., carpeting, drapes, upholstery) to retain VOCs, slowly releasing them to the indoor environment over a period of weeks or more.

Other background sources include outdoor ambient sources such as those related to automotive exhaust, smoking indoors (e.g., benzene) and commonly emitted solvents (PCE, TCE, etc.). Before concluding that a chemical is present only as a result of background contamination, consideration should be given to the possibility that detected non-COC may also be attributed to vapor intrusion from other unknown subsurface sources. The likelihood of this possibility would largely depend on how adequately the nature and extent of contamination has been defined at a site. Subslab sampling as part of the indoor air sampling may also help with identifying chemicals migrating into the structure.

Additional information on background contamination and multiple lines of evidence can be found in Boyer 2004.

3.5.5 Sampling and Analysis Plan

Once the data gaps have been identified and the investigative locations (i.e., properties or buildings) selected, sampling methodologies and DQOs should be developed in conjunction with the preparation of the sampling and analysis plan. Keep in mind this is an iterative process and you may have to continually revise and update your investigative strategy based on new data (e.g., for larger sites preliminary soil gas samples may be used to pinpoint structure sampling). The CSM should be consulted (and updated) in parallel with the sampling and analysis plan.

Sampling plans should be reviewed to ensure that the objectives are consistent with the DQOs for the vapor intrusion pathway. Detection limits associated with the available data should be reviewed to ensure that methods chosen provide sufficient sensitivity to detect volatile chemicals at levels of concern. As previously noted, the CSM and its relationship to the USEPA DQO process are presented in Appendix B of the USEPA draft VI guidance (USEPA 2002b).

The definition of the nature and extent of contamination in groundwater and/or the vadose zone should be assessed to ensure that all COCs and areas of contamination have been identified. Groundwater concentrations should be measured or reasonably estimated using samples collected at the top of the water column from wells screened at or across the top of the water table. Soil gas, indoor air, and ambient sampling should be performed in accordance to any relevant standard operating procedures (SOPs). See Appendix D for information regarding sampling methodologies.

3.5.6 Groundwater Sampling Issues

Preferably, groundwater monitoring data should reflect the concentration at the groundwater-vadose interface (top of the water table) as that is the point where partitioning from the groundwater to soil gas occurs. In the event that sampling shows no contamination at the groundwater-vadose interface, the project manager may correctly interpret this as indicating no vapor intrusion risk to overlying buildings unless other sources of the contaminant are known in the vadose zone sufficiently near the building of potential concern.

Surficial recharge that occurs along the predominantly horizontal flow path of a groundwater plume will tend to establish a downward vertical hydraulic gradient and cause the affected groundwater plume to also migrate downward in proportion to the amount of recharge and in relation to total flow in the hydraulic unit. This effect is often referred to as a “diving” or “sinking” plume. While it is most apparent in situations where a groundwater plume has migrated over a significant lateral distance, in some situations plumes may start to dive relatively close to their source area. The value of techniques that sample from the upper horizon (with the zone of seasonal water table fluctuations) of the groundwater cannot be minimized. Where rainfall is abundant, sinking plumes can occur even with dissolved contaminants that are traditionally thought of as “floaters.” Targeting collection of groundwater samples from the top of the water table can provide significant data that will drastically reduce the extent of area over which one should consider vapor intrusion to be an issue, regardless of climate (wet, arid, etc.). For additional information, refer to NJDEP 2005b, Chapters 2 and 6.

In practice, many groundwater monitoring wells are screened in portions of the aquifer other than the interface. In addition to not revealing the conditions at the groundwater-vadose interface, purging and sampling these wells results in average contaminant concentrations that may under/overestimate soil gas concentrations and subsequently the vapor intrusion risk. Where possible, groundwater data from a relatively narrow interval across the water table should be used in the vapor intrusion assessment. The California Department of Toxic Substances Control states that a screen length of 10 feet or less will yield representative groundwater data suitable for vapor intrusion assessment (Cal DTSC 2004).

The investigator may be asked to determine whether vapor intrusion may pose a risk beyond the known plume boundaries for groundwater plumes that have not reached steady-state conditions. Information regarding the groundwater flow direction and gradient is often useful in determining the potential for contaminant migration. Groundwater characterization can entail groundwater flow direction; vertical and horizontal gradients, including as appropriate, seasonal variation, tidal influences, and the effects of groundwater withdrawal; the rate of groundwater flow movement; and the integrity of any confining units or other barriers to migration of groundwater. Groundwater movement and its associated impact upon distance from the source to the receptor should be considered. Three factors that affect contaminant levels in groundwater that affects contaminant levels in soil gas are dispersion, dilution, and recharge.

3.5.7 Community Outreach and Information Plan

Throughout the process, investigators should keep in mind that vapor intrusion will affect communities and individuals. Learning about vapor intrusion can be stressful. In the scientific world, there are many unknowns. Communities want facts and answers. After being told about the potential for vapor intrusion in their community, homes, and businesses, it is only natural for individuals to be concerned about the air they breathe, their health and welfare, the effect of vapor intrusion on property value, and retaining clean and healthy environments. Investigators must be ready to work with communities and share findings in a respectful, understanding, and clear manner. Thus, it is critical that a community outreach plan be prepared and implemented at vapor intrusion sites. Depending on the size and complexity of the site, the plan can be anything from a one-page contact sheet to a highly detailed plan of action.

Below are some of the most common techniques for raising public awareness at contaminated sites.

- **Holding public meetings.** Public meetings may be required if further characterization is planned at any given site. This is a chance to explain the purpose as well as the potential consequences of the investigation. If there are going to be presentations about specific chemicals and risk, expect questions about how risk is calculated and what the numbers really mean. Remember, it is unrealistic to expect that people will leave the meeting with a clear understanding of the technical and policy issues associated with the site. Vapor intrusion is too “new” and complicated for many members of the general public to absorb the most important lessons in one sitting, even with the best of presentations.
- **Contacting mass media.** The mass media, including newspapers, TV, radio and the Internet, can be a positive tool to let people know about contamination issues. Take time to meet the reporters and share the facts. If there are unknowns, just state that you are unsure of certain issues (and make sure you follow up with them when you get the information). Clearly give the print media no more than three main messages. Take the time to educate the reporter on the key issues. Thus, there will be less chance of inaccuracy or sensationalism quoted in the paper. For a TV interview, consider the amount of time the broadcaster will provide to ensure that the most important message gets through.
- **Establishing Community Advisory Groups.** CAGs are generally small groups of residents who meet regularly with agencies and responsible parties. They have no decision-making authority, but they often prove influential. They provide an opportunity for the public to gradually gain an understanding of the complexities of vapor intrusion investigations. In such settings, initial adversarial relationships usually break down, and community members often come up with constructive advice.
- **Newsletters and Web Site.** An excellent tool for communicating with local residents or workers is to prepare periodic newsletters or establish a Web site with site-related information (e.g., www.redfieldsite.org).

Investigators should also develop contingency plans for responding to public concerns as they arise. What if contamination is found in sensitive areas, such as schools or day care centers? If evidence shows that the public has been exposed to levels of contamination in drinking water or air that are considered unacceptable, will there be a way to address their likely demands for an independent health study? What if the groundwater plumes extend farther than previously believed? How are results going to be delivered to the occupants and the community as a whole?

3.5.8 Requesting Access

Effective public involvement is an important part of any environmental investigation, but because vapor intrusion investigations often require sampling near, in, or under the places where people live or work, building trust and cooperation is a critical path item for a successful project. To maximize chances of getting permission to sample in areas where existing data suggest that it should be done, it is necessary to target the outreach. This is usually a difficult, time-consuming process, but it can be made easier by a successful community-wide program of education, as described above. A typical community potentially affected by vapor intrusion contains all types of people with a variety of attitudes. Some people insist that their homes be tested even though they live a good distance from known contamination. Others refuse to permit anything that might show a health risk and/or lower their property values. Some want to cooperate, but they may find that sampling, as proposed, is impractical or inconvenient. Conversely, investigators will meet individuals that are cooperative and friendly, wanting to assist in anyway possible.

The first stage in gaining permission is to determine who is authorized to give permission. The second stage is preparing materials that explain the purpose and extent of the permission. Any right-of-entry document should be written in plain language, and people should not be asked to authorize anything more than is necessary to conduct the investigation. The final stage, contacting people to gain permission, will vary from community to community. Contact by telephone or by “door knocking” is a matter of discretion. CAGs or local leaders working with the regulatory agency can often advise the best approach. They can also advise whether the outreach team should include speakers of languages other than English. In some communities, it may be best to enlist or hire a community-based organization with a continuing relationship with community members. These groups have experience in assisting with issues of mistrust, risk of deportation, and language barriers. Field personnel should be polite and considerate of the assistance that the homeowner/tenant is providing.

Access Issues: Be Prepared

Questions that typically need to be answered:

- Are the occupants owners or the renters?
- Who has the authority at a large commercial structure?
- Who is responsible for any common areas?
- Is access different for invasive activity, such as drilling holes in floors or wells in lawns, versus passive sampling?

Answers may vary from state to state, and in some cases the questions will not get clear answers.

Once contact is made, it's essential that household members understand what is entailed in the investigation. Homeowners are likely to ask numerous questions. Will holes be drilled? Will it be necessary to remove certain household products or recently dry-cleaned clothes (background sources)? Will it be necessary to close up the house or turn on/off heating or cooling systems? Will family members or pets be moved out of the home during the sampling? A good program

should figure out how to achieve sampling objectives while minimizing disruption of family life. The same is true in commercial structures. Will the investigation interfere with day-to-day business? Will it scare away customers or clients? Will fact sheets be necessary to inform casual entrants to the property what is going on? How long will it take to get the results, and how will they be communicated?

Finally, it should be clear from the start what the long-term implications of the study are. How many times, over what length of time, will sampling occur? What are the response options if unacceptable indoor air levels are found? Who will pay the costs? When, if ever, will things be back to normal?

3.5.9 Implementation and Scheduling

For vapor intrusion investigations, it is critical that a schedule be developed that coordinates all the various activities necessary to complete the work plan. Since the investigation is likely to involve accessing off-site properties, schedules have to be flexible, adjusting to changes that will happen. Anticipate potential pitfalls and be prepared to resolve them. It is also advisable to develop a decision logic in advance of data collection so there will no arguments over responses in the “heat of the moment.”

Some of the activities that need to be reflected in the schedule are as follows:

- regulatory approvals
- permits and local approvals
- community education and access
- scheduling tests and potential logistical challenges
- evaluating data and determining if data are adequate
- reporting and communicating results
- being ready to make risk management decisions

3.5.10 Identifying Impacted Structures

The investigator may first delineate the extent of the subsurface contamination using exterior investigative tools. For a large site involving a significant number of buildings, identify primary, secondary, and tertiary buildings based on the magnitude of groundwater and/or soil gas concentrations. Then, as necessary, implement an interior investigation (e.g., subslab soil gas sampling, indoor air sampling) initially in the primary buildings. Some states may start with an interior sampling effort, targeting a primary, secondary, and tertiary zone, based solely on groundwater concentrations. If some of the primary buildings reveal evidence of unacceptable vapor intrusion, the interior investigation is expanded to the secondary buildings. This approach is referred to as a “step-out process,” where buildings adjacent to impacted buildings are investigated in an

Building Triage

Sampling all structures for VI may be impractical for larger sites, so existing data can be used to determine which buildings should be targeted first. The building triage approach involves assessing the magnitude of the subsurface concentrations (e.g., soil gas, groundwater) into zones to assist in targeting initial investigations. The zones are primary, secondary, tertiary.

outward, sequential manner until a perimeter with no impacts (or below screening levels) is established.

When vapor intrusion impacts are discovered, there is usually significant pressure from the community and other stakeholders to test and mitigate (or take other appropriate action) as quickly as possible. This should be done, of course, but not at the expense of good science or wise use of resources. For example, testing of a large number of buildings or properties beyond the known area of impact may result in unnecessary tests and wasted time and resources. This is particularly harmful when testing proceeds in the wrong direction due to a lack of data to guide the investigation. Therefore, a step-out process to delineate the impacted area should be developed, at least conceptually, prior to beginning the investigations. At some sites, a two-house rule has been followed—testing does not proceed more than two houses in any direction beyond the buildings known to be impacted. Refer to the Colorado indoor air guidance (CDPHE 2004a) for additional information.

In addition, the approach to the step-out testing program does not necessarily have to be the same as the initial testing program. Once the occurrence of vapor intrusion has been established at the initial building(s), knowledge gained from these investigations may suggest that soil gas tests, subslab soil gas tests, or other approaches may be sufficient to make risk management decisions. Testing of multiple buildings or properties often results in spatial patterns and other data correlations that can be used to evaluate the results of individual tests, potentially reducing the number of tests required to make decisions.

3.6 Step 10: Implement the Vapor Intrusion Investigative Work Plan

Once the vapor intrusion investigative work plan has been approved by the regulatory agency, it's time to implement it. The investigator needs to be prepared to adjust the schedule based on field modifications that are bound to occur. Unlike groundwater investigations where the drilling crew works consistently installing monitor wells until they're done, vapor intrusion investigations are dictated by schedules often outside the control of the field samplers. Off-site access agreements may stipulate specific hours when exterior or interior fieldwork can be completed. Collecting indoor air or subslab soil gas samples is dependent on the occupants' being available to let the field samplers into the building. Since interior sampling may involve either very early morning or late evening hours, field samplers should consider appropriate safety concerns.

Heavy rains can delay the collection of exterior soil gas samples. Thus, the investigator needs to have contingency plans in place to avoid falling too far behind in the schedule. In addition, the investigator must be responsive to the results as they are received, showing flexibility to accommodate stakeholder concerns. Verification testing may have to be implemented immediately to address unexpected data.

3.7 Step 11: Evaluate the Data

Before evaluating the analytical results for chronic risk to occupants, a review of Step 1 from the preliminary screening phase is appropriate. At all stages of the assessment, the investigator has

to consider the potential for acute exposure of building occupants to contaminants from the vapor intrusion pathway. Although the potential for acute exposure (Step 1) is minimal, it has to be evaluated whenever additional data are obtained.

Both the preliminary screening (Step 6) and data evaluation (Step 11) stages require the use of various decision-making tools to assess the potential for human health risks. For example, in the preliminary screening step, existing site groundwater data can be compared to generic screening levels as means of evaluating whether subslab soil gas and/or indoor air samples should be collected. Similarly, as part of the data evaluation step, subslab data can either be compared to generic screening levels or used in a predictive model to determine whether indoor air samples should be collected or mitigation measures should be implemented. The regulatory agency should be consulted prior to making decisions from the data evaluation steps.

The three primary decision-making tools discussed below are generic screening, predictive modeling, and data evaluation using multiple lines of evidence. In general, generic screening will most commonly be used as part of the preliminary screening process, while predictive modeling and evaluation of multiple lines of evidence will be used to evaluate data collected during preliminary screening or site characterization phases. In addition, many states use generic screening levels in combination with the multiple-lines-of-evidence approach to make remedial decisions.

3.7.1 Comparison with Generic Screening Levels

In generic screening, it is assumed that all detected volatile chemicals in subsurface media samples above applicable generic screening levels are COCs. The applicable generic screening levels (in those states where they exist) are typically conservative, non-site-specific values. Appendix H provides a more detailed discussion of the types and sources of generic screening levels available.

If all detected chemical concentrations are less than the generic screening levels, no significant human health risks would be expected, and further assessment is not required, as long as the analytical data are sufficient and reliable. While an applicable, generic screening can indicate the absence of unacceptable health risks under many circumstances, the presence of chemical concentrations exceeding the screening levels may not definitively identify unacceptable human health risks (due to the conservative assumptions utilized in developing the screening levels). Due to the generic nature of the screening levels, an exceedance could simply be an indication that further site-specific evaluation is needed. For example, if a review of groundwater (or deep soil gas) data resulted in an exceedance of the screening level, it would be appropriate to collect subslab or indoor air samples for further evaluation.

Mitigation Versus More Investigation

Despite the lack of verifying data, choosing to mitigate based on exceeding generic screening levels may be acceptable as a proactive, protective measure.

3.7.2 Predictive Modeling

If any of the data collected during the vapor intrusion evaluation indicate concentrations greater than generic screening levels, predictive modeling may be used to assess whether the subsurface media concentrations are high enough to potentially migrate into overlying structures. Groundwater, soil gas, and subslab data can be used to estimate indoor air concentrations in buildings using vapor intrusion contaminant transport modeling. Alternatively, indoor air samples may be collected to obtain direct measurements of chemical concentrations in indoor air. However, there are typically confounding factors when using indoor air sampling results to assess the likelihood that vapor intrusion is occurring.

Models provide predictive capability, but their reliability is difficult to defend with limited site-specific data (Johnson et al. 2002, Hers et al. 2003). The use of models should be approved by the regulatory agency. It is often helpful to start with a screening level model using mostly generic and conservative input parameters at the early stages of a site assessment to understand, in general terms, the relative magnitude and significance of vapor intrusion. As additional site information becomes available during the course of the site investigation, these data can be incorporated into the model, yielding progressively more site-specific and typically less conservative results. It is recommended that investigators (working with regulators) determine the critical parameters (Johnson et al. 2002) and conduct sensitivity analysis whenever predictive modeling is employed. The use of extreme and nonrepresentative assumptions is the most common weakness of predictive modeling.

As noted in the Vapor Intrusion Survey (ITRC 2004b), the USEPA spreadsheet version of the Johnson and Ettinger (J&E) model is the most commonly used model for estimating chemical concentrations in indoor air (www.epa.gov/Athens/learn2model/part-two/onsite/JnE_lite.htm). With input of groundwater or soil gas concentrations, the model estimates the associated indoor air concentration. The USEPA J&E model is a simple, deterministic model, having single-point inputs and outputs. It is based on the basic principles of contaminant fate and transport, contaminant partitioning between media, and the physical and chemical properties of the contaminants themselves. The model incorporates both diffusion and advection as mechanisms of transport of subsurface soil gas into the indoor air environment. Diffusion is the dominant mechanism for vapor transport within the vadose zone. Once the soil gas enters into the “building zone of influence,” the soil gas is swept into the building through foundation cracks by advection due to the indoor-outdoor building pressure differential. The distance of the building zone of influence is usually less than a few feet. The USEPA J&E model uses the conservation-of-mass principle and is based, in part, on the following assumptions:

- Steady state conditions exist.
- An infinite source of contamination exists.
- Air mixing in the building is uniform.
- Preferential pathways do not exist.
- Biodegradation of soil gas does not occur.
- Contaminants are homogeneously distributed laterally beneath the building.
- Contaminant vapors enter a building primarily through cracks in the foundation and walls.

- Buildings are constructed on slabs or with basements.
- Ventilation rates and soil gas flow into the building are assumed to remain constant.

The USEPA J&E model is most suitable under homogeneous site conditions with uniform building construction features. Conversely, the model is weakest under variable conditions and cannot evaluate significant preferential pathways; wet basements; substantial lateral transport of soil gas; tall buildings in cold climates; large buildings with potential localized sources of vapors beneath them; and shallow, fractured-bedrock conditions. Each of these conditions has the potential to significantly increase the rate of vapor intrusion beyond the model's predictions. With an understanding of the above-mentioned limitations and the use of conservative input parameters (see USEPA 2004b for typical parameter ranges and conservative values), the USEPA J&E model can enable users to quickly screen sites for vapor intrusion risk.

To facilitate its use in evaluating potential risk due to the inhalation of vapor in indoor air, USEPA has programmed into the J&E model a health risk component that calculates the human health risk from inhaling a specific chemical at the concentration estimated in indoor air. An updated version of the spreadsheet will soon be released that offers significant advantages over versions released in 2001 and 2003. The spreadsheets allow the use of either groundwater or soil gas data; soil matrix data are not allowed). The spreadsheet contains a number of default parameters that can be changed to site-specific values. Typically, agencies customize the spreadsheet by changing the default values and putting limitations on the parameters that can be changed with site-specific data. When using the USEPA J&E model, the input parameters for a given site must be appropriately conservative and match site-specific conditions. Model details are presented in the USEPA 2004b.

The USEPA J&E model should be used only when site conditions match the model assumptions using reasonable, site-specific, or regulator-approved input parameters (USEPA 2004b). Less used, one-dimensional analytical models are also available to simulate the effects of biodegradation, source depletion of contaminants in soils, and various building construction types, such as crawl spaces. Although not included in the current (2004) version of the USEPA J&E model, future revisions are expected to include an option for evaluating buildings with crawl spaces (i.e., dirt floors). For more complex sites, multidimensional numerical models can evaluate spatial and temporal processes in the vapor intrusion pathway.

3.7.3 Evaluation of Indoor Air Data Using Multiple Lines of Evidence

Indoor air data may be collected from existing buildings at any time during a vapor intrusion evaluation. For some states, it is recommended that indoor air samples be the primary sample media and basis for evaluating vapor intrusion. In other states, indoor air sampling is not recommended or is collected as the final data type in the evaluation of vapor intrusion, if warranted based on exterior and/or subsurface soil gas data. For instance, if the cumulative health risk using soil gas data and an attenuation factor calculated using the USEPA J&E model for a future building scenario is considered unacceptable, institutional or engineering controls may be warranted. If the cumulative health risk for an existing building scenario is considered unacceptable, the model results can be verified by collecting subsurface and/or indoor air samples.

If measured indoor air concentrations are greater than the screening levels, it is necessary to assess whether the measured chemical concentrations are due to subsurface vapor intrusion, interior background sources, or ambient outdoor air.

Background Concentrations

A complicating factor in evaluating the potential for vapor intrusion using indoor air data is the potential presence of some of the same chemicals at or above background concentrations separately or in combination with chemicals that may be associated with vapor intrusion. There may be multiple sources of chemicals in indoor air that are not associated with the investigated chemical release (from the ambient air and/or background sources in the building). These other sources may confound the interpretation of indoor air samples results. Thus, attribution of measured chemicals in indoor air can become a relatively complex and difficult task.

When volatile chemicals with multiple potential sources are measured in indoor air, it may be necessary to gather multiple lines of evidence to support a remedial decision either to include or exclude certain chemicals from the risk evaluation. The premise is that if it can be demonstrated through multiple lines of evidence that an indoor air concentration above a remediation goal is not derived from a subsurface source, no remediation is warranted because the indoor air concentrations are due to background source(s). The more evidence gathered to support such a conclusion, the stronger the justification for the resulting decision. Site-specific decisions should be made as to the number and types of information employed. The use of many lines of evidence may not be required if only a few or even one provide clear evidence of either background or vapor intrusion sources.

It should be noted there is some uncertainty associated with such an assessment, regardless of the number of lines of evidence considered. The relative strength or significance of each line of evidence is also a factor to consider. The importance of a line of evidence based on one or two data points (or sample results) is quite different than that of evidence using 20–30 data points. Decisions should be made based on reasonable and logical professional judgment. Clearly, a successful exit strategy is more likely if a site-specific plan is developed and consensus reached with decision makers prior to implementing the investigation.

The following lines of evidence, listed in no particular order, may be used to identify whether measured indoor air contamination is derived from subsurface impacts or background sources. Other lines of evidence may be available depending on the site-specific circumstances.

Chemicals of Concern

The easiest and probably most important line of evidence is the identification of COCs at the site. Provided sufficient characterization has occurred, the investigator should be able to establish the principal contaminants associated with the original discharge or spill. Using this information, along with any degradation products related to these chemicals, the COCs can be identified. Thus, an investigator can limit the scope of the data evaluation and the analytical parameters for any future sampling events.

Building Construction and Current Condition

Information regarding the construction and operation of a building may be used to establish the likelihood of subsurface soil gas entering. For example, if a building's HVAC system generates positive air pressure within the structure, it may be reasonable to conclude that this system will minimize or prevent soil gas from migrating into the building from a subsurface source (if positive pressure is the remedy chosen, see Section 4.3.1.6).

Other building factors that should be considered are age; foundation and slab type; building materials; the presence of sumps, perimeter drains, elevators; the height of buildings (particularly in cold climates); basement details; crawl spaces; vapor barriers or radon remediation systems; and surface cover outside the building. Refer to Appendix C for additional information. Facts regarding the building construction and current condition may help with assessing the potential for soil gas contamination to migrate into a building.

Subslab Data

Soil gas measurements collected from beneath a building will provide a good indication of what volatile chemicals could migrate into it. If COCs in the subslab soil gas or crawl-space vapor samples are not observed to be equal to or higher than indoor air concentrations in the building, it is reasonable to conclude that any measured constituent in the indoor air samples is derived in part from other background sources. (Note: Some structures subslab samples will vary in concentration.) The difficulty with this line of evidence is ensuring that representative soil gas samples are collected from beneath the structure. Since soil gas naturally attenuates to some degree in the migration from the subsurface into an overlying structure, a detection of a chemical in the subslab soil gas sample supports, but does not necessarily confirm, that the chemical observed in indoor air is attributable to the subsurface source. Barometric pressure fluctuations can cause reversible vapor flow and can contribute vapors from interior sources to subslab samples. Thus, other lines of evidence may be important to evaluate to establish the presence of concentration gradients inside and outside the structure.

Constituent Ratios

Evaluating the ratio between concentrations of different COCs in groundwater, soil gas, subslab and/or indoor air may help to identify potential vapor intrusion contributions or to screen out background sources. For many volatile chemicals, the background concentration ratios are distinct from groundwater-derived volatile chemical ratios. This characteristic allows the volatile chemical ratios from other media to be used to eliminate indoor air constituents.

It is possible that, even if the ratio analysis suggests that indoor or ambient sources are likely responsible for some of the measured indoor air concentrations, subsurface sources may still be contributing to indoor air concentrations. Conversely, if the ratios of

Concentration Ratios of Different Chemicals

Example: If the concentration of TCE is 10 times higher than that of PCE in groundwater, deep soil gas, and/or subslab soil gas but PCE has a higher concentration than TCE in indoor air, it is reasonable to conclude there is an interior or background source of PCE (e.g., dry-cleaned clothes, carpet spot remover). Check with the regulatory agency when using constituent ratios.

constituents in the indoor air sample are similar to the ratios observed in the subslab soil gas sample, one may conclude that the two are linked and that there is a contribution from the subsurface sources, especially if subsurface concentrations are significantly higher than indoor air concentrations.

Comparison of chemical ratios in groundwater to ratios in indoor air may also be considered. However, these ratios should be adjusted for different relative volatilities of the COC using their Henry's law constants and, if significant, different rates of retardation and/or biodegradation in the vadose zone. The comparison of soil gas ratios to Henry's law adjusted groundwater ratios may be another line of evidence for assessing background contributions or vadose zone sources. It should be recognized that background sources might result in ratios that fall within the range predicted for groundwater or measured in soil gas data. Therefore, ratios can screen out obvious background sources but will not necessarily confirm vapor intrusion or eliminate the potential for background contributions.

The presence of marker chemicals (those constituents that are associated with the subsurface contamination but not typical background air sources, such as 1,1-DCE) in indoor air samples is a good indication that intrusion is occurring and that the observed constituents are derived from the subsurface. The converse assumption may also be true—the absence of a marker chemical in indoor air samples is a good indicator that little to no contamination is coming from the subsurface, suggesting that any air contaminants observed are from background sources. However, this second assumption will depend on the relative abundance, volatility, diffusivity, and reporting limit of the marker chemical compared to other COC.

In theory, if a marker chemical is found in the subsurface and indoor air, the indoor air concentrations of other chemicals can be estimated by multiplying the subsurface concentration ratio (nonmarker/marker) by the indoor air concentration of the marker chemical. If the measured indoor air concentrations of the second chemical are greater than that predicted by this method, the additional amounts found in indoor air may be due to background contributions.

Spatial Correlation

The use of spatial correlation is another tool for differentiating vapor intrusion sources from background. For example, use of COC ratios might eliminate a number of background outliers but still leave buildings with ratios that are consistent with either vapor intrusion or background source. Spatial analysis might show that a cluster of such ratios is consistent with a groundwater plume, whereas in other area buildings the ratios appear to be randomly distributed and are more likely associated with background levels. Also, evaluate the results of the ambient (outdoor) air sample. If the data reveal measurable concentrations of multiple chemicals in ambient air, compare these concentrations and concentration ratios with similar chemicals and ratios in indoor and subsurface soil gas samples.

The spatial distribution of volatile chemicals measured within a building may also help with the identification of the source of the vapor. For instance, concentration gradients or hot spots may indicate indoor air sources. The results of air samples taken in various parts of a building can be reviewed and compared to assess whether there are any contaminant concentration gradients or

hot spots among the various floors or rooms in a building. In general, if basement concentrations are elevated above background and there is a decreasing contamination gradient from the source (e.g., basement) area on up, there is a relatively good chance that detected concentrations are due to a subsurface source of contamination. However, it is also possible that other sources (e.g., stored products) may be present in the basement and possibly even in the living area, potentially confounding site-related concentration gradients. Ultimately, though, this approach is both expensive and not very practical.

3.7.4 Assessment of Potential Human Health Risks

Exposure to a volatile chemical due to vapor intrusion does not necessarily mean that health effects will occur. Whether or not a person experiences health effects depends on several factors, including the length of exposure, the amount of exposure, the frequency of exposure, the toxicity of the volatile chemical, and the individual's sensitivity to the chemical. The main concern is whether the chemicals may pose an unacceptable risk of chronic health effects due to long-term exposure. It should be noted that the vapor intrusion pathway may not be the only complete pathway for a particular receptor. Each potentially complete pathway (e.g., dermal contact, ingestion, etc.) may be assessed in a risk assessment prior to determining whether and what remediation may be warranted. Some regulatory agencies may mitigate a structure to interrupt completed pathways, (e.g., install a carbon system on a well or install a subslab depressurization system on the house).

Once the COCs and their representative exposure point concentrations are identified and a risk assessment is determined to be the next step, the potential for significant health risk can be assessed. The identified exposure point concentrations should be used in conjunction with appropriate exposure assumptions to complete a site-specific risk assessment. The risk assessment provides a quantitative estimate of the excess lifetime cancer risk and the potential for noncancer health effects. These estimates are then compared to USEPA and/or state-defined screening levels or are evaluated on a case-by-case basis by the regulatory agency to make a risk management decision to determine whether mitigation measures are needed. When evaluating the potential for human health risk, it is important to note that vapor intrusion may not be the only complete exposure pathway for a particular receptor. A site-specific risk assessment should consider all potentially complete exposure pathways for each receptor to make appropriately protective risk management decisions.

Extensive guidance on conducting risk assessments is available from USEPA and many state agencies. The individual state agencies should be consulted to identify any state-specific guidance and/or regulations that should be addressed. These guidance documents should be consulted when completing a site-specific risk assessment. Some of the primary references that provide guidance for the assessment of risk to public health are USEPA 1989, 1996a, 1996b, and 2002d).

3.8 Step 12: Is Additional Investigation Warranted?

Step 12 highlights the iterative process of the vapor intrusion investigation. Upon execution of the work plan and review of the results, the investigator determines whether the site has been

adequately characterized. Have the COCs been properly delineated? Has the potential for vapor intrusion at all possibly affected buildings been assessed? Are there sufficient data to reach a remedial decision at the site?

If the answers to these and similar questions are “yes,” the investigator can move on to Step 13. However, if the evaluation of the investigative results identifies data gaps that prevent reaching a final conclusion at the contaminated site, additional investigations are warranted, and the process returns to Step 8 to develop a new work plan for the next round of investigation.

To expedite this iterative process, supplemental stages of investigation can be built into the original work plan to avoid long delays while new work plans are developed and approved by the regulatory agency. For example, a standard investigative approach can be developed for assessing vapor intrusion at each building at a site where a large number of structures may be impacted. This way, the initial investigation can center on the worst-case buildings, with subsequent rounds of sampling targeting adjacent buildings (the step-out process). Keep in mind that subsequent work plans can focus on the scope of work and rely on previously approved methods.

At any point in the process, many state and federal agencies will allow a responsible party to implement a remedial action to address vapor intrusion, even prior to confirming the pathway is complete. This proactive approach can be viewed as both responsive to the concerns of public health and economically rationale when compared to the cost of a full investigation.

Alternatively, the decision may be made to conduct long-term monitoring, particularly for undeveloped parcels, until such time as the vapor intrusion pathway source is remediated or future development will likely introduce receptors (people) that could be exposed to unacceptable indoor contaminants from vapor intrusion.

3.9 Step 13: Is Mitigation Warranted?

If the vapor intrusion investigation is complete, the review of the data must be made to determine whether some form of remedial action is appropriate at the site. Step 13 is the final decision point in the assessment of the vapor intrusion pathway. The investigator must reach a conclusion on the status of the site—no further action, additional monitoring, or mitigation. This decision is often left to the regulatory agency. Mitigation is discussed further in Chapter 4.

4. REMEDIATION

Remediation of vapor intrusion impacts may be required when the results of the site investigation phase (Chapter 3) indicates that indoor air concentrations of volatile compounds exceed screening levels in existing buildings or are likely to exceed screening levels in future buildings. When remedial action is required, a remedy or combination of remedies must be selected, implemented, operated, maintained, and/or monitored to control vapor intrusion until the source of the vapors is eliminated.

Remedies may address two possible scenarios: emergencies and nonemergencies. This document focuses on chronic exposure concerns and does not discuss appropriate responses to emergency situations where immediate safety is the primary concern. Remedies can be further separated into three types: sitewide remediation, institutional controls, and building controls. Of these, building control remedies are discussed in the most detail because they are most commonly implemented at sites impacted by vapor intrusion.

4.1 Sitewide Remedies

Sitewide remedies address the source of vapors found in buildings, such as contaminated soil and groundwater, rather than controlling the entry of vapors in buildings. Sitewide remedies may be sufficient in situations where the vapor concentrations in buildings are very low or where source remediation can be conducted very quickly. In most cases, however, sitewide remedies are considered to be the long-term solution to vapor intrusion (and other) impacts, while institutional or building control remedies are considered to be short-term or interim remedies, implemented until the long-term or sitewide remedy is complete.

Sitewide remediation of soil and groundwater contamination may include technologies to reduce contaminant concentrations in soils and soil gas, such as soil vapor extraction, or technologies which would reduce concentrations in the groundwater, such as in situ bioremediation or pump-and-treat remedies. For sitewide remedies to be protective, exposures to unacceptable levels of vapor intrusion must be controlled until concentrations in soil and/or groundwater reach acceptable levels. Therefore, until the remedy has met its cleanup goals, the vapor intrusion pathway must be effectively controlled in all potentially impacted and inhabited structures.

In general, source removal and soil vapor extraction sitewide remedies are likely to have the potential to reduce or eliminate soil gas migration in the short term and thus preempt the need for interim control (e.g., institutional or building control) remedies. Sitewide remedies are not the focus of this document.

4.2 Institutional Control Remedies

In the event that sitewide remedies are not immediately effective in reducing or eliminating the potential for vapor intrusion, institutional controls may be put in place on either an interim or permanent basis to protect human health while longer-term sitewide remedies are being developed and implemented. An example of such a control would be legal actions to limit the use of certain parcels. If risks associated with vapor intrusion were unacceptable for unrestricted use of the property, for example, restrictions could be established to allow only those land/building uses that would be associated with acceptable health risks. These legal actions can take many forms, including restrictive covenants, zoning, excavation prohibitions, and groundwater advisories.

At undeveloped sites, or at sites where land use may change in the future, institutional controls may be necessary to ensure that the vapor intrusion pathway is effectively addressed in the future. Institutional controls at undeveloped sites could include mechanisms to require the preemptive installation of vapor intrusion controls, such as subslab depressurization systems, in

new buildings This step would avoid some of the difficulties associated with attempting to predict the potential for vapor intrusion 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 this measure to be necessary.

A significant drawback to institutional controls is that they can be difficult to implement and enforce over time in many states that do not have adequate statutory authority to implement them. Institutional controls that incorporate periodic inspections and monitoring may be required to ensure that engineering controls are operated and maintained over time to retain their effectiveness.

Institutional controls, like sitewide media remedies, are not the focus of this document; however, they are often integral to vapor intrusion remedies. The investigator should refer to other guidance documents that have been developed to address the use of institutional controls as part of environmental remediation.

4.3 Building Control Remedies

Building control remedies are typically required at vapor intrusion sites (in both existing and new buildings) until long-term, sitewide remedies reduce soil and/or groundwater concentrations to acceptable levels. The following sections discuss various vapor intrusion building control technologies, factors affecting technology selection, and design and installation issues.

4.3.1 Building Control Technologies

Several building control technologies are identified below that can reduce or eliminate the potential for vapor intrusion impacts in new and existing buildings. A brief summary of each technology is provided, along with some of the advantages and disadvantages of each system. In addition, a typical range of installed costs for each technology is provided. Because vapor intrusion controls are often added to older buildings, the potential need for and additional costs of lead paint and asbestos abatement should be considered on a case-by-case basis. In some cases, excessive costs associated with these issues could affect technology selection. For a quick summary of the typical attributes of each technology, refer to Table 4-1.

Table 4-1. Comparison of mitigation methods

Technology	Typical applications	Challenges	Range of installed costs*
Passive barrier	<ul style="list-style-type: none"> New construction Crawl spaces Often combined with passive or active venting, sealing openings in the slab, drains, etc. 	<ul style="list-style-type: none"> Preventing tears, holes May not suffice as a stand-alone technology Some states do not accept Ensuring caulking seals cracks in floors, etc. 	<ul style="list-style-type: none"> \$0.50–\$5/ft² Thinner, less-expensive barriers likely to be inadequate
Passive venting	<ul style="list-style-type: none"> New construction Low soil gas flux sites Should be convertible to active system if necessary 	<ul style="list-style-type: none"> Relies on advective flow of air due to wind and heat stack effects Air flows and suction typically far less than achieved by fans 	<ul style="list-style-type: none"> \$0.75–\$5/ft²

Technology	Typical applications	Challenges	Range of installed costs*
Subslab depressurization (SSD)	<ul style="list-style-type: none"> New and existing structures Sumps, drain tiles, and block wall foundations may also be depressurized if present 	<ul style="list-style-type: none"> Low permeability and wet soils may limit performance Otherwise, highly effective systems 	<ul style="list-style-type: none"> \$1–\$5/ft² Residential systems typically in the \$1–2/ft² range
Submembrane depressurization	<ul style="list-style-type: none"> Existing structures Crawl spaces 	<ul style="list-style-type: none"> Sealing to foundation wall, pipe penetrations Membranes may be damaged by occupants or trades people accessing crawl space 	<ul style="list-style-type: none"> \$1–\$6/ft² Residential systems typically in the \$1.50–2/ft² range
Subslab pressurization	<ul style="list-style-type: none"> Same as SSD Most applicable to highly permeable soils 	<ul style="list-style-type: none"> Higher energy costs and less effective than SSD Potential for short-circuiting through cracks 	<ul style="list-style-type: none"> \$1–\$5/ft²
Building pressurization	<ul style="list-style-type: none"> Large commercial structures, new or existing Sensitive receptors 	<ul style="list-style-type: none"> Requires regular air balancing and maintenance May not maintain positive pressure when building is unoccupied 	<ul style="list-style-type: none"> \$1–\$15/ft² Heavily dependent on size and complexity of structure
Indoor air treatment	<ul style="list-style-type: none"> Specialized cases only 	<ul style="list-style-type: none"> Typically generates a waste disposal stream Effective capture of air contaminants may be difficult Energy-intensive, with significant operation, maintenance, and monitoring burden 	<ul style="list-style-type: none"> \$15K–\$25K per application not atypical Actual costs heavily dependent upon type of technology employed
Sealing the building envelope	<ul style="list-style-type: none"> Cracks and holes in existing buildings 	<ul style="list-style-type: none"> Access to perforations Permanence 	<ul style="list-style-type: none"> Highly dependent on the extent of sealing required

*Square footage costs based on building footprint.

4.3.1.1 Passive Barriers

Passive barriers are materials or structures installed below a building to physically block the entry of vapors. Passive barriers ideally cause soil gas that would otherwise enter the building under diffusion or pressure gradients to migrate laterally beyond the building footprint. In reality, it may be very difficult to completely prevent (or even substantially prevent) the entry of vapors into a building by passive barriers alone (see Table 4-2). Therefore, passive barriers are generally not recommended by themselves for vapor intrusion control, although they may enhance or increase the efficiency of other technologies, such as subslab depressurization (SSD) systems.

Table 4-2. Passive barrier pros and cons

Advantages	Disadvantages
<ul style="list-style-type: none"> Low to moderate capital cost No mechanical parts 	<ul style="list-style-type: none"> Even small holes can render ineffective Likely not effective without venting Limited applications for existing structures

Most passive barriers consist of thermoplastic or elastomeric flexible membranes or spray-on rubberized asphalt emulsions. In new structures, barriers are placed beneath the floor slab to prevent subslab soil gas from entering the structure through cracks or construction joints in the slab. In existing structures, membranes can be used to retard the intrusion of vapors in crawl spaces or over dirt floors.

To be effective, passive barriers must provide a complete barrier to vapor intrusion since, by definition, passive barriers do not include any active measures to control the movement of soil gas. Even small imperfections in the barriers (e.g., due to holes, tears, or incomplete seals at the footings or pipe penetrations) may provide a significant migration route for soil gas when buildings are underpressurized. Occupants may accidentally penetrate the barrier as part of general building maintenance. No standard criteria have been developed for minimum passive barrier thickness or physical properties, such as puncture resistance and tear strength. Nevertheless, thin polyethylene films (often called “vapor barriers” because they have been traditionally used to prevent moisture from accumulating behind drywall walls) are easily damaged and are unlikely to survive normal construction abuse, even when cushioned by sand (ASTM 1998). Even thicker (e.g., 10–20 mil) polyvinyl chloride membranes are likely to be damaged during construction, particularly if placed below concrete slabs. Workers are likely to step onto and force aggregate and other sharp objects into the membrane and may actually poke holes into the membrane to encourage water drainage during concrete placement and curing. Studies of flexible membrane liners used for liquid containment in impoundments have shown that even placement of sand and other earth materials is likely to cause a certain amount of puncturing.

The potential for punctures may be reduced by using thicker membranes (e.g., 60–100 mil high-density polyethylene [HDPE] or similar materials); thick (e.g., 1/4-inch) layers of spray-on rubberized asphalt emulsions; and cushioning materials above and/or below the membrane, such as geotextiles, sand, or fine rounded gravel (pea gravel). Some proprietary vapor barrier products incorporate cushioning, barrier, and sealing material layers in one material. Nevertheless, no specific criteria have been developed for passive vapor intrusion barriers, and some degree of imperfection (e.g., punctures, incomplete seals at seams and edges) should be expected in virtually all applications. The potential for high concentrations of certain chemicals to adversely impact membrane or solvent seam integrity should also be considered.

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 not adequate

In addition to specifying reasonably adequate membrane thicknesses, passive barrier designs should include QA/QC plans that address the potential for damage to the membranes during installation, subsequent concrete pours, and building construction activities and protocols for minimizing such damage. Specifications should 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 (e.g., pressure tests, smoke tests,

post-construction indoor air tests). See ASTM Standard E 1643-98 (ASTM 1998) for more information regarding the use of water vapor barriers, although these standards may not be sufficient to address chemical vapor intrusion or associated low indoor air screening levels.

Passive barrier designs that rely on complete elimination of vapor intrusion are unlikely to succeed, for the reasons discussed above. If only low reductions in vapor intrusion rates are required, passive barriers may be sufficient; however, some method of measuring the performance of the passive barrier should be specified, and the design should allow for the addition of venting or other measures to address inadequate performance. In most cases, however, passive barriers without venting layers are not likely to be effective unless subsurface conditions are conducive to natural venting. For example, experience shows that in existing structures sealing alone reduces radon levels only 0%–50%, often due to some points of vapor entry that are obscured from view or have no access. Therefore, in most situations, at least passive venting should be combined with passive barriers, as discussed below.



Figure 4-1. Liquid Boot® being applied during construction. Courtesy LBI Technologies, Inc.

Estimated costs for flexible membranes range \$4–\$50/m² (about \$0.50–\$5/ft²) of building area. Less expensive (and thinner) materials are probably inadequate to be relied on alone as a passive barrier. Spray-on asphaltic emulsions (Figure 4-1) have been installed for \$21–\$32/m² (\$2–\$3/ft²). Price ranges vary based on several factors, including overall area to be covered, number of protrusions that require sealing, and the material used. The barrier thickness and QC measures likely necessary for a passive barrier design to succeed on its own (e.g., without venting) may well result in costs that exceed the ranges quoted above. On the other hand, when passive barriers simply augment other active systems (see below) and are not required to be 100% effective, costs may be closer to the lower end of these ranges.

4.3.1.2 Passive Venting

Passive 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. Therefore, passive venting is generally feasible in only new construction (see Table 4-3). Because passive venting relies, in part, on soil gas not entering the building before it can vent laterally, passive vents should be combined with passive barriers, as discussed above. Passive venting layers must be permeable enough to allow unimpeded lateral migration of soil gas. Sands or pea gravel (i.e., nonangular materials that will not damage the membrane) are generally preferred below liners. Nonwoven geotextiles with sufficient vapor transmissivity or geogrids may also function as passive venting materials; however, care must be taken to ensure that

concrete and fine-grained soils do not penetrate and block the pores of thin geosynthetic materials. Similarly, no venting media will function properly if saturated by water due to high groundwater tables or surface drainage problems (see Section 4.3.2.6). In addition to the venting layer, perforated collection pipes are typically routed at the periphery or through the venting media to collect soil gas and convey it to an exhaust point outside the building (Figure 4.2). Note that collection pipes are generally not required in the venting layer when active depressurization systems are installed. USEPA 1995 provides architectural drawings of passive venting systems for residential homes, including a drawing showing the additional components needed for activation of a passive system (i.e., the addition of a fan).



Figure 4-2. Passive sump mitigation system.

Courtesy Kansas Department of Health and Environment

Table 4-3. Passive venting pros and cons

Advantages	Disadvantages
<ul style="list-style-type: none"> • Often applied when vapor intrusion is possible but has not occurred • Can be modified to an active venting system if designed accordingly • More applicable to new than to existing buildings • Avoids the long-term operating and maintenance costs of active venting 	<ul style="list-style-type: none"> • Not as effective as active venting • Ambient temperatures and winds can adversely impact success • Not suitable for existing structures unless very modest concentration reductions are required • Upgrade to active venting likely to be necessary for new structures when large reductions in concentrations (e.g., greater than ~90%) are required)

Passive venting designs rely on natural diffusion or pressure gradients to cause soil gas to migrate to collection pipes and exhaust to the atmosphere. Advective flow due to pressure gradients is preferred over diffusion due to chemical gradients in passive venting systems because significant concentrations of soil gas will have to build up below the building before chemical gradients will result in lateral diffusion of soil gas. The elevated concentrations that drive lateral soil gas migration may also cause vertical migration into the building through any imperfections in the passive barrier (see Section 4.3.1.1). Advective flow will occur if the venting layer is depressurized with respect to ambient or atmospheric pressures outside the building and indoor air pressures.

Passive venting systems rely on natural thermal and wind effects to achieve a lower subslab air pressure relative to indoor and outdoor air pressures. For example, by routing the vent pipe through the heated space of the building, the natural thermal stack effect of the house may create enough suction to depressurize the venting layer and draw soil gas up the pipe. However, air may sink down through vent pipes in air-conditioned houses in the summer (a reverse-stack effect). Wind blowing over the tops of exhaust pipes may also create sufficient suction to depressurize

passive venting layers. However, air will not necessarily vent from a passive system at all times; hence the need for a sound passive barrier (see above) without significant leaks.

Passive venting systems generally result in less depressurization and lower air flow rates than active depressurization systems with fans (USEPA 1993b). 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, all things being equal. Even so, consistent depressurization of the venting layer should not be expected, and passive venting systems are unlikely to perform as well as active systems in most buildings (USEPA 1993b). In existing buildings, where installation of venting media and passive barriers is generally not practicable (except in crawl spaces), only moderate reductions in vapor intrusion concentrations (30%–70%) are expected (USEPA 1993b). Slightly better but still variable performance is reported for some new construction passive systems, with maximum reductions still no greater than 90% (USEPA 1993b).

It may be possible to rely on wind-driven ventilation to augment passive systems, particularly in areas where relatively sustained winds are common. In this case, wind-driven turbines are used to depressurize the pipe and venting layer.

Key Elements of Passive Venting Systems

- Generally not adequate 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

Some jurisdictions may not allow the use of passive barrier designs for vapor intrusion mitigation, preferring to go directly to active designs. However, for new construction sites, where vapor intrusion has only 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. In all cases, criteria should be developed, preferably in advance of construction, for determining when passive systems need to be upgraded to active (e.g., when subslab soil gas exceeds certain concentrations based on conservative, assumed attenuation factors). Smoke or tracer gas could also be injected into the passive venting layer while the building is depressurized through operation of building ventilation fans. The detection of smoke or tracer gas inside the building would then indicate the need for an active system.

Installed passive venting system costs for new structures range \$10–\$50/m² (about \$1–\$5/ft²), not including the cost of a passive barrier (see above). Most of the system cost is associated with the venting media material and installation; collection and riser pipes are generally a relatively small part of the overall cost. Some vendors have developed geosynthetic venting materials that can be applied in strips along foundation walls. In general, for roughly equivalent performance, passive venting systems cost more to install than active venting layers because passive systems rely more heavily on transmissivity of the venting layer and the integrity of the barrier layer to function. Nevertheless, when they perform adequately, passive venting systems lack the long-term operation and maintenance costs of active system fans.

4.3.1.3 Subslab (Active) Depressurization

Subslab depressurization (SSD) is widely considered the most practical vapor intrusion mitigation strategy for most existing and new structures, including those with basement slabs or slab-on-grade foundations (see USEPA 1993b). SSD systems function by creating a pressure differential across the slab that favors movement of indoor air down into the subsurface. This 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 (Figure 4-3). 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 it to the atmosphere. In existing structures, SSD systems entail the cutting of one or more holes in the existing slab, the removal of a quantity of soil from beneath the slab to create an open hole or “suction pit” (6–18 inch radius), and the placement of vertical suction pipes into the holes. These pipes are then manifolded together and connected to a fan, which draws soil gas from the subslab area through the piping and vents it outdoors.



Figure 4-3. Active subslab depressurization system.

Courtesy Kansas Department of Health and Environment

In new construction, permeable venting layers and passive barriers may be placed under the slab to increase the efficiency of the SSD system, essentially by extending the suction field and reducing the number of suction pits. However, venting layers and passive barriers do not have to be as robust for active SSD systems as they do for passive systems.

Active SSD systems are the most reliable, cost effective, and efficient technique for controlling vapor intrusion in the majority of cases, with concentration reductions in the 90%–99% range (USEPA 1993b) and 99.5% or greater in carefully designed and installed systems (Folkes 2002). Subslab depressurization in the range of 0.025–0.035 inches H₂O is generally sufficient to maintain downward pressure gradients (USEPA 1993b).

Experience has shown that one or two suction pits are adequate to depressurize typical residential homes unless tight or wet soils or unusual foundation conditions inhibit the propagation of the suction field (USEPA 1993b). The suction pit location is usually not critical, but the system may perform better when pits are located near the perimeter of the home, closer to the major air entry routes (construction joints and utility penetrations). In tight

Key Elements of SSD Systems

- Most widely applied and effective systems for vapor intrusion control
- Applicable to new and existing construction
- One or two suction pits adequate in most existing single-family homes
- Typically combined with venting layer and passive barrier in new construction
- Performance may be limited by low-permeability subsoils
- May be combined with drain tile or block wall depressurization

soils, more permeable backfill materials around the footings may also allow suction fields to extend further around the slab perimeter (USEPA 1993b).

When present, sumps and associated drain tile systems may also be depressurized. Interior (i.e., inside the foundation wall) drain tile systems can help distribute the suction field under the slab. Since most drain tiles are located near the foundation wall, depressurization of the drain tile should help control vapor entry at the joint between the foundation wall and slab. Depressurization of exterior drain tile systems may also control vapor intrusion around the slab perimeter but may be less effective toward the center of the slab (USEPA 1993b).

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 actual depressurization of the block wall (USEPA 1993b). Block wall depressurization is usually combined with subslab depressurization systems. However, because uniform depressurization of block walls can be difficult and, in some cases, cause basement depressurization and enhanced vapor intrusion (or back-drafting of fireplaces and combustion appliances) block wall depressurization is suggested only when subslab or drain tile depressurization prove inadequate to control intrusion (USEPA 1993b).

A number of factors must be considered when designing and installing SSDs to ensure the safe and effective performance of the systems (Table 4-4). It is beyond the scope and intent of this document to provide detailed design and construction standards. However, extensive guidance is available for the design, sizing, installation, and testing of SSDs for radon control in existing homes (USEPA 1993b, ASTM 2002b, MassDEP 1995), new residential construction (USEPA 1994a), and schools and other large buildings (USEPA 1994b). The general recommendations of these guidance documents should be followed for mitigation of vapor intrusion, with appropriate modifications for site-specific conditions and regulatory or building code permit requirements. While these guidance documents were developed specifically for radon control, experience at a number of chlorinated solvent sites has shown that SSDs can also effectively reduce VOC concentrations, achieving the relatively lower mitigation criteria currently in effect for these compounds (Folkes and Kurz 2002). SSDs should be designed and installed by qualified persons, typically consisting of environmental professionals and licensed radon contractors.

Table 4-4. Subslab depressurization pros and cons

Advantages	Disadvantages
<ul style="list-style-type: none"> • Successful track record of performance, 90%–99% reductions typical, 99.5% or greater reduction possible with well-designed systems • Adaptable technology, applicable to a wide variety of site conditions and geology • Simple gauges show whether the system is working 	<ul style="list-style-type: none"> • Requires periodic maintenance • Wet and low-permeability soils retard soil gas movement • Building-specific conditions may limit options for suction pit, riser pipe, and fan locations

Although the capital cost of this technology is a function of building size and condition, a reasonable estimate of installed capital costs for these units is \$10–\$50/m² (\$1–\$5/ft²). Material costs, especially for residences, are quite low and include little more than the cost of the fan,

pipng, strapping, and cement. Typical installed costs for SSDs in residential homes range about \$1000–\$2500, including electrical and mechanical permit fees.

Although the fans for houses are low wattage and rarely require separate electrical circuits, they are commonly installed by an electrician and usually require inspection before operation. Annual operation and maintenance costs for these systems are typically very low. Running a 90-watt fan typically costs less than \$100 per year, and most fans have an expected life span of 5–15 years, with a replacement cost of about \$100 plus labor.

Commercial/industrial systems may use larger, more expensive blowers, which consume more power, often requiring a separate 120 or 240 V AC circuit.

4.3.1.4 Submembrane Depressurization

Submembrane depressurization (SMD), where a membrane is used as a surrogate for a slab to allow depressurization of the soil, has been demonstrated to be the most effective mitigation method in crawl spaces (USEPA 1993b). Properly installed SMD systems have resulted in concentration reductions of up to 99.5%, similar to SSD systems (Folkes and Kurz 2002). An impermeable membrane covers the exposed dirt surface of a crawl space while the depressurization system withdraws soil gas from beneath the membrane and prevents its intrusion into the space above. Table 4-5 lists the pros and cons of this technology, and Figure 4-4 illustrates its application.

Table 4-5. Submembrane depressurization pros and cons

Advantages	Disadvantages
<ul style="list-style-type: none"> • Similar to SSD's • Applied in situations (e.g., crawl spaces) where SSD is not practicable • Can be combined with SSD 	<ul style="list-style-type: none"> • Similar to SSDs • Membranes can be easily damaged and must be sealed well at edges to prevent leaks • System needs to be periodically inspected to confirm leaks are not present



Figure 4-4. Crawl-space mitigation using submembrane depressurization. Courtesy Kansas Department of Health and Environment

The membrane must be sealed well 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 residents and technicians to access 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 important for SMDs.

When membranes are placed directly on low-permeability soils, it may be necessary to extend the soil gas extraction pipe to more than one point below the membrane using either a perforated intake pipe or a manifold system with multiple suction points (USEPA 1993b). Nonwoven geotextiles may also help extend the suction field of the system while protecting the membrane from angular objects in the soil. When the system is operating, the vacuum created by the mitigation fan should flatten the membrane against the ground. As for SSDs, USEPA guidance (1993b) for the design and installation of SMDs in crawl spaces is recommended.

Key Elements of SMD Systems

- Most widely applied and effective systems for crawl space homes
- Applicable to new and existing construction
- Suction field extension (e.g., perforated pipe) may be required for tight soils
- 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, and/or block wall systems

A variation of this technology involves placing the membrane over the crawl-space surface and using a fan to gently withdraw the air within the space above (crawl-space depressurization). These systems, while presumably effective in venting portions of the crawl space, tend to be less effective than SMD systems at preventing vapor intrusion since subsurface soil gas is not actually removed. Crawl-space depressurization also typically results in higher heating and air conditioning costs. Natural crawl-space ventilation may be an option in warm climates but may result in higher heating costs and problems with freezing pipes in colder climates. The performance of natural crawl-space ventilation is variable, however, and typically does not result in more than 50% reduction in vapor intrusion (USEPA 1993b).

Costs for SMD systems are generally consistent with those of passive barriers and SSD: \$10–\$50/m² (\$1–\$5/ft²). Typical costs for installation of SMDs in residential homes range about \$1000–\$2500. Annual operating and maintenance costs for these systems are similar to those for SSD, though post-mitigation monitoring, inspection, and repair costs may be higher.

4.3.1.5 Subslab Pressurization

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. The intention is to increase the subslab air pressure above ambient levels, forcing soil gas from the subsurface to the sides of the building. USEPA 1993b 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 (Table 4-6).

Table 4-6. Subslab pressurization pros and cons

Advantages	Disadvantages
<ul style="list-style-type: none"> • Does not require soil gas to be collected within structure • May be more efficient than SSD in highly permeable soils 	<ul style="list-style-type: none"> • More energy-intensive than SSD • Cracks or slab openings may result in short-circuiting, leading to vapors inside structure • May not be appropriate for tight soils

Cracks or openings in the slab or foundation walls could cause short-circuiting of the system so that air forced below the slab reenters the building, potentially pulling in some of the vapors that the system intended to keep out. Since 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 (EPA 1993b) have observed that small pits at the discharge end of the vent system have improved performance of SSP systems; however, this represents yet another design challenge associated with implementing this technology at an existing structure.

Key Elements of SSP Systems

- Generally less effective than SSD systems
- May be appropriate in high-permeability subsoils
- Higher energy costs than SSD systems

Limited cost information is available for SSP systems, but costs are expected to be similar to those for SSD systems: \$10–\$50/m² (\$1–\$5/ft²). Energy costs of a SSP systems are typically higher than those of SSD systems.

4.3.1.6 Building Pressurization/HVAC Optimization

In some instances, it may be advantageous to positively pressurize the building interior (relative to the subslab), thereby preventing vapor intrusion (Table 4-7). This effect is typically achieved through mechanical means and is frequently employed at commercial buildings with “clean rooms” where no amount of outside air (or vapor intrusion) is acceptable. It may be possible to tune the building’s existing HVAC system to achieve this positive pressurization, or a new system can be installed. Typically, only small increases in building pressure (e.g., <0.001 inches H₂O) are required to prevent vapor intrusion (EPA 1994b). Building pressurization is applicable to both existing and new buildings, although it may be easier to achieve and more cost-effective in new buildings.

Table 4-7. Building pressurization pros and cons

Advantages	Disadvantages
<ul style="list-style-type: none"> • Can be applied equally well to both new and existing structures • May be the most effective technology at preventing vapor intrusion 	<ul style="list-style-type: none"> • Generally more costly than other techniques • Regular maintenance and air balancing needed to maintain consistent, positive pressure • Not commonly an option for single-family residences

Positive pressurization of buildings is usually practicable only when the building is relatively tight, i.e., when there are few doors or other openings. Therefore, warehouses with large bay doors are not good candidates for positive pressurization. On the other hand, well-ventilated buildings are less likely to have vapor intrusion problems. Typically, only the lower floor of the building will require positive pressurization, although this will be a benefit only if airflow between floors is limited.

This technology is effective if regular maintenance and air balancing of the system is undertaken. Appropriate pressure tests and monitoring should be incorporated in the design of HVAC remedies for vapor intrusion to ensure that sufficient positive pressures are maintained throughout the areas of the building that could be subject to vapor intrusion.

The HVAC systems of many buildings operate during normal working hours and are shut off during the night and on weekends. In these cases, vapor intrusion could occur while the systems are off, contaminating indoor air. The degree of impact on indoor air quality during this time and the length of time the impact persists after the HVAC system is restarted must therefore be evaluated in determining the measure's effectiveness. Further, care should be taken to ensure that soil gas is not simply deflected to adjacent, unprotected areas (e.g., into a strip mall or multiunit commercial facility).

Key Elements of Building Pressurization

- Generally practicable only in commercial buildings
- Requires relatively "tight" buildings to limit airflow 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

Typically applied to large commercial structures, building pressurization may be the most cost-effective method of vapor intrusion mitigation if the HVAC system already creates positive pressures. In other cases, positive HVAC pressures can be achieved with minor adjustments to existing systems, resulting in small or negligible capital costs but potentially increasing energy costs. The increased energy costs associated with positive HVAC system operation will be building-specific, depending on the additional airflow required to achieve positive pressures and heating and/or air conditioning requirements, but could exceed \$1/ft² annually. Computer-controlled systems may minimize increased energy costs by limiting the amount of airflow to that needed to maintain positive pressures.

Some new building HVAC systems range in cost \$100K–\$500K or more, depending on the size and complexity of the structure. Moreover, newer building designs are "tighter" and can be more cost-effectively modified than older structures.

4.3.1.7 Indoor Air Treatment

As an alternative to other forms of vapor intrusion mitigation, air within the structure can also be directed to air pollution control equipment (e.g., carbon adsorption systems) to remove toxic air contaminants from the building interior. This technique is not widely practiced since it encourages the collection of contaminant vapors within the structure and is dependent on the treatment system's uninterrupted performance to protect receptors (Table 4-8). However, it can be an effective mitigation strategy when combined with other techniques to control vapor concentrations in problem rooms. Indoor air treatment is an alternative to whole-building pressurization (see above) when subsurface depressurization and/or pressurization methods are not feasible (e.g., high water tables and wet soils). Indoor air treatment is generally only applied in existing buildings, since more cost-effective systems can generally be installed in new buildings.

Table 4-8 Indoor air treatment pros and cons

Advantages	Disadvantages
<ul style="list-style-type: none"> • Results in the physical removal and disposal of the air contaminant, not simple redirection • Less susceptible to malfunction or leaks than most other technologies 	<ul style="list-style-type: none"> • Less effective than other control methods (when applicable) • 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 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 (e.g., SSD) rather than treating the indoor air of a structure. This advantage is associated with the smaller volumetric rate of air that would require treatment with SSD than if the entire indoor space required treatment.

Indoor air treatment is expensive compared to other mitigation strategies. It requires large amounts of energy and/or may present waste disposal concerns. Capital costs in the range of \$20K and annual operating expenses of \$15K–\$20K are not uncommon (ITRC 2003). Operation and maintenance costs for these systems vary by type of equipment but can easily approach \$15K–\$30K or more, annually.

Key Elements of Indoor Air Treatment

- Less effective than other vapor intrusion control methods
- Expensive to install, operate, and maintain
- Typically generates waste (e.g., spent carbon)

4.3.2 Factors Affecting Building Control Technology Selection

As discussed below, a number of factors may affect technology selection for vapor intrusion mitigation of buildings, including building type and use, foundation type, subsurface conditions, the COCs, and the degree of reduction required.

4.3.2.1 New Versus Existing Buildings

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 will be case-specific and should be critically evaluated during system design and verified during post-mitigation diagnostic testing (see Section 4.3.3.4). 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/or 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 (commercial buildings), and outside air supply for gas furnaces and water heaters. Some of these items can be retrofitted into existing buildings. Finally, new buildings can incorporate suction points, collection and riser pipes, and other features into the design, allowing optimal location of systems without the aesthetic problems often encountered with existing buildings.

Therefore, if possible, mitigation should occur at the time that the building is constructed, rather than retrofitted after it is constructed. Such decisions may confront property owners wishing to develop property where contaminated shallow groundwater or soils pose a potential threat to indoor air quality via vapor intrusion. While the owner may choose to wait and test indoor air after the building is constructed, hoping that no mitigation will be needed, it is generally preferable for the owner and responsible parties to agree in advance on building modifications during the design phase. Costs for the mitigation can then be minimized, and it can be better integrated with other building features.

4.3.2.2 *Building Size*

The building size may have some effect on technology selection and system design, though 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 vapor intrusion due to the 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 those of residential homes. So when deciding what type of mitigation is best for the building of concern, thought must also be given to which portions of the building the system must effectively mitigate.

Radon mitigation experience suggests that buildings up to 50,000 ft² can be mitigated by SSDs with one suction point, provided that subslab materials are permeable and the suction field is not short-circuited by cracks or other penetrations through the slab (USEPA 1993b). However, in most cases such a large building would likely require multiple SSD suction points and either multiple in-line fans or one larger blower. Multiple suction points can be connected to one large 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 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.

4.3.2.3 Building Use

Current and likely future building use should be considered when selecting mitigation technologies. Reliance on positive HVAC pressures is more suitable for commercial and industrial buildings than for residential homes because commercial HVAC systems are more readily adapted to provide continuous positive pressures and are more likely to receive routine maintenance and monitoring to ensure that positive pressures are maintained. Buildings that are occupied only for short periods or during working hours may not require the same degree of reduction, depending on the assumptions used to develop risk-based indoor air screening levels, if applicable. Building use may affect how and where mitigation piping is routed. Piping arising from the middle of warehouse areas may be in the way of operations and be at risk from damage caused by forklift or other vehicle traffic. Institutional controls—supplemental to a mitigation system or as the mitigation itself (such as building occupancy or use restrictions)—may also be feasible in commercial and industrial buildings, as long as these also ensure that any change in use will trigger a reevaluation of mitigation requirements.

4.3.2.4 Foundation Type and Condition

Foundation types include basements, crawl spaces, slabs on grade, and any number of combinations of these basic types. Foundation type affects design of only those 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. Many buildings require both SSD and SMD systems, which can often be connected to the same fan.

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 vapor intrusion 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 vapor intrusion unless properly sealed to prevent entry of both soil gas and groundwater containing VOCs. Elevator operations might enhance building depressurization and increase the rate of vapor entry into the building. Elevator shafts and other vertical conduits might also increase the movement of 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, 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 not sealed at the top of the wall. Mitigation strategies for such conditions include installation of suction points and depressurizing 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. Typically, these must be covered by membranes or walled off to enable 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 enable depressurization.

In some cases, crawl-space areas are not accessible for installation of SMDs (Section 4.3.1.4). 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 concern), installation of horizontal soil gas extraction pipes below the crawl space, and positive pressurization of the crawl space to inhibit vapor entry.

4.3.2.5 Soil Conditions

Foundation soil conditions may affect the design of depressurization systems. In the absence of a permeable venting layer below the slab, low-permeability soils 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 2002).

Depressurization systems are generally very 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 is discussed in USEPA 1993b 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 building(s) of concern. In very permeable soils where depressurization is difficult, subslab pressurization (where 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) may be more effective (see Section 4.3.1.5 and USEPA 1993b).

4.3.2.6 High Water Table Conditions

Saturated soils may prevent effective depressurization of the subslab region by filling soil pores and making them unavailable for vapor transport. Soils beneath the building can become saturated due to various conditions and may stay wet for relatively long periods. In these situations, it may be necessary to first solve the water problem before addressing vapor mitigation. If the wet conditions are due to a high groundwater table containing volatile COCs, actions directed to keeping the water away from the building must take precedence over intrusion concerns associated with subsurface soil gas.

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 vapor intrusion (see Section 4.3.1.3). If French drain systems are retrofitted in existing structures, the drain pipes should be sufficiently large to drain the water and still leave a headspace for depressurization.

If high water table conditions are episodic, risk assessments may indicate that occasional loss of vapor intrusion control (due to loss of depressurization) does not result in a significant increase in long-term risk. Alternatively, the SSD system could be augmented by a fan that either ventilates or pressurizes the basement with outside air whenever the sump pump switches on, provided that flooding only occurs during warmer weather.

If dewatering is not practicable, then basement and/or crawl-space pressurization may be the most cost-effective method of vapor intrusion control. However, if water is actually entering the basement or crawl space, pressurization will not prevent direct partitioning of volatile compounds into the basement or crawl-space air, which would then flow into other parts of the building. In these cases, it may be necessary to depressurize the basement or crawl space, although energy costs due to heat loss may be high. In some cases, it may be possible to install a false floor above a slab or earth floor and create a thin venting layer that could be depressurized.

Finally, high water table conditions may be due to “clean water” that is infiltrating the ground after precipitation events. In this case, the water below the floor slab may actually provide a clean water lens that prevents or minimizes vapor intrusion into the building. Therefore, the SSD would need to operate during only low water table periods, when depressurization would be feasible.

4.3.2.7 Chemicals of Concern

The COCs may affect mitigation system design in at least three ways. First, potentially combustible vapors (i.e., those 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, COC action levels, if any, will 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 1993b). 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/or increased numbers of suction points and fans may be required for higher reductions (Folkes and Kurz 2002).

4.3.3 Design 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.

4.3.3.1 Design Approach

Design of vapor intrusion controls for new buildings should consider all of the factors discussed in the previous section. Vapor intrusion 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 vapor intrusion. 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. Vapor intrusion control designs should include system layout drawings, minimum material specifications, installation procedures, construction QC procedures, and post-installation testing procedures.

Design of vapor intrusion 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 is likely the only step required before installation (USEPA 1993b, Folkes 2002). However, for larger commercial buildings, or if subsurface or building characteristics indicate that an SSD system may not work well, premitigation diagnostic testing may be required (see Section 4.3.3.3).

For most existing residential homes, it is usually sufficient to install a relatively standard system without building-specific designs or premitigation diagnostic tests, relying on the mitigation contractor's experience in the area (USEPA 1993b). While this "standard design" approach allows systems to be installed more quickly (which may be important at larger sites with a number of homes requiring mitigation), some form of post-mitigation 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 2002).

For larger, more complex buildings or when visual inspections indicate SSD systems may not function well, detailed diagnostic tests prior to mitigation and prepare building-specific designs may be appropriate. Commercial building owners may provide access only 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 to apply for preinstallation permits and/or to provide the public opportunity for preimplementation review and comment.

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. Table 4-9 summarizes the advantages and disadvantages of each approach.

Table 4-9. Mitigation design approach considerations

Approach	Advantages	Disadvantages
Detailed diagnostic testing and design followed by installation and testing	<ul style="list-style-type: none"> • Post-installation adjustments less likely to be required • May be more effective for unique building types or unusual conditions • May be more effective when a high degree of reduction (e.g., >95%) is required • May be required if multiple reviewers/stakeholders must agree on design specifics 	<ul style="list-style-type: none"> • Higher initial design and testing costs • More site visits required for design and initial installation • Likely to be more expensive for multiple residential mitigations (it takes longer 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	<ul style="list-style-type: none"> • Lower initial design and installation costs • Fewer visits required to install system, less disruption to occupants • A larger number of systems can be installed per time period (although some may require adjustments) • Standard design can be adjusted over life of project based on performance of first group of systems • Most appropriate for homes and when mitigators (and regulatory reviewers) have prior experience with similar homes in the same area 	<ul style="list-style-type: none"> • 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 post-mitigation tests may be necessary to demonstrate adjusted systems working adequately

4.3.3.2 Owner/Tenant Preferences

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 mitigated building must live (or work) with that system, and its owner will want to maintain its investment value, regardless of how many pipes, fans, and holes in the floor are deemed necessary by others. What the tenant and owner prefer, then, in terms of mitigation design features, should be taken into account as they would in any radon mitigation installation. Owners/tenants will often have strong opinions about where fans and piping are located, what level of fan noise is acceptable, how readable different system-operation gauges and meters are, and what quality of construction craftsmanship is satisfactory. If the mitigation contractor is considering an attic location for a fan, owners and tenants will need to be questioned about the current and near-future use of that space. When there are multiple mitigation options (for example, at a large commercial building where the mitigation could be based on SSD or could, alternatively, be an adjustment to the HVAC system to pressurize the building) the responsible party should fairly present the options to the building owner and tenant, explaining the advantages and disadvantages associated with each and describing why the preferred alternative should be the option installed.

4.3.3.3 *Premitigation Diagnostic Tests*

When necessary, premitigation 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. They 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 shop vacuum or a portable radon fan) and observing the movement of smoke downward into construction joints and/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 premitigation diagnostic testing necessary prior to design and installation of SSD systems (USEPA 1993b).

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/or 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 a large number of mitigation systems need to 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 4.3.3.4).

4.3.3.4 *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 two (MassDEP 2002) to long-term indoor air testing programs (CDPHE 2004). When only two post-mitigation 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 30–45 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).

In some cases, no indoor air testing is required, and post-mitigation suction field testing is considered sufficient to demonstrate SSD performance, assuming downward pressure gradients are measured or observed at all points over the slab. Post-mitigation suction field extension testing can be conducted immediately after system installation or after a short period of

operation. In cases of widespread contamination in the state of New York, indoor testing of a representative number of buildings may be considered (NYSDOH 2006).

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 2002), including the following:

- improved 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 addition fans
- increasing fan size

4.3.3.5 Access and Scheduling

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 will often want to schedule tests before or after work. To address these concerns, it is highly advisable that an access agreement between the property owner and the investigating/mitigating entity be executed.

4.3.3.6 Lead-Based Paint/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 speaking, 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 impact the overall project schedule. Fortunately, most SSD systems are installed in basements and crawl spaces and, whenever possible, in unfinished portions of the house, limiting the potential for disturbing lead paint or materials containing asbestos.

4.3.3.7 HVAC Issues

When one or more ventilation techniques are used to address vapor intrusion, these systems affect the overall balance of air flow within the structure. If the ventilation equipment and combustion devices within a structure (e.g., furnaces, wood stoves, clothes dryers, and water heaters) are not properly balanced, 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 (e.g., SSD). If back-drafting is occurring, it should be corrected prior to installation to avoid safety hazards.

Most residential mitigations utilizing pressurization and/or 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 licensed radon contractors familiar with the potential for back-drafting. Although not currently required of radon contractors, USEPA has *recommended* (USEPA 1993b) that the following procedures be undertaken to investigate the possibility of back-drafting:

- Close all windows and doors, both internal and external.
- Open all HVAC supply and return air duct vents/registers.
- Close fireplace and wood stove dampers.
- Turn on all exhaust and air distribution fans and combustion appliances except the appliance being tested for back-drafting.
- Wait five minutes.
- Test to determine the indoor/outdoor pressure differential in the room where the appliance being tested is located. If the pressure differential is -5 pascals or more, assume that a potential for back-drafting exists.
- To begin a test for actual entrainment of flue gases, turn on the appliance being tested. If the appliance is a forced-air furnace, ensure that the blower starts to run before proceeding.
- Wait five minutes.
- Using either a smoke tube or a carbon dioxide gas analyzer, check for flue gas entrainment near the vent hood.
- Repeat the last six steps for each natural draft appliance being tested for back-drafting. Extreme or unusual weather conditions need to be considered when evaluating these data.

Although cold (outside) air supply vents for gas furnaces or water heaters are typically required by building codes in newer homes, older homes may not have them, resulting in greater negative pressures when furnaces turn on and greater potential for both back-drafting and vapor intrusion. In some cases, providing cold air vents alone may mitigate very minor vapor intrusion problems and in all cases should enhance the performance of SSD systems.

4.4 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. The plan should

identify what must be done following start-up of the system, as well as a schedule for conducting these activities. If a large number of systems are installed (e.g., a multihome vapor intrusion site), a standard OM&M plan could be prepared to cover all of the systems, with house-specific drawings and details contained in an appendix.

Indoor air testing is often part of a long-term performance monitoring program, although long-term indoor air monitoring may not be warranted for every system installed. Once proper operation of the system has been confirmed by physical tests and/or post-mitigation indoor air testing (see Section 4.3.3.4), indoor air testing may be warranted only in instances where the system design was complex or the construction problematic. In situations where premitigation levels were very high, however, more frequent monitoring may be necessary. Long-term indoor air testing could also be considered for a portion (e.g., 10%) of systems as QA check on installation. If, during inspections, the inspector believes that the building foundation or components of the mitigation 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.

Mitigation systems should be inspected periodically. Maintenance should include a visual inspection to confirm the integrity of the system and (by checking manometer readings) that original suction levels are being maintained. Crawl-space membranes should look as if they are being sucked down against the soil, particularly close to suction points. Suction field extension testing may be warranted if manometer readings indicate reduced suction levels or indoor air tests show increasing trends. SSD system fans generally do not require routine maintenance; however, fans should be replaced as necessary throughout the operating life of the system. Noisy fans typically indicate problems with ball bearings and should be replaced. Routine inspections should also include an evaluation of any significant changes made to the building (e.g., remodeled basement, new floor penetrations, new furnace) that would impact the design of the mitigation system or the environment in which it is operated.

The need for air permits and/or exhaust gas controls for SSDs and SMDs should be determined on a site-by-site basis, in compliance with applicable state or local air quality control regulations. In certain cases, particularly those that involve large numbers of structures requiring mitigation within a certain area or those where the mitigation creates high vapor flux rates, it is possible that redirection of soil gases from beneath the building to the ambient air may result in unacceptably high cumulative air quality impacts at receptor points within the community. In such cases, therefore, it may be necessary to apply emission controls on mitigation systems to reduce the concentrations of VOCs being discharged to the atmosphere. Generally, when there appears to be the potential for unacceptable ambient air impacts, a dispersion modeling analysis of the emissions point(s) may be used to estimate whether resulting ambient air quality impacts exceed applicable state toxic thresholds or other health-based standards. Finally, in rare instances, a community ambient air monitoring network may be established to demonstrate that the local population is not being exposed to unacceptable levels of air contaminants resulting from the vapor intrusion mitigation processes. Evaluation of the issue to date in New York has indicated that a requirement for vapor phase controls on these systems is unnecessary, but ambient air studies are ongoing to confirm this conclusion.

4.5. Closure

At most sites, long-term cleanup efforts will eventually reduce volatile compound concentrations in soil or groundwater to levels that no longer result in vapor intrusion impacts requiring mitigation. At this point, vapor mitigation systems could be turned off and/or removed, depending on the preferences of the building owners and obligations of responsible parties. Likewise, institutional controls could presumably be retired. This is what is meant by “closure” in the following paragraphs. For the most part this section refers to active, not passive, systems used to prevent vapor intrusion, although passive system piping could be removed if accessible. Unless there is something to “turn off” and/or take away, the concept of closure is primarily an administrative one.

Regulatory personnel and responsible parties should consider early on in the project how to determine when vapor mitigation is no longer required, as this will affect the type of data that will need 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 could be the same as those used to identify vapor intrusion impacts; however, a smaller number of confirmation tests might be justified by an improved understanding of site conditions. In any case, the decision to no longer require vapor mitigation in a building will likely be based first on groundwater, soil, and/or soil gas concentrations, which may indicate that the vapor source has been effectively eliminated. However, just as it is difficult to predict vapor intrusion impacts in any particular building based only on media concentrations, it may also be difficult to predict when subsurface media concentrations have become sufficiently low to curtail vapor intrusion mitigation.

Therefore, responsible parties may wish to develop correlations between subsurface media and indoor air concentrations early on in the project to use as a tool for deciding when to commence closure evaluations, if consistent with applicable regulatory requirements. As long as some form of confirmation testing is eventually conducted to determine whether closure is appropriate, the decision to begin such testing could be based on a conservative but not extreme correlation values. For example, if correlation data indicated that a certain percentage of the homes at a site were not unacceptably impacted by vapor intrusion when groundwater or soil gas concentrations were below a certain level, it might be cost-effective to commence confirmation tests at this level, with the expectation that the same percentage of the time confirmatory results would indicate that continued system operation was no longer necessary to mitigate vapor intrusion. The selection of the media concentration that triggers closure (confirmation) testing is largely a matter of economics and site-specific considerations. The length of time that the media must remain below these levels will also be site-specific decision, based on judgments of whether the media has been permanently remediated and how many environmental measurements over time are needed to demonstrate this condition. Of course, if there is good documentation that the source of the contaminated vapors has been completely cleaned up (e.g., excavation of soils to below detection or conservative vapor intrusion-based screening levels), then no or limited confirmation testing may be warranted. Although the time required for soil gas fluxes to diminish after source removal vary site to site, evaluations by Johnson et al. (2002) indicate that

soil gas concentrations (and, therefore, indoor air concentrations due to vapor intrusion) are likely to decrease in a relatively short period of time.

Mitigation systems must be shut down before confirmation tests can be conducted. Indoor air testing of mitigated buildings while the system is in operation cannot 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 recommended only if the lines of evidence indicate that short-term exposures to conservatively estimated indoor air concentrations (from vapor intrusion) are not likely to result in unacceptable health impacts and if this approach is acceptable to the building occupants and owners.

Alternatively, subslab soil gas samples could 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. However, this approach requires estimation of the slab attenuation factor, as discussed in Appendix D. In some cases, comparison of soil gas profiles with baseline data may also indicate that vapor intrusion is no longer occurring. In the absence of indoor air measurements, however, subslab and soil gas to indoor air attenuation are commonly conservatively estimated. As a result indoor air concentrations and the potential for vapor intrusion based on soil gas and subslab soil gas data may be overestimated.

SSD system exhaust gases or subslab soil gas may be measured while the mitigation system is operating. However, at this point there is little if any information available indicating how well these measurements compare to subslab concentrations when the system is turned off. For example, system exhaust gases may include ambient air from outside the foundation wall, which could dilute the COC concentrations in the system exhaust stream. Subslab soil gas concentrations may be different while the system is operating due to the more rapid movement of the soil gas through the soil. Therefore, investigators may wish to develop data allowing correlations between exhaust gases and indoor air and/or subslab concentrations during the initial investigation and operation and monitoring phases of a site, to provide another potential line of evidence for closure evaluations.

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 testing only 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 and there is 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, then closure decisions for the entire area may 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 vapor intrusion due to 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. However, the responsible party that originally installed

and operated the vapor mitigation system would probably not be held responsible for the system under the applicable regulatory program once controls were no longer required.

4.6 Other Issues

In the case of undeveloped or redeveloped property, new construction presents an opportunity to deal with one of the more vexing VI problems: mitigating subsurface conduits that may become migration routes for soil gas. For example, sewer, water, underground cable and electrical lines are often placed on porous gravel or soil to maintain good drainage. Yet this practice also fosters inadvertent vapor transport requiring construction provisions that contain barriers to vapor transport, either through the design of the conduit or the use of nonporous materials. Currently, the National Aeronautics and Space Administration (NASA) requires this for new construction at the NASA Research Park, located at Moffett Field in California.

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APPENDIX A

Community Stakeholder Concerns

COMMUNITY STAKEHOLDER CONCERNS

This appendix was written by stakeholders who represent communities affected by vapor intrusion to give investigators an understanding of the issues building occupants may be concerned with regarding vapor intrusion.

As stated in the text, when communities become aware of vapor intrusion, many concerns are raised involving not only a person's own residence, intrusive sampling, and remedies, but also the air that their children breathe while playing out of doors and at school and secondarily the retention of property values and a clean and healthy environment. At many sites, these issues become "hot button" issues, driving the discussion and sometimes the strategy that regulators will take in addressing vapor intrusion.

Based on discussions and experience of community stakeholders at various sites and the experience of stakeholder team members, the following is a brief description of major concerns that communities, property owners and others have voiced. It should be noted, however, that this list of concerns is not exhaustive. As this issue continues to develop, other issues will undoubtedly arise. It should also be noted that many of the issues below are touched on in the preceding text. However, we believe that it is important to articulate these concerns, as they would be presented from a community's point of view.

- **It is important to develop a complete CSM.** Communities want the CSM to consider all sources, receptors, and migration routes. Often, the conceptual model is restricted because the regulating agency has authority to address only some of the sources and/or migration routes. This problem requires state agencies to work together with city and county health departments, as well as with air quality management districts.
- **The quality of outdoor air is important to consider in the conceptual model and in remedy selection.** Some agencies limit their definitions of vapor intrusion to indoor exposure. To many communities, outdoor contamination through subsurface volatilization or direct discharge into the air is part of the same problem. Most guidance addresses vapors intruding into indoor spaces. Yet children spend long periods of their day in backyards, school yards, and playgrounds. This is an important consideration for communities and should be given attention at many sites. Residents also want to minimize discharges from building ventilation systems and groundwater treatment systems.
- **Communities want health-conservative analysis and standards.** Potentially impacted residents want vapor intrusion investigations and remedies to err on the side of caution. Residents want investigations to use very low screening levels and even to require mitigation and response based on the most stringent standards.
- **Cumulative and synergistic risk from multiple contaminants should be considered.** Often, more than one contaminant is the subject of vapor intrusion. Communities are concerned that the cumulative and synergistic effects of these combinations are not well understood or addressed. When it is not possible to understand or estimate these effects, risk assessment procedures should err on the side of caution.

- **Understanding transformation products and the half-lives of contaminants is often not considered in decision making.** Communities are concerned there is not enough care paid to the transformation products and the half-lives of various contaminants. For example, volatile organic compounds are transformed in groundwater and soil. Likewise, as vapors are exposed to the atmosphere, they are also converted. It is important to fully understand the half-lives of the various contaminants that are in the air, as well as considering all of the transformation products.
- **Screening programs and modeling tools are often suspect.** Initial site screening programs that eliminate sites on the basis of modeling and attenuation factors are not well understood by communities and should be used together with site-specific information. Communities are suspicious of the most common model used (J&E) as it sometimes misses the problem, either from improper use or due to shortcomings in the model. For example, there have been reports that the J&E model does not account for lateral transport of soil gas or directly consider preferential pathways. If the issue of vapor intrusion is raised, site-specific information is often required to allay a community's concerns, regardless of the models used by regulators. In addition, soil gas and groundwater plumes should be fully characterized prior to eliminating sites. There have been instances where the plume definition data indicate that no vapor intrusion could be present (assuming standard attenuation factors and vapor modeling), yet samples taken inside of residences indicate that vapor intrusion has occurred. History has reinforced many communities' distrust of models, and many want direct measurements taken.
- **Indoor air sampling is often desired by communities before a site can be eliminated.** Communities generally question findings of acceptable risk based solely on models. There has been sufficient evidence that indoor air concentrations are sometimes substantially above modeled levels. Recognizing that it would be impossible to test the air of every residence, communities that have any sign of vapor intrusion will often demand that indoor air sampling be done. Some occupants are willing to put up with the inconvenience of sampling, as well as a survey of chemicals within their homes. Indoor air samples should also include those buildings occupied by the most vulnerable among us, including day care centers and schools. Often, communities are asking that every room be sampled because of extreme variations in results due to vapor migration routes.
- **Sampling and analysis procedures should be done as quickly as possible and should follow proper procedures.** Near-real-time or real-time sampling techniques (e.g., trace atmospheric gas analyzer) that help identify sources and migration routes are preferred by community stakeholders. Stakeholders often want to know the results of any tests involving their homes as soon as possible. It's also important that good and consistent practices be followed when conducting indoor air sampling. Sometimes windows have been left open or heating systems turned off when conducting indoor air sampling, both of which cause improper readings.
- **Accelerated remediation is often the best long-term solution for vapor intrusion problems.** In most cases where vapor intrusion is caused by groundwater and soil contamination that is being actively remediated, the long-term solution to vapor intrusion is

to accelerate cleanup. At sites where subslab membranes or soil gas ventilation systems are in place to prevent indoor vapor intrusion, residents do not think of these methods as a long-term solution. Settling, earthquakes, power outages, aging, and new construction at existing buildings are barriers for these mitigation techniques. As long as there is potential exposure, health is at risk. The best way to ensure that subsurface contamination does not enter homes or other structures is to remove and/or destroy the toxic compounds. Historically, this process has been slow and difficult, but vapor intrusion sites are ideal candidates for the deployment of innovative remedial technologies.

- **Monitoring, backed by institutional controls and contingency plans, is needed to reinforce both passive and active mitigation.** In all cases where there is vapor intrusion, mitigation techniques (barriers, venting, etc.) should include a long-term monitoring plan and a contingency plan. Monitoring should be supported by institutional controls until such time that it can be shown that vapor intrusion is no longer a threat. Furthermore, the costs of such long-term management activities over the life of the contamination should be weighed against permanent treatment or removal costs (i.e., accelerated cleanup) in the selection of remedies. If in new development, consideration should be given to requiring some type of financial assurance, such as a security bond.
- **New development on sites with vapor intrusion potential should be carefully regulated.** Vapor intrusion hazards should be identified and addressed before new construction occurs. At a number of sites, new development is being proposed where vapor intrusion is likely, even in areas with ongoing vapor intrusion investigation and mitigation efforts. Regulatory agencies should work with cities and other local planning jurisdictions to screen development sites for potential vapor intrusion, ensure maximum cleanup before construction, alter building design to minimize risk, and require the installation of reliable mitigation before the fact. Potential residents should be notified of possible risks. Where necessary, notification requirements should be enforced by institutional controls. A proactive strategy toward property reuse at contaminated sites should cut down on the litigation that typically occurs once the news about vapor intrusion rises to the surface.

Where sites have the *potential* for vapor intrusion, prophylactic measures such as requiring passive barrier systems that can be monitored and actively vented if post-construction monitoring shows the need. This “precautionary” approach would increase costs somewhat, but less than the costs of investigation and remediation. The precautionary approach also reduces downstream human health and litigation (and therefore financial) risk. Cities and developers may also take proactive measures such as ensuring that sewer and utility conduits are built to avoid typical vapor migration.

- **Retaining property values is an important component of public outreach and remedy selection.** It is apparent that many community members regard first reports of vapor intrusion as an insult not so much to their health as to their pocketbooks. It is crucial that this component of a potential vapor intrusion problem not be overlooked.

APPENDIX B

Conceptual Site Model Checklist



CONCEPTUAL SITE MODEL CHECKLIST

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

Utilities and Process Piping

- ☐ Locate and map out all underground utilities near the soil or groundwater impacts. Pay particular attention to utilities that connect impacted areas to occupied buildings.
- ☐ Locate and map out all underground process piping near the soil or groundwater impacts.

Buildings (Receptors)

- ☐ Locate and map out existing and potential future buildings.
- ☐ Identify the occupancy and use of the buildings (e.g., residential, commercial). You may need to interview occupants to obtain this information.
- ☐ Describe the construction of the building including materials (e.g., wood frame, block), openings (e.g., windows, doors), and height (e.g., one story, two story, multistory). Determine whether there is an elevator shaft in the building.
- ☐ Describe the foundation construction:
 - Type (e.g., basement, crawl space, slab on grade)
 - Floor construction (e.g., concrete, dirt)
 - Depth below grade
- ☐ Describe the HVAC system in the building:
 - Type (e.g., forced air, radiant)
 - Equipment location (e.g., basement, crawl space, utility closet, attic, roof)
 - Source of return air (e.g., inside air, outside air, combination)
 - System design considerations relating to indoor air pressure (e.g., 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 (e.g., for methane) or moisture barriers below foundations.

Source Area

- ☐ Locate and map out the source area for the vapor-phase contaminants related to the subsurface vapor intrusion pathway.
- ☐ Describe the presence, distribution, and composition of any NAPL at the site.
- ☐ Identify the vapor-phase contaminants that are to be considered for the subsurface vapor intrusion pathway.
- ☐ Describe the status and results for the delineation of contamination in environmental media, specifically soil and groundwater, between the source area and the potential impacted buildings.
- ☐ Describe the environmental media (e.g., soil, groundwater, both) containing contaminants.
- ☐ Describe the depth to source area.
- ☐ Describe the potential migration characteristics (e.g., stable, increasing, decreasing) for the distribution of contaminants.

Geology/Hydrogeology

- ☐ Review all boring logs, monitoring well construction, and soil sampling data to understand the following:
 - Heterogeneity/homogeneity of soils and the lithologic units encountered and the expected/observed contaminant migration:
 - Depth and lateral continuity of any confining units that may impede contaminant migration
 - Depth and lateral continuity of any highly transmissive units that may enhance contaminant migration
 - Depth of vadose (unsaturated) zone, capillary fringe, and 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 of any perched aquifers.
- Note where the water table intersects the well screen interval or the presence of submerged screen.
- ☐ Describe distinct strata (soil type and moisture content, e.g., moist, wet, dry) and the depth intervals between the vapor source and ground surface.
- ☐ Describe the depth to groundwater.
- ☐ Describe groundwater characteristics (e.g., seasonal fluctuation, hydraulic gradient).

Site Characteristics

- ☐ Estimate the distance from edge of groundwater plume to building.
- ☐ Determine nearby potential sources.
- ☐ Estimate the distance from vapor source area to building.
- ☐ Describe the surface cover between the vapor source area and the potentially impacted building.

APPENDIX C

Building Types

BUILDING TYPES

Basements

Buildings completed below grade with a basement or partial basement may be prone to vapor intrusion for several reasons. Floor and walls may have small voids and cracks that allow soil gas to enter the building. Buildings with earthen floors (as one would find in a cellar) are especially problematic because there is a large surface area for migration of soil gas into the overlying structure and ventilation may not be present to dilute any significant vapor intrusion. Finished basements (with living spaces) are of concern because of the combination of insufficient ventilation and because the residential space is closer to the subsurface contaminant source than is living space completed at the surface. Other “red flag concerns” should be raised with basements if sumps are present or the walls are built with moisture barriers or are wet during the rainy season. Evidence of drywells, cisterns, or other voids below the basement should be identified.

Wet Basements

In areas of shallow water tables, there may not be an unsaturated zone of any significant thickness beneath the building. Building practice typically incorporates a drain around the perimeter of the footings and often a sump pump to prevent flooding of the basement. Nevertheless, this scenario is often referred to as a “wet-basement” condition. Obviously, it is not possible to assess vapor transport through the unsaturated zone beneath a building if there is no unsaturated zone. Depending on the amount of groundwater removed by the perimeter drain and sump pump, a wet-basement scenario may disrupt the formation of a clean water lens.

Slab on Grade

Slabs with cracks, utility piping, and drains may act as conduits for vapor intrusion. In some areas, homes are built with “floating slabs” where the floor is poured separately from the foundation wall. Vapors can enter the building through the perimeter crack between the wall and the floor. In areas where swelling and shrinking soils are a concern, the floor is designed to move independently of the footwalls, and the perimeter gap may be as large as 1–2 inches around the perimeter of the building.

Crawl Spaces

In some regions of the country, houses with crawl spaces may be the least likely candidates for vapor intrusion, whereas in other regions, house with crawl spaces may be especially prone to vapor intrusion problems. In warmer, humid regions, homes are often built over crawl spaces that are well ventilated to prevent the floors from rotting. While the foundation walls may have vents with movable covers, these are usually left open most of the year and may not seal tightly when closed. The extra ventilation may dilute vapor that accumulates in the crawl space. There is a further attenuation of the vapor concentration moving into the living space. Vapor transport studies of similar structures in Holland and Australia suggest that only 10%–25% of the air in the

living space enters by way of the crawl space (Turczynowicz and Robinson 2001, Waitz et al. 1996). By nature of its design, a structure such as this may have a low attenuation factor and hence may be an unlikely candidate for vapor entering the living spaces of the home, although an investigator must consider other lines of evidence as well before excluding a structure from further consideration based upon this factor alone.

In contrast, buildings in colder, dry climates may be constructed to be energy efficient for cooling and/or heating purposes and hence be more airtight. In some regions, homes may be constructed with crawl spaces that exist as large open patches of soil within an enclosed basement. Foundation walls may be built without vents or designed to seal tightly against the cold to prevent frozen pipes. Buildings of newer construction tend to be designed to allow for relatively less ambient air exchange, contributing to the problem of vapor buildup. Depending on furnace configuration, etc., most of the air in the living space enters by way of the crawl space. In these cases, vapor may easily enter the structure.

A common fallacy in evaluating vapor intrusion into crawl spaces comes in considering plastic “vapor barrier” membranes laid over the ground in the crawl space as a suitable layer of prevention against vapor intrusion. Vapor barriers may not form a complete seal and are often made of plastics that are permeable to many of the contaminants commonly encountered as vapor intrusion problems. Unless specifically designed and installed to prevent organic vapors from entering the crawl space, the presence of vapor barriers should not factor into any decision not to proceed further with evaluation.

Row Houses (Multiple Residential Units on a Single Floor Slab)

Row houses or townhouses may be constructed with multiple units on a single floor slab. It may seem reasonable to assess the potential for vapor intrusion by selecting a single unit as representative of the entire row, but experience has shown that vapor intrusion may be dominated by a discontinuity in the slab (e.g., a poorly sealed utility penetration), which may not be visible, and therefore a given unit may or may not be representative of the entire row. Additional consideration should be given to the potential for preferential pathways within the structure that may create dissimilar vapor migration routes between units.

Tall Buildings

Tall buildings in cool or cold climates generally have a significant stack effect caused by thermal convection currents. Air inside the building is heated, and hot air rises, causing a net upward flow, pressure in the upper floors, and a vacuum in the lower floors. The magnitude of the vacuum in the lower floors is proportional to the height of the building and the temperature difference between the indoor and outdoor air. This pressure differential may contribute to vapor intrusion from the subsurface and increase the potential for vapor intrusion into upper floors.

Mobile Homes and Portable Buildings

USEPA and others have offered little to no guidance on how to deal with vapor intrusion with regard to mobile homes and portable buildings. As with houses constructed over crawl spaces,

there may be a wide range of mobile-home building practices across the country, leading to a wide variation in the indoor vapor intrusion risk. The investigator evaluating vapor intrusion sites potentially affecting mobile homes should strive to factor in the building practices that are most prevalent in the area.

The undersides of mobile homes are usually sealed during manufacture with impermeable bituminous paper to protect the floor insulation during transport. Normally, this seal remains in place after the mobile home is installed at a site and can provide an extra measure of protection against vapor intrusion.

Mobile homes can be placed with or without permanent foundations. Mobile homes placed without permanent foundations or on raised concrete pilings are not likely to pose vapor intrusion risks. Even if these foundations are enclosed with metal or vinyl underskirting, which are typically attached for cosmetic purposes or to keep animals from under the mobile home, the natural ventilation through gaps and joints in the underskirting may be sufficient to dilute any contaminant soil gas emanating from the subsurface.

In some areas, mobile homes are placed directly on concrete slabs, which offer more protection against vapor intrusion if no cracks are present. Even if the slab has cracks, vapor intrusion into the living space is unlikely to occur because the metal beams on the mobile home bottom typically hold the bottom of the home several inches above the slab. The resulting horizontal channels move any soil gas away from the slab instead into the overlying mobile home.

At the other end of the spectrum, mobile homes placed on permanent foundations may be somewhat susceptible to vapor intrusion depending largely on the foundation type. In some parts of the country, mobile homes are placed on raised perimeter foundations that essentially form an enclosed crawl space under the mobile home. These mobile homes are subject to many of the same considerations as conventional houses built over crawl spaces. With this construction type, the primary factor affecting vapor intrusion into the mobile home is whether the crawl space is ventilated or not, depending on local building practices. However, even mobile homes attached to unventilated crawl spaces may have less vapor intrusion than similarly constructed conventional housing by virtue of the sealed undersides. Also, air-handling systems in mobile homes typically do not draw air from the crawl spaces, as can occur with some systems in conventional construction.

Parking Structures

Buildings may contain enclosed first-floor aboveground or subsurface parking. In accordance with Unified Building Codes, the ventilation (air exchange rates) for these parking areas is generally higher than those for other occupied building floors. These parking areas also generally have ventilation systems that are separate from the overlying occupied floors, if present. In these cases, these floors of parking act as barriers to potential vapor migration into overlying occupied floors (e.g., commercial and/or residential areas). The receptors for potential vapor intrusion evaluation for these types of parking areas would be users of the parking structures and parking attendants.

Other Building Characteristics

Ventilation

The conceptual model for vapor transport assumes that vapor is drawn into the building through openings by the pressure difference between the soil and the interior of the building. The pressure differential is induced by a combination of wind and stack effects due to building heating and mechanical ventilation. Therefore, consideration should be given to the ventilation regimes within a building, including furnace/air conditioning type (e.g., forced air, radiant), furnace/air conditioning location (e.g., basement, crawl space, utility closet, attic, roof), source of return air (e.g., inside air, outside air, combination), and system design considerations relating to indoor air pressure (e.g., positive pressure is often the case for commercial buildings). Additional consideration should be given to the operational period of the ventilation systems, including daily and seasonal variations.

Vapor Barriers

Some buildings are constructed with passive vapor barriers that may reduce vapor flux into a building. More information on passive barriers can be found in Section 4.3.1.1.

Preferential Pathways

USEPA guidance (2002b) suggests that buildings within 100 feet of a contamination plume or source should be evaluated for vapor intrusion unless a significant conduit (preferential pathway) exists (in which case, the area to evaluate should extend to some unspecified distance). Refer to Section 1.6.3 for examples of preferential pathways for the vapor intrusion pathway.

Elevators may also constitute a preferential pathway, since they are typically required by building codes to have perforations to allow water to drain and the elevator may act as a piston to induce an intermittent air-pressure gradient. Most buildings have subsurface utility penetrations, so their presence alone is not considered “preferential.” Some increased component of vapor flow into the building is usually required to consider the migration route to be “preferential.”

Surface Cover

Surface cover (e.g., asphalt pavement) between the vapor source area and building should be considered for the potential vapor capping effect that may affect subsurface vapor migration.

APPENDIX D

Toolbox

TOOLBOX

This appendix discusses in greater detail the investigative methods or “tools” used in vapor intrusion investigations. Each section is designed to give the investigator a better understanding of how to use a tool and when it is appropriate. References are provided in case the investigator wants additional information about a tool. The tools are broken down in two categories, exterior and interior. Soil gas sampling is the principal investigative tool for potential VI sites; therefore, supplemental information regarding soil gas sampling is provided. Additional details are also provided on groundwater sampling since groundwater is often the principal source of contaminated soil gas and data are usually available on groundwater concentrations. Interior sampling generally refers to data that require entry into buildings of interest, including subslab, crawl-space, and indoor air data. Ambient outdoor air sampling is usually coupled with indoor air and crawl-space sampling. Several additional tools are also discussed.

It should be noted that during any sampling activities certain objectives should always be considered. These include using the appropriate sampling methodologies, containers, sample locations and frequency, and DQOs. Most of these objectives are defined within the discussion for the specific tools since they may vary according to the tool chosen. Basic DQO principles apply to all of the tools discussed below.

A summary of the various quantitative options utilized to evaluate the vapor intrusion pathway are provided in a matrix in Table D-4, near the end of this appendix. In addition, Table D-5, at the end of this appendix, provides the advantages and disadvantages of various investigative strategies. Please refer to these tables during the development of a vapor intrusion investigative work plan.

D.1 DATA QUALITY OBJECTIVES

It is necessary to establish DQOs before sampling is conducted. These are usually addressed during the work plan preparation. Some typical DQOs that should be addressed are listed below. This list is not complete, as special circumstances at any given site may dictate very specific DQOs.

- Define study goals.
- Identify COCs and screening levels.
- Choose sampling and analysis method with appropriate reporting limits.
- Complete presampling building survey (interior sampling).
- Establish appropriate sampling conditions, number of samples, and duration of sampling.
- Collect QC samples (e.g., field blanks, duplicates).
- Establish data validation procedures.

D.2 GROUNDWATER (EXTERIOR)

D.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 the investigation, especially if groundwater contamination has been delineated and the plume has reached steady state conditions (i.e., is no longer expanding). In deciding whether existing data are sufficient, consideration should be given to the site-specific CSM. Groundwater data should be from wells screened across the water table at the time of sampling. In addition, the likelihood of significant vertical changes in groundwater quality near the water table, the sampling method used, the construction of existing wells sampled (e.g., screen length and placement across water table), 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 to be used for vapor intrusion assessment.

Drinking water supply wells may or may not be appropriate, depending upon 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 should be considered a possible basis for further investigation, but in most situations the data should not be used to determine whether the pathway is complete.

D.2.2 Interpolation of Nearby Data

If groundwater data *immediately* upgradient from the structure are not available, surrounding data points can be used to construct contaminant isoconcentration maps. However, this step should be done only if data points are available on at least two sides of a structure. Complex geologic settings or the anticipated presence of steep concentration gradients warrants a denser sampling grid. Groundwater contours should consider the rate and direction of groundwater flow and the time since chemicals were released to compare the expected length of the plume to measured concentration data. In general, the distribution of chemicals in groundwater will elongate in the direction of groundwater flow (shaped like a feather, hence the term “plume”) with relatively little vertical or transverse dispersion.

D.2.3 Obtaining New Groundwater Data to Evaluate the VI Pathway

If new or additional groundwater data are needed to complete the VI investigation, the goal of the sampling effort should be to determine volatile concentrations in the uppermost groundwater beneath or near potential structures.

USEPA (2002c) and various state agencies (NJDEP 2005a) 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 for collecting groundwater data suitable for vapor intrusion assessment (Cal DTSC 2005) are as follows:

- Proper Screen Intervals. Contaminants at the top of the water table, rather than deeper contamination, are responsible for causing potential vapor intrusion problems. Hence, monitoring wells used to make vapor intrusion evaluations should be screened across the air-water interface, meaning the well screens should not be submerged below the top of the water table.
- Proper Screen Lengths. Monitoring wells with excessively long well screens, regardless of screen placement, should not be used to make vapor intrusion 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 vapor intrusion 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 5–10-foot screen is generally recommended unless this approach conflicts with other site investigation objectives. Additional construction recommendations are discussed in NJDEP 2005b.
- 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 alternative/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 due to 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 most shallow 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.
- 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. 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 practice will drain the filter pack and introduce potential for volatilization losses during recovery. If adequate purging cannot be conducted without excessive drawdown because of low permeability, consider using passive diffusive samplers, which do not require purging.
- Proper Well Sampling. Sampling methods that minimize the loss of VOCs during sample collection and handling, such as bladder pumps or submersible pumps, are preferred. Other methods, such as peristaltic pumps and bailers, may cause unacceptable volatilization of chemicals if not properly implemented (USEPA Technology Verification Program,

www.epa.gov/etv/verifications/verification-index.html). Passive diffusion samplers may be useful, as described below.

D.2.4 Groundwater Spatial 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 due to heterogeneities in source areas and in the subsurface media. Given the distance criterion between vapor source and potentially affected structures (check with your regulatory agency for the appropriate distance), a more detailed delineation of the extent of groundwater contamination may be appropriate in some situations.

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 (e.g., storm water retention pond or a transition from a mostly paved surface to a vegetated park/open field) located between the upgradient edge of a plume and a structure, a sampling location downgradient of the recharge area should be selected to be representative of any fresh water lens that may be present.

D.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/near structures, exist year-round, and are below nearby building foundations should be sampled if they are of sufficient thickness that a sample can be obtained. Professional judgment must be used in more complex situations, but 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 enable a more precise evaluation of the current and potential future risk of VI.

D.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 should be done where groundwater concentrations exceeding screening levels are close to, but not currently within, the applicable distance criterion to a potential receptor.

D.2.7 Groundwater Sampling Methods

Table D-1, prepared by NJDEP (2005b), summarizes some alternative groundwater sampling methods that may apply to VI investigations. Sampling guidance for VI investigations may differ from other guidance in the documents because of the objective to determine very shallow groundwater quality.

Table D-1. Groundwater sampling methods for vapor intrusion investigations

Method	Example guidance documents	Advantages or disadvantages
Direct-push and alternative groundwater sampling methods	NJDEP <i>Field Sampling Procedures Manual</i> (2005a), Section 6.9.2.1, www.nj.gov/dep/srp/guidance/fspm	<ul style="list-style-type: none"> • 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
Passive diffusion bag samplers	<ul style="list-style-type: none"> • NJDEP <i>Field Sampling Procedures Manual</i> (2005a), www.nj.gov/dep/srp/guidance/fspm • USGS <i>User's Guide for Polyethylene-Based Passive Diffusion Bag Samplers to Obtain Volatile Organic Compound Concentrations in Wells</i>, Part 1, www.itrcweb.org/gd_DS.asp • ITRC <i>Technical and Regulatory Guidance for Using Passive Diffusion Bag Samplers to Monitor Volatile Organic Compounds in Groundwater</i> (2004a), www.itrcweb.org/gd_DS.asp 	<ul style="list-style-type: none"> • Can use existing wells for ongoing monitoring • May not be adequate where/for: <ul style="list-style-type: none"> ◦ VOC highly soluble in water, such as methyl tertiary-butyl ether ◦ in-well vertical flow occurs ◦ permeability is very low
Low-flow purging and sampling	NJDEP <i>Field Sampling Procedures Manual</i> (2005a), Sections 6.9.2.2 and 6.9.2.3, www.nj.gov/dep/srp/guidance/fspm	<ul style="list-style-type: none"> • May generally target interval closer to the water table in some settings • Discrete interval sample not obtained
Volume-averaged purge and sample collection	NJDEP <i>Field Sampling Procedures Manual</i> (2005a), Section 6.9.2.4, www.nj.gov/dep/srp/guidance/fspm .	<ul style="list-style-type: none"> • Not recommended to generate new groundwater data specifically for VI investigations because of the potential for vertical averaging

D.2.8 Passive Diffusion Samplers

Passive diffusion samplers come in several varieties, as described in ITRC 2004a. Passive diffusion bag samplers (PDBSs) may be the most common for VOCs. PDBSs 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, transfer of volatiles from the sampler water into less contaminated well air space would occur. If the upper sampler is exposed to the air space, the upper sampler should be resuspended 2 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 PDBSs 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. PDBSs are not applicable to all compounds (e.g., semivolatile organic compounds [SVOCs] and soluble compounds such as acetone, styrene, methyl tertiary-butyl ether [MTBE], and 4-methyl-2-pentanone [MIBK]), so the target analytes must be confirmed.

D.2.9 Low-Flow Purging and Sampling

If evaluating the VI pathway is the *only* sampling objective, it is recommended that two modifications to the typical low-flow purging and sampling procedure be employed:

- 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 1.5–2 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 (tubing and pump, etc.). While measuring water quality indicator parameters is preferred (but not necessary), drawdown should be measured and not excessive.

D.3 SOIL (EXTERIOR)

At most sites soil matrix data are available. However, these data are less than ideal for evaluating vapor intrusion risk because of the uncertainty associated with using partitioning equations and the potential loss of VOCs during sample collection. Field extraction with methanol or hexane is good for reducing volatilization losses, but it results in elevated detection limits.

To evaluate vapor intrusion, soil matrix must be converted to soil gas concentrations using assumptions about the partitioning of the contaminant into the gas phase. Soil solid-to-soil gas partitioning equations are readily available, but using them increases the uncertainty in evaluating vapor intrusion.

Hartman (2002) has found that in the case of hydrocarbons, calculated soil gas values from soil solid data often overestimate actual soil gas concentrations. Conversely, soil solid data for chlorinated hydrocarbons often underestimates soil gas concentrations.

When soil is sampled for VOCs, soil samples should be collected using procedures specifically designed to minimize volatilization losses, such as SW-846 Method 5035A and augmented USEPA Method 5035A (Cal DTSC 2004). More details on the interpretation of soil data and phase partitioning calculations can be found in the Cal DTSC vapor intrusion guidance (2005). Existing soil data should be used as part of the line-of-evidence approach. In general, soil matrix data are not recommended as a stand-alone screening tool for a vapor intrusion investigation. They can be used to delineate sources or “screen in” sites for vapor intrusion assessment, but not to eliminate sites from further assessment.

D.4 ACTIVE SOIL GAS METHODS (EXTERIOR)

Active soil gas methods consist of the withdrawal of the soil gas from the subsurface and subsequent analysis. These methods give concentration data (e.g., $\mu\text{g}/\text{m}^3$), which can be directly compared to risk-based screening levels or used in predictive models. Soil gas sampling is the preferred sampling and investigative tool for most vapor intrusion investigations.

Soil gas sample collection techniques for vapor intrusion applications require much greater care than techniques historically used for typical site assessment applications (e.g., assessing whether a underground storage tank has leaked) because risk-based concentration levels for vapor intrusion scenarios are so low (1,000–10,000 times lower than concentration levels previously of concern). The quality of soil gas data depends greatly on the collection protocols. The following overview attempts to identify alternatives, express advantages and disadvantages, and provide appropriate flexibility and cautions where warranted by the current available knowledge and experience. Some of the primary factors that can influence the measured results are summarized below. A checklist summarizing some of the key QA/QC issues is provided in Appendix E. For supplemental or up-to-date references, please refer to the ITRC Vapor Intrusion Web page (www.itrcweb.org/vaporintrusion).

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).

D.4.1 Driven Probe Rod (Temporary Method)

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 (Figure D-1). 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 typically ranging 12.5–50 mm. Small-diameter, inert, replaceable tubing runs down the center of the drive rod to eliminate potential contamination from the inside of the rod. The probes can be driven by hand, direct-push systems, or larger drill rigs using the wire-line hammer. The driven rod method is typically faster than the buried tube method and also does not leave any materials in the ground. Probe installation can be difficult in consolidated or coarse-grained soils, especially at greater depths, where the rods are more susceptible to deflection. A surface seal is usually employed, but this 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 may help to verify the absence of atmospheric air entry during sampling.



Figure D-1. Hollow rod used to collect soil gas.

Courtesy H&P Mobile Geochemistry

D.4.2 Burial of Soil Gas Sampling Tubes (Semipermanent or Permanent Method)

This method consists of the burial of a small-diameter (typically 1/8- to 1-inch outside diameter) inert (e.g., stainless steel, Teflon®, HDPE, polyetheretherketone, Nylaflow®) tube or pipe 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. Sand is used as backfill around the tip, and the remainder of the borehole annulus is sealed, usually with 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 (as shown in Figure D-2), providing the seals between intervals are tight and are often referred to as “multilevel” soil gas wells or probes. They can also be installed in nearby individual boreholes (nested soil gas wells or probes).

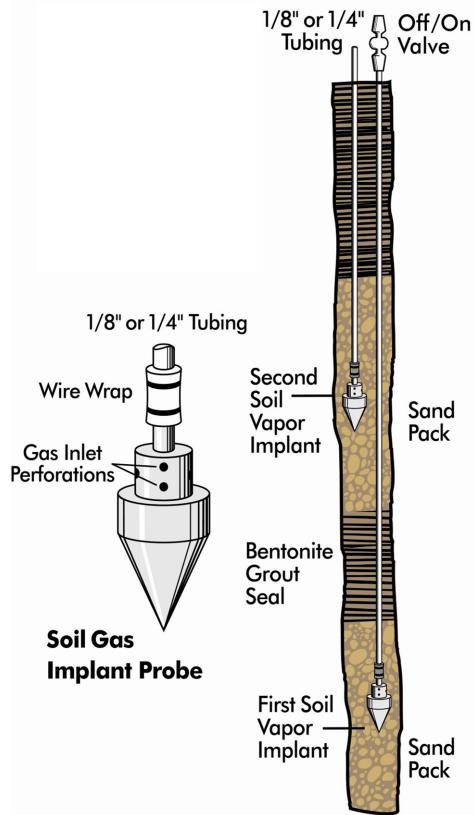


Figure D-2. Typical configuration of nested well.

Courtesy H&P Mobile Geochemistry

D.4.3 Soil Gas Sampling from Existing Groundwater Wells

Soil gas samples can be collected from groundwater wells that are screened across the water table. If 3–5 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, the soil gas sample will reflect 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. In the first case, three to five casing volumes should be extracted prior to sampling to ensure the sample is representative. Field screening can be conducted to demonstrate stable readings before sample collection. Groundwater monitoring wells typically have vented caps, so a retrofit will be required to cap the well with an airtight cap and valve.

D.4.4 Purge Volume

Sampling systems with small internal volumes minimize potential sample-integrity problems compared to sampling systems with larger internal volumes, although reliable samples can be collected with the latter, especially when the probes are deeper than 5 feet. Stagnant air inside soil gas probes and sampling trains must be purged prior to sample collection. Three to four

system purge volumes are recommended as a minimum value. The dead volume of the sand pack should be purged if samples are collected within a few hours of installation. Larger purge volumes may result in a more integrated soil gas concentration under some conditions, providing the concentration versus purge volume is assessed using handheld meters (PID, flame ionization detector [FID], O₂, CO₂) or a mobile laboratory. If air rotary drilling is used to emplace the tubes, longer periods of time are required for the sand pack to equilibrate with the soil gas. API 2004 gives an equation to estimate the time required to reach steady state conditions. A test of concentration versus time can be used to determine when values stabilize.

D.4.5 Sample Volume and Purge Volume Tests

To reduce the uncertainty of where the soil gas sample is from and potential breakthrough from the surface, smaller volume samples (<1 L) and proper seals are recommended, especially for soil gas samples collected at shallow depths (<3 feet bgs or subslab). However, three recently published studies compared soil gas concentrations collected from volumes ranging 0.5–100 L (DiGiulio et. al. 2006a, McAlary and Creamer 2006, DiGiulio et. al. 2006b). The results of these studies, done in relatively course-grained soils, show no significant differences in concentrations. If the investigator is concerned about withdrawing larger (>3 L) sample volumes, a test of the sample concentration versus amount withdrawn might be appropriate to demonstrate there is no relationship between soil gas concentration and volume withdrawn. This can be done similar to the purge volume test described in the preceding paragraph.

D.4.6 Flow Rate and Vacuum

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 are requiring flows less than 200 mL/min.

This conservative approach limiting flow rate may not be necessary in soils permeable enough to maintain vacuums less than 15% of atmospheric pressure (~5 inches of Hg, 60 inches of H₂O). A recent study by McAlary and Creamer (2006) actually measured soil gas concentrations over different flow rates ranging from 100 mL/min to 100 L/min at a hydrocarbon-contaminated site. They saw no significant difference in measured concentration. This study suggests that for relatively course-grained soils, flow rate does not appear to be an important variable on soil gas concentration.

D.4.7 Leak Tests

To ensure that valid soil gas samples are collected with no breakthrough of air down the probe rod or through leaks in the sampling train, a tracer compound may be applied at the base of the probe where it contacts the surface and near all connections in the sampling train. Connections can also be leak-tested using a “shut-in” test (API 2004). Seal integrity is then confirmed by analyzing collected soil gas samples for the tracer. Gaseous compounds (propane, butane, helium, SF₆) using shrouds or liquid compounds (isopropyl alcohol, pentane, freons) applied to towels are commonly used. Both types of tracers have pros and cons. Gaseous tracers offer some

advantages but are harder to use, especially to cover leakage in the sampling train. Helium offers a nice advantage in that it is readily measured on site with a field meter. Volatile liquid tracers offer logistical simplicity but are more qualitative. Liquid tracers are easily and quickly supplied at multiple locations (i.e., probe, sampling rod, sampling train, etc.) simultaneously. Liquid tracer methods are better suited for sampling through the probe rod since it can be applied to multiple leak points that may not be close to each other.

A small amount of tracer in a sample does not necessarily indicate an unreliable sample. Some agencies, such as the New York State Department of Environmental Conservation, allow tracer concentrations up to 10% of the starting concentration before considering the soil gas sample compromised. For gaseous tracers, the starting concentration is the measured concentration under the shroud. For liquid tracers, the starting concentration either is assumed as equal to the vapor pressure of the compound at ambient temperature or can be measured if on-site analysis is available. For liquid tracers such as isopropanol, a 10% leak would give a value in the sample of approximately 10,000 µg/L, assuming a starting concentration equivalent to its vapor pressure. To account for the possibility that the starting concentration is not equal to the vapor pressure, some agencies have established a specific concentration level, such as 100 µg/L, that can not be exceeded. This value corresponds to a 0.1% leak, assuming a starting concentration equal to the vapor pressure of the compound or a 1% leak if the starting concentration is only 10% of the vapor pressure, a conservative assumption. Table D-2 lists common tracers with their relative advantages and disadvantages.

Prevent Atmospheric Short-Circuiting

- Soil gas probes should be sealed above the sampling zone with a bentonite slurry for a minimum distance of 3 feet 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 bentonite between probes to create discrete sampling zones (Figure D-2) or separate nested probes should be installed.
- 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.

—from NYSDOH (2006) guidance

Table D-2. Common tracers

Tracer	Advantages	Disadvantages
Helium	<ul style="list-style-type: none"> • Can to check for leaks on site with handheld detector • Can quantify amount of leakage accurately • Does not interfere in TO-15 analysis 	<ul style="list-style-type: none"> • Party-grade helium may have low ppbv VOC contamination • Process is more cumbersome than some others • Cannot be analyzed by TO-15 • Can be difficult to apply to sampling train connections
Liquid tracers	<ul style="list-style-type: none"> • Easy to use in identifying leaks • Can be detected by VOC analytical methods • Easier to apply to sampling train connections 	<ul style="list-style-type: none"> • Concentration introduced to leak is estimated • Large leak may lead to VOC analysis interferences • No simple field screening method • May leave residual contamination on sampling train

Tracer	Advantages	Disadvantages
Sulfur hexafluoride	<ul style="list-style-type: none"> • Can check for leaks with on-site instrument with very low detection limits 	<ul style="list-style-type: none"> • Very expensive • Field instrument subject to interference with chlorinated solvents • Cannot be analyzed by TO-15 • Is a greenhouse gas

D.4.8 Collection of Samples with Sampling Assemblies

Sampling assemblies (connecting tubing, fittings, gauges, flow controllers, etc.) should be ensured to be leak-tight 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.

D.4.9 Collection of Samples on Adsorbents

An alternative approach to collecting soil gas in a sample container is to concentrate the soil gas on an adsorbent. This type of method is required for SVOCs (generally compounds heavier than naphthalene). Typically, a pump is used to draw soil gas through the adsorbent, and the adsorbent is then analyzed by a laboratory. A variety of adsorbent cartridges and pumping systems are available from commercial vendors. All of the collection issues and criteria discussed in this section apply when using adsorbents. In addition, it is essential that the soil gas be drawn through the adsorbent by the pump, not pumped through the adsorbent to eliminate the chance for cross-contamination by the pump. It is often recommended to use two tubes in series to avoid breakthrough losses in areas of suspected higher concentrations. The adsorbent, purge rate, and sample volume must be determined by discussion with the analytical laboratory.

D.4.10 Variations in Soil Gas Values Due to Temporal Effects

Variations in soil gas concentrations due to temporal effects are principally due to temperature changes, precipitation, and activities within any overlying structure. Variations are greater in samples taken close to the surface and dampen with increasing depth. In 2006 there were a number of studies on temporal variation in soil gas concentrations, and more are under way or planned in 2007 by USEPA and independent groups. To date these studies have shown that short-term variations in soil gas concentrations at depths 4 feet or deeper are less than a factor of 2 and that seasonal variations in colder climates are less than a factor of 5 (Hartman 2006). Larger variations may be expected in areas of greater temperature variation and during heavy periods of precipitation, as described below.

IBM, Endicott, New York

Recent data from a large site in Endicott, New York collected over a 15-month period showed soil gas concentration variations of less than a factor of 2 at depths greater than 5 feet bgs.

- Temperature. Effects on soil gas concentrations due to actual changes in the vadose zone temperature are minimal. The bigger effect is due to changes in an overlying building's

heating or HVAC system and the ventilation of the structure due to open doors and windows. In colder climates, worse-case scenarios are most likely in the winter season. The radon literature suggests that temporal variations in soil gas are typically less than a factor of 2 and that seasonal effects are less than a factor of 5. If soil gas values are more than a factor of 5 below acceptable levels, repeated sampling is likely not necessary regardless of the season. If the measured values are within a factor of 5 of allowable risk levels, then repeated sampling may be appropriate.

- Precipitation. Infiltration from rainfall can potentially impact 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 penetrates into only the uppermost vadose zone. In general, soil gas samples collected at depths greater than about 3–5 feet bgs or under foundations or areas with surface cover are unlikely to be significantly affected. Soil gas samples collected closer to the surface (<3 feet) with no surface cover may be affected. If the moisture has penetrated to the sampling zone, it typically can be recognized by difficulty in collecting soil gas samples. If high vacuum readings are encountered when collecting a sample or drops of moisture are evident in the sampling system or sample, measured values should be considered as minimum values.
- Barometric Pressure. Barometric pressure variations are unlikely to have a significant effect on soil gas concentrations at depths exceeding 3–5 feet bgs unless a major storm front is passing by. A recent study in Wyoming (Luo et al. 2006) has shown little to no relationship between barometric pressure and soil gas oxygen concentrations for a site with a water table at ~15 feet bgs.

In summary, temporal variations in soil gas concentrations, even for northern climates, are minor compared with the conservative nature of the risk-based screening levels. If soil gas values are a factor of 5–10 times below the risk-based screening levels, there likely is no need to do repeated sampling unless a major change in conditions occurs at the site (e.g., elevated water table, significant seasonal change in rainfall).

D.4.11 Choosing an Appropriate Analytical Method

A variety of analytical methods are available to measure soil gas samples, all of which can give accurate results when followed with appropriate QA/QC. Table D-3 (at the end of this appendix) summarizes the most common methods. The primary criteria for choosing the appropriate method are as follows:

- the COCs
- concentrations that may be encountered during sampling
- required detection level and other DQOs
- sampling logistics
- cost

The planning stages of the investigation should include discussions with your laboratory to ensure the appropriate analytical method is utilized.

D.4.12 Sample Containers and Storage

For fuel-related compounds (BTEX, total petroleum hydrocarbons [TPH]) and biogenic gases (CH_4 , CO_2 , O_2), allowable containers include Tedlar® bags, gas-tight (glass or stainless steel) vials, and passivated (Summa) stainless steel canisters. Tedlar bags are generally not considered to be reliable for more than 48 hours, but some agencies may have different requirements.

For halogenated compounds (e.g., TCE, TCA, PCE), allowable containers must be gas tight but also dark to eliminate potential photodestructive effects.

Adsorbents are suitable for most VOCs and SVOCs. However, multiple adsorbents may be required to deal with complex mixtures.

If stored samples are to be subjected to changes in ambient pressure (e.g., shipping by air), gas-tight vials or canisters are recommended. Tedlar bags to be shipped by air should be only partially filled to prevent rupture.

Allowable storage times in canisters vary among states, ranging from 3 days (Cal DTSC 2005) to 30. Most agencies require analysis within 14 days of collection.

It is not necessary to chill soil gas samples during shipping and storage.

D.4.13 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), allows recognition of spurious 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 enable rapid screening for vapor migration routes around and into structures. However, most field-screening instruments are limited to the ppmv range, which may not provide sufficient resolution. Quantitative oxygen, carbon dioxide, and methane data are possible from handheld portable meters for concentrations in the percentage range. Helium detectors are available with a range of 0.01%–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 1–100 $\mu\text{g}/\text{m}^3$.

D.4.14 Recommended Soil Gas Sample Locations for Vapor Intrusion Assessments

The initial criteria to apply in determining where to collect soil gas samples for vapor intrusion assessments are the location of the contamination source relative to the receptor, the depth of the contamination source, and the type and construction of the receptor. The following sections give brief recommendations on where to collect soil gas samples both laterally and vertically for some typical situations. Additional suggestions can be found in API 2005, NYSDOH 2006, NJDEP 2005b, and EPRI 2005. For supplemental or up-to-date references, refer to the ITRC Vapor Intrusion Team Web page (www.itrcweb.org/teampublic_Vapor.asp).

D.4.15 Sample Density

Sufficient soil gas samples should be taken to make appropriate decisions. When subsurface contamination is encountered near buildings, soil gas samples should be collected to assess the contaminant distribution in sufficient detail to identify buildings that may have unacceptable levels of vapor intrusion. Characterization should continue until concentrations of VOCs meeting acceptable risk-based levels are encountered in the subsurface laterally and vertically between the source and potential receptors.

The exact number and spacing of samples (i.e., sample density) will vary on a site-specific basis. Ideally, there should be a soil gas sample for every existing or future building for smaller sites (i.e., houses surrounding a dry cleaner or a gas station) and sufficient spatial coverage to be representative for larger distributions (e.g., groundwater plume under hundreds of houses). 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 get a representative value of the soil gas concentration (analogous to placing enough borings on a typical site). If statistical averaging methods are being used to process the data, a minimum number of locations might be required depending upon the statistical method employed.

D.4.16 Selection of Lateral Soil Gas Sampling Locations

It is important to consider the following parameters when selecting lateral sample locations.

Subsurface Contamination Adjacent to a Structure: If the contamination source is not directly below the structure, collect samples on the side of the structure closer to the source. Collect samples in any known subsurface migration routes, such as sewers or utility lines that extend towards the contamination. If concentrations exceeding screening levels are detected, it may be appropriate to proceed to interior sampling (e.g. subslab).

Subsurface Contamination underneath a Structure: If the contamination source is directly below the structure, collect samples directly underneath the structure foundation if possible and/or indoor air samples. If possible, collect enough samples to get a representative value under the footprint of the structure and locate them to provide an indication of the spatial distribution of

the contamination. If subslab samples are not possible, collect near slab soil gas samples around all sides of the structure to determine the concentration distribution and get an idea of the possible concentration under the structure. An alternative approach may be required for very large buildings.

Surface Contamination Within or Immediately Adjacent to a Structure: This situation is most likely applicable to commercial facilities with adjoining businesses (e.g., dry cleaners at strip malls) or industrial settings with partitioned or immediately adjacent buildings. The contamination enters the shallow vadose zone from the surface, as a dense vapor or as a liquid spill, and then migrates laterally underneath the building slab. Collect samples directly underneath the structure slab covering the area of concern in the structure.

D.4.17 Selection of Vertical Soil Gas Sampling Locations Exterior to the Building

The closer to the ground surface or structure foundation, the greater the chance that surface processes such as atmospheric pumping, precipitation, and advective flow induced from the overlying structure will affect the soil gas concentration. In general, the effects due to these processes are considered to be minimized at depths 3–5 feet below the ground surface or building foundation, and measured soil gas concentrations are less likely to fluctuate. However, some processes, such as bioattenuation, oxygen replenishment, and substructure flushing, occur primarily at shallower depths (<3 feet), so sampling in this zone should not necessarily be precluded. If soil gas data from depths <3–5 feet bgs or below the level of the foundation are collected, additional sampling events may be appropriate to ensure representative values, especially if the measured values yield risks that are near acceptable levels.

Multiple-depth samples should be collected as needed to define vertical trends in soil gas concentrations or to determine maximum concentrations at the contamination source. Deeper samples tend to minimize temporal variations. The tension-saturated zone above the water table (capillary fringe) should be avoided if possible because high water saturation makes soil gas sampling difficult.

Exterior soil gas samples collected from just above the source or about 10 feet below the lowest floor slab are expected to provide a conservative estimate of subslab concentrations, as described further in Section D.6.

Some general recommendations regarding selection of vertical samples follow:

Subsurface Contamination Adjacent to a Structure. Collect samples between the structure and the source at about 3–5 feet below the lowest floor or shallower if the contamination source is shallower. For structures with basements, at least one vertical profile along the basement wall facing the contamination is advised.

Subsurface Contamination Underneath a Structure. If accessible, collect samples immediately below the structure's foundation. For hydrocarbons, collect near-structure samples at about 3–5 feet below the lowest floor or shallower if the contamination source is shallower. For chlorinated hydrocarbons, collect samples near the source and at least 10 feet below the foundation (but no

deeper than the top of the capillary fringe). If concentrations exceeding screening levels are detected, either collect additional samples around the structure to allow better determination of the concentration distribution around the structure or proceed to interior sampling (subslab and/or indoor air).

Surface Contamination Within or Immediately Adjacent to Structure. As described in the prior section, this situation is most likely applicable to commercial facilities with adjoining businesses (e.g., dry cleaners at strip malls) or industrial settings with partitioned or immediately adjacent buildings. Collect samples directly underneath the slab covering the area of concern in the structure.

D.4.18 Applications of Vertical Profiles of Soil Gas Concentrations

Vertical profiles of soil gas concentrations can be useful for the following situations:

- determining the source of the contamination if not previously known
- determining the attenuation of contaminants in the soil gas in the vadose zone due to bioattenuation or other processes

Depending on the depth of groundwater, vertical profiles should consist of a minimum of three sampling depths, fewer for shallower aquifers. If repeated data are desired, install soil gas monitoring tubes for easy re-sampling.

D.5 PASSIVE SOIL GAS METHODS

Passive soil gas methods consist of the burial of an adsorbent in the ground (Figure D-3) with subsequent retrieval and measurement of the adsorbent. With passive sampling, there is no forced movement of soil gas. Instead, as the vapors migrate, the sorbent acts as a sink for the organic compounds in the soil gas. This method gives a time-integrated measurement and therefore reduces the uncertainty due to temporal variations.

Passive soil gas methods directly measure a mass of contaminant that has diffused onto an adsorbent media. Reporting units are typically in terms of mass (e.g., micrograms). Using relative mass levels, passive soil gas can be a viable, cost-effective, and simple screening tool to determine potential areas of concern. While published methods exist that describe the procedures to generate contaminant concentration data from a passive sorbent-based sampler in air in the absence of soil (ASTM 2002a, 2003), no published data or documents have demonstrated the applicability of the



Figure D-3. Installing a passive soil gas module.
Courtesy W.L. Gore & Associates, Inc.

method to soil gas. The fundamental difference is that the gas-phase diffusivity is known in the air, enabling a calculation of concentration from the adsorbed mass, but it is unknown in the vadose zone.

Field studies to calibrate the passive method to actual soil gas concentrations are still too limited to validate the use of this method for quantitative soil gas concentrations. For this reason, passive soil gas is not presently considered to be applicable for stand-alone assessment of vapor intrusion risk. However, passive soil gas sampling does have applications in vapor intrusion assessments. 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. The composition of subsurface soil gases can be determined from passive soil gas samples, and the location of sources and subsurface plumes can be mapped, particularly edges of plumes to determine whether contamination is near current or future buildings. Passive soil gas sampling methods can also be useful in situations where active methods may not be applicable, e.g., low-permeability areas and high-moisture settings. Further, they are capable of detecting and reporting compounds present in very low concentrations.

Special considerations for passive soil gas surveys include the following:

- The adsorbent material should be hydrophobic to minimize water vapor uptake.
- Exposure time—The sampler must be deployed long enough to adsorb a detectable mass, but not so much as to allow the adsorbent to become saturated.
- Desorption and analytical method—The adsorbed compounds can be removed from the adsorbent by thermal desorption or solvent extraction and analyzed using gas chromatography (GC) or GC-mass spectrometry (GC/MS). Methods using thermal desorption have the benefit of greater method sensitivity than those using solvent extraction.
- Sampler installation—For subslab sampling, a narrow-diameter hole is drilled through the slab, and the sampler is slipped into the hole beneath the slab, while the hole itself is sealed. Deeper soil gas sampling generally involves drilling a narrow-diameter hole at least 3–5 feet bgs. The passive sampler is inserted to depth and the installation hole is secured. (See Section 6.0 below for special considerations regarding drilling through slabs.)
- 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.

Appendix E provides a checklist summarizing additional QA/QC issues.

D.6 SUBSLAB SOIL GAS SAMPLES (INTERIOR)

Subslab samples are 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 (e.g., 1/8- or 1/4-inch outside diameter) stainless steel or another inert material and stainless steel compression fittings. The probes are

cut at a length to either float in the slab or to extend just to the base of the slab (Figure D-4). If repeated sampling is anticipated, surface completions may need to be flush with the surface (trip-proof) and cosmetically clean, especially in residences.

Special considerations for subslab soil gas samples include:

- Subslab samples should be avoided in areas where groundwater might intersect the slab.
- Underground utilities (e.g., 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 are analogous to those in other types of soil gas sampling; however, risk-based screening levels for subslab samples are lower than those for 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 minimal.



Figure D-4. Installation of subslab soil gas sample port. Courtesy Kansas Department of Health and Environment

USEPA published an SOP for subslab sampling (USEPA 2006) in March 2006. The NJDEP guidance document (2005b) has a modified version of these procedures. There is also an SOP in the EPRI (2005) handbook. For supplemental or up-to-date references, please refer to the ITRC Vapor Intrusion Web site (www.itrcweb.org/vaporintrusion).

D.7 NEAR-FOUNDATION (EXTERIOR) VERSUS SUBSLAB (INTERIOR) SAMPLING

Subslab sampling is intrusive and sometimes impossible due to access limitations or disturbances to the occupants. In many situations, soil gas samples near the foundation at a depth of ~3–5 feet below the lowest floor may be an appropriate surrogate for subslab sampling for screening purposes, with approval of the regulatory agency. However, there is no consensus regarding the conditions under which near-slab soil gas samples collected around a structure can be used to predict subslab concentrations beneath a structure. Data presented by Digulio, Wertz, and Abreu at the March 2006 Association for Environmental Health and Sciences workshop indicate that exterior shallow soil gas samples (<10 feet below foundation) may underestimate subslab concentrations for nonbiodegradable compounds. Existing data for hydrocarbons (Davis 2006) suggest otherwise. More studies are currently in progress comparing exterior soil gas concentrations at various depths to subfoundation concentrations.

When subslab soil gas sampling is not possible, it is conservatively recommended to collect multiple near-slab soil gas samples at some depth below the bottom of the lowest floor of the building. See presentations posted at the Indoor Air Vapor Intrusion Database (<http://www.iavi.rti.org/WorkshopsandConferences.cfm>).

In general, the subslab soil gas concentration cannot be higher than the source concentration. If the soil gas concentrations at the source are below acceptable levels for subslab samples, then subslab samples should not be necessary. In areas of shallow (<25 feet) groundwater, soil gas samples from just above the capillary fringe should be readily obtainable.

For biodegradable hydrocarbons, recent data compiled by Utah Department of Environmental Protection (Davis 2006) indicate that if oxygen levels in the vadose zone are >5% and the source is at least 3–5 feet below the receptor, then the vapor pathway is complete in less than 6% of the sites. Hence, in this situation, if adequate soil porosity exists and areas for air penetration (e.g., lawns and gardens) exist around the structure, it is likely that bioattenuation is occurring under the slab, and near-slab data might be considered to adequately reflect subslab levels, especially for structures with small slabs such as single-family homes.

D.8 MEASUREMENT OF INDOOR AIR (INTERIOR)

Indoor air samples are normally collected after subsurface soil gas characterization and other environmental samples (e.g., groundwater and/or soil gas) indicate the need to conduct an internal site-specific assessment. The analyte list should minimally focus on compounds identified in subsurface samples at concentrations above screening levels, their possible breakdown products, and potentially compounds that may be useful as marker compounds. Since some state agencies require full parameter analysis, confirm the parameter list with the appropriate regulators.

Temporal variability will depend on the duration of the sample. Grab (instantaneous) samples are generally not recommended. 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 workday. The sample duration should be evaluated and agreed upon during work plan preparation. In addition, confirm the appropriate ventilation conditions with the regulatory agency. Some states require that sampling be performed only in areas where windows and doors have not been opened and air-handling systems have not been operating for several hours.

Short-term temporal variability in subsurface vapor intrusion occurs in response to changes in weather conditions (temperature, wind, barometric pressure, etc.), 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 2–5 for 24-hour samples (Kuehster, Folkes, and Wannamaker 2004; McAlary et al. 2002). If grab samples are used to assess indoor air quality, a factor of safety (at least a factor of 5) should be used to adjust for short-term fluctuations before comparing the results to risk-based target concentrations. 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 the need to collect indoor air samples before completing the subsurface soil gas characterization due to 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 and/or quantitatively characterize the contamination
- if high readings are obtained in a building when screening with field equipment (e.g., PID, organic vapor analyzer, or explosimeter) and the source is unknown
- 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 (e.g., sump pit overflows), and subsurface soil gas sampling is not feasible
- regulatory agency requires indoor air sampling
- presence of light, nonaqueous-phase liquid directly below the building
- fractured bedrock potentially creating a preferential pathway into the structure

D.8.1 Presampling Building Surveys

Assessing the vapor intrusion pathway using indoor air analysis may be complicated by the impact of background contaminant sources. Differentiating the common household sources of poor indoor air quality from those associated with contaminated groundwater or subsurface soil is a legal and fiscal dilemma facing both regulatory agencies and potential responsible parties throughout the country.

One of the tools used to identify background sources in the indoor air environment is the “Indoor Air Quality Questionnaire and Building Inventory” prepared by NYSDOH (2006) and provided herein as Appendix G. The questionnaire enables the investigator to document various information on the building, the occupants, and potential sources of indoor air contamination. The questionnaire has been revised and updated over the years by numerous state agencies, including NJDEP, New Hampshire Department of Environmental Services, Vermont Department of Health, and MassDEP. Handheld field screening instruments can be useful to evaluate these types of VOC sources that are unrelated to vapor intrusion.

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, as well as sumps, should be screened during the presampling site visit.

D.8.2 Sample Collection Methods

Time-integrated sampling is typically used when conducting indoor air exposure assessments associated with vapor intrusion investigations. A time-integrated sample represents a sample taken at a known sampling rate over a fixed period of time. Two methods are commonly employed: collection of samples in an evacuated canister and collection of samples on adsorbent media.

Collection of Samples in an Evacuated Canister

The sampling canister (Figure D-5) is a passivated or specially lined inert container (e.g., Summa, Silco[®]) sent to the field under vacuum and 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 calibrated and set in the laboratory. Initial and final vacuums are recorded for each canister. The main advantages of canister sample collection are the capability of analyzing multiple samples from the same canister and the ease of deployment and retrieval. Canister methods are most commonly employed in North America. To ensure the canisters are filling at the proper rate, they should be rechecked after deployment. Canisters with dedicated vacuum gauges facilitate this effort and are strongly recommended. The canister must be retrieved prior to being completely filled (with some residual vacuum remaining) to ensure proper collection period.



Figure D-5. Stainless steel canisters.

Collection of Samples on Adsorbents

Sample collection on an adsorbent—an option for VOCs and a requirement for SVOCs—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 amount of air that is passed through the tube. 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. A primary disadvantage of adsorbent sampling is that typically only one analysis is possible from a tube. Other complications of sorbent sampling are potential compound breakthrough and sorbent contamination from passive adsorption of VOCs.

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 placed into an airtight container until analysis of the

media. Exposure times must be determined based on estimated sample concentrations such that the sampler does not reach a state of equilibrium (or saturation) with the environment, a common source of low bias.

D.8.3 Sample Locations and Frequency

A typical single-family residential dwelling (approximately 1500 ft²) 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 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 (e.g., partial crawl spaces, sumps, elevators). Any sampling approach should take into account the different exposure scenarios (e.g., day care, 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 the following:

- Samples should be collected in the breathing zone, ~3–5 feet off the ground, in high-use areas.
- In structures with basements, both the occupied living areas and basement areas may be sampled from a risk management perspective.
- For multistory residential buildings, consideration should be given to collecting one sample on each floor or other appropriate sample locations.
- If indoor air samples are being collected as a stand-alone determination of the VI pathway, a second confirmation sample may be necessary in colder climates 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.
- However, in those cases where the results are an order of magnitude below the appropriate screening levels, a second round of sampling is likely not necessary.

D.8.4 Analysis Methods

The most common contaminants of potential concern for VI investigations are VOCs though SVOCs are also of concern. Table D-3 (at the end of this appendix) lists available methods for VOCs and SVOCs.

The TO-14A and TO-15 methods are 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 RLs is not always the best or most viable option. TO-15 utilizes a GC/MS as the detector. The MS can be run in two different modes: full scan and selective ion monitoring (SIM). (Note: Some compound selectivity and the ability to identify unknowns may be lost in the use of SIM analysis due to limiting the masses scanned.) Standard TO-15 is normally run in the full-scan mode and can give a large list of approximately

70 compounds with RLs ranging 0.2–0.5 ppbv. This analyte list and RLs are generally more than sufficient when analyzing soil gas. In the SIM mode, TO-15 has the ability to reach RLs ranging 0.002–0.010 ppbv for a smaller list of (12–15) compounds. (Check with your laboratory, which may have its own list of compounds.) Because soil gas samples generally have COCs at higher concentrations than the SIM method can calibrate to, the SIM method is appropriate for only indoor and ambient air samples.

It is important to note that QA/QC protocols may vary greatly among 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.

D.9 SAMPLING OF CRAWL SPACES (INTERIOR)

Many crawl spaces are designed with vents and may allow outdoor air exchange, so the concentration in the crawl space may be inversely proportional to the ventilation rate, which is not usually controlled. This effect can influence sampling results, as well as the vapor intrusion migration pathway analysis. Other types of crawl spaces have limited access, making it more difficult to collect samples.

Typically, crawl-space samples are collected following protocols similar to those for 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 get a representative value in the crawl space.

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).

D.10 AMBIENT (OUTDOOR) AIR SAMPLING

When sampling indoor air as part of a vapor intrusion study, outdoor ambient air samples should be also collected to characterize site-specific outdoor air background conditions. Ambient air could possibly contain numerous volatile compounds, especially in highly populated or industrialized areas. The outdoor ambient air levels of some volatile compounds 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 ~3–5 feet off the ground (at the approximate midpoint of the ground-story level of the building) and ~5–15 feet away from the building.

Representative samples should be placed to minimize bias toward obvious sources of volatile chemicals (e.g., automobiles, lawn mowers, oil storage tanks, gasoline stations, industrial

facilities, etc.). Outdoor air samples should be collected and analyzed by the same method as indoor air samples.

For determining ambient air concentrations, USEPA recommends that ambient sampling begin at least 1 hour and preferably 2 hours before indoor air monitoring begins and continue until at least 30 minutes before indoor monitoring is complete. This practice is recommended since 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.

D.11 SUPPLEMENTAL TOOLS/DATA USEFUL FOR VI INVESTIGATIONS

D.11.1 Emission Flux Chamber Method

Flux chambers are enclosures placed directly on the surface (e.g., ground, floor) for a period of time, and the 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 assuming a room ventilation rate. The calculated room concentration can be compared directly to allowable room concentrations for the volatiles 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. The method has long been used by regulatory agencies at hazardous waste sites and it is widely used for measuring trace emissions from natural soils, but its application to vapor intrusion assessments is relatively limited.

The testing is typically conducted in one of two modes: dynamic or static. In dynamic systems, a sweep gas is introduced into the chamber to maintain a large concentration gradient across the emitting surface. The effluent air from the chamber is collected using canisters and analyzed for COCs. This 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, sumps, etc.) are often concealed by floor coverings, walls, stairs, etc. For structures, the method has more 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 vapor intrusion.

Flux chambers are best suited for situations where measurement from bare soils is desired, such as the following:

- homes with dirt basements or crawl spaces
- mobile homes above unfinished slabs or soil
- evaluation of future-use scenarios at sites without existing buildings
- to demonstrate the occurrence of bioattenuation from areas with shallow soil gas contamination (<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 get a representative value under the footprint of the building (analogous to placing enough borings on a typical site), 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, it is recommended that chambers be deployed for long enough periods to enable temporal variations to be assessed, similar to indoor air measurements (8–24 hours depending upon the conditions; 24 hours if large temperature differences exist between day and night (County of San Diego *Site Assessment Manual*)).

More details on the flux chamber method can be found in Kienbusch 1986, Eklund 1992, and Hartman 2003.

D.11.2 Determination of Slab-Specific Attenuation Factor Using Tracers

Measurement of a conservative tracer inside the structure and in the subslab soil gas can enable calculation of a site-specific attenuation factor. 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-DCE or cis-1,2-DCE, 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. However, if subslab samples are being collected, concurrent collection of radon or another tracer data may prove useful and is generally not too 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 2006), but analysis of the samples may not be readily available from most commercial laboratories.

D.11.3 Determination of Room Ventilation Rate Using Tracers

The indoor air concentration is inversely proportional to the room ventilation rate: doubling the ventilation rate halves the indoor air concentration. The default ventilation rates used by USEPA and many other agencies are conservative: room exchange rates of once every 1–4 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 measured or assumed at the default value. ASTM Method E 741 describes techniques for measuring ventilation rates using gaseous tracers such as helium or sulfur hexafluoride (SF₆).

Typically, a pulse input of tracer gas is 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 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 (i.e., typically after three or four air exchanges).

The 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.

D.11.4 Differential Pressure Measurements

Models and look-up values used by USEPA and many state regulatory agencies are based on assumed advective flow into the structure due to a pressure gradient of 4 pascals. This assumption can be checked in the field to provide another line of evidence to evaluate vapor intrusion using a digital micromanometer attached to a subslab soil gas probe. It is often advisable to use one with data-logging capabilities 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 could provide information on the contaminant source. For example, if a building is overpressured relative to the subsurface, measured indoor concentrations might be more likely attributable to aboveground sources. Conversely, if the building is underpressured relative to the subsurface, measured indoor concentrations might be more likely attributable to subsurface sources. Commercial buildings with large HVAC systems, and perhaps residences with air-conditioning units, may fall into the former category. Many structures in cold environments, especially residences, will fall into the latter category when the heaters are running. These data will usually be used as a secondary line of evidence in support of indoor air quality data or other lines of evidence.

D.11.5 Real-Time and Continuous Analyzers

As with any type of site investigation, it is difficult to reach any conclusions with any degree of confidence with only a handful of data points. Vapor intrusion data sets consisting of one soil gas and/or indoor air analysis per structure may be very difficult to interpret, but cost and access limitations often preclude multiple analyses. Real-time analyzers can be used less expensively to collect multiple samples that can be used to locate problem structures, vapor migration routes into structures, and volatile sources inside the structures. 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 allow forensic approaches to be applied.

A variety of real-time analyzers exist, including handheld logging instruments (PID, FID, thermal conductivity detector [TCD], infrared analyzers, z-Nose®, and ppbRAE), automated GCs, portable MSs, and USEPA's own Trace Atmospheric Gas Analyzer (TAGA). Many of these will have applicability that is limited by their sensitivity or cost.

D.11.6 Forensic Data Collection and Analysis

Forensic approaches attempt to determine the source of any detected volatiles through a detailed study of the nature of contamination with 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 developed to provide data for regulatory purposes. The environmental forensics approaches are more sophisticated analytical techniques that have the ability to produce chemical fingerprints that are source specific. Potential fingerprinting strategies include the following:

Forensics Used at Colorado's Redfields Site
Forensic approaches were used at the Redfield Rifles site in Colorado to determine whether the source of subsurface contaminants was in the vadose zone or the overlying structure (McHugh, De Blanc, and Pokluda 2006).

- Using compound ratios (e.g., DCE/TCE) and comparing them in the soil gas and indoor air results
- Distinguishing between different types of hydrocarbons (e.g., diesel, gasoline, jet fuels) using comprehensive analysis of the samples, including total chromatographic patterns
- Using isotope ratios (e.g., Cl-36, C-13) to distinguish between chlorinated solvent manufacturers and identify multiple sources in comingled groundwater plumes

Environmental forensics is a developing approach that will likely be increasingly important in regulatory enforcement actions and cost-recovery litigation.

D.11.7 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 employed. Air permeability of the vadose zone can be determined from either in situ or laboratory measurements. In situ measurements test a larger portion of the subsurface than a laboratory measurement of a small core sample. In situ measurements of air permeability should 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 unsaturated zone, which may act as partial vapor barriers.

D.11.8 Meteorological Data

A variety of weather conditions can influence soil gas or indoor air concentrations. The radon literature suggests that temporal variations in the soil gas are typically less than a factor of 2 during a season and less than a factor of 5 from season to season). Recent soil gas data from

Endicott, New York and Casper, Wyoming are in agreement with the radon results. For soil gas, the importance of these variables will be greater the closer the samples are to the surface and are unlikely to be important at depths greater than 3–5 feet below the surface or structure foundation.

Indoor air may be more susceptible to weather conditions, so collection of meteorological data can be helpful to assessing the vapor intrusion risk:

- Rainfall events—Precipitation can affect vapor intrusion rates and possible soil gas concentrations. Percolation of water through the soil can displace soil gas and lead to a short-term spike in vapor intrusion. The increased soil moisture after a rain event can reduce vapor transport through the soil due to reduced effective porosity and permeability. Measurements made during or immediately after a significant rain event (e.g., >1 inch) may not be representative of long-term average conditions. For other sites, however, frequent rainfall is common, and testing soon after a rain 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 condition can create a number of situations including an inflow of air into the vadose zone on the windward side of a building, outflow of soil gas on the leeward side, and overpressurization of the area under the building versus the building itself. Such a flow pattern can lead to higher oxygen concentrations at deeper depths on one side of a building than on the other, which is relevant at sites with hydrocarbon contamination. Recent studies by the American Petroleum Institute suggest 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. Unusually windy conditions should be avoided for sampling to the extent possible.
- 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, so these conditions should be noted where applicable.
- 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 on soil gas concentrations will be minimal; however it may be significant near or during major storm events or for sites with very deep unsaturated zones, especially if the geologic materials are fractured (Parker 2003).

D.11.9 Pneumatic Testing

In some cases, geologic layers can form partial or complete barriers to upward vapor transport toward overlying buildings, particularly 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, where 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, 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 screening in the geologic layer below the fine-grained unit, where the vacuum versus time data collected at the monitoring well is analyzed using the Hantush-Jacob (1955) leaky-aquifer solution to calculate the vertical leakage (or absence thereof) through the fine-grained “confining” layer, as described by Thrupp, Gallinatti, and Johnson (1996). 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.

D.11.10 Manipulating Pressure Differentials

One possible method for distinguishing subsurface vapor intrusion from background sources is to collect indoor air samples with and without manipulating the pressure differential from the subsurface to indoor air. This 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 vapor intrusion, the concentrations of chemicals intruding from the subsurface will be reduced and the concentrations of chemicals from background sources will be largely unaffected. Folkes (2000) reported measured indoor air concentrations for several chlorinated hydrocarbons before and after the operation of a subsurface depressurization system to mitigate subsurface vapor intrusion.

Table D-3. Summary of analytical methods for soil gas, indoor and ambient air samples^a

Parameter	Method	Sample media/storage	Description ^b	Method holding time	Reporting limit ^c
VOCs					
BTEX, MTBE, TPH	TO-3	Tedlar bag or canister/ambient temperature	GC/FID	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 and nonpolar 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 and nonpolar VOCs	TO-17 ^d	Sorbent tube, chilled <4°C	GC/MS	30 days	1–3 µg/m ³
VOCs	8021B modified ^e	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 ^e	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 ^d	High-volume collection (may require large sample volume, e.g., 300 m ³)/PUF/XAD media, chilled <4°C	GC/MS	Extracted within 7 days of collection and analyzed within 40 days of extraction	5–10 µg/sample
Low-level polycyclic aromatic hydrocarbons (PAHs)	TO-13A SIM ^d	High-volume collection (may require large sample volume, e.g., 300 m ³)/PUF/XAD media, chilled <4°C	GC/MS	Extracted within 7 days of collection and analyzed within 40 days of extraction	0.5–1 µg/sample
Pesticides and polychlorinated biphenyls (PCBs)					
Pesticides and PCBs	TO-4A ^d or TO-10A ^d	High-volume collection (may require large sample volume, e.g., 300 m ³)/PUF media, chilled <4°C	GC/ECD	Extracted within 7 days of collection and 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

Parameter	Method	Sample media/storage	Description ^b	Method holding time	Reporting limit ^c
Fixed gases (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
<i>TPH–alkanes</i>					
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 ^d
C4–C12	TO-15	Canister or Tedlar bag/ambient temperature	GC/FID	3 days for Tedlar bag, 30 days for canister	0.1 ppmv

^a This is not an exhaustive list. Some methods may be more applicable in certain instances. Other proprietary or unpublished methods may also apply.

^b ECD = electron capture detection, FID = flame ionization detection, GC = gas chromatography, MS = mass spectrometry, PID = photoionization detection, TCD = thermal conductivity detection

^c 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.

^d The indicated methods use a sorbent-based sampling technique. The detection limits will depend on the amount of air passed through the media.

^e Method is generally applicable only for on-site analysis of soil gas samples.

Table D-4. Matrix of various quantitative options to evaluate vapor intrusion

Measurement approach	Source at depth (> 5 feet) directly under building				Shallow source (<5 feet) under building				Source in vadose zone adjacent to building				Special conditions			
	Undeveloped site	Residential with basement or slab-on-grade floor	Residential with dirt floor or crawl space	Commercial/industrial	Undeveloped site	Residential with basement or slab-on-grade floor	Residential with crawl space or dirt floor	Commercial/industrial	Undeveloped site	Residential with basement or slab-on-grade floor	Residential with crawl space or dirt floor	Commercial/industrial	Petroleum hydrocarbons	Vapor migration routes	Wet basement	Very-low-permeability soils
Shallow groundwater (near water table)	P	P	P	P	P	O	O	O	O	O	O	O	S	O	P	O
Deep (> 5 feet) soil gas	P	P	P	P	N	N	N	N	P	P	P	P	P	O	N	N
Shallow (5 feet) soil gas	P	P	P	P	P	P	P	P	P	P	P	P	P	P	N	N
Subslab soil gas	N	P	N	P	N	P	N	P	N	S	N	S	P	O	N	P
Vertical profile of soil gas	O	O	O	O	N	N	N	N	O	O	O	O	P	O	N	N
Indoor air	N	S	S	S	N	S	S	S	N	S	S	S	S	P	S	S
Ambient (outdoor) air	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Passive soil gas sampling	S	S	S	S	S	S	S	S	S	S	S	S	S	S	N	S
Emission flux chambers	O	N	S	O	O	N	S	O	O	N	S	O	O	N	N	O
Tracer testing for alpha factor	N	O	O	O	N	O	O	O	N	N	N	S	O	O	N	O
Tracer testing for ventilation rate	N	O	O	S	N	O	O	S	N	O	O	O	O	O	O	O
Pressure differential monitoring	N	O	O	O	N	O	O	O	N	O	O	O	O	O	N	O
Real-time analyzers	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O
Meteorological data	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O	O

This rating indicates that each tool can be used for the category lower in the hierarchy.

P = primary investigative tool, can potentially be used as a principal tool for assessing VI.

S = secondary investigative tool, can be used to develop CSM and/or as a line of evidence in support of another line of evidence.

O = Optional investigative tool, may be useful to further define VI pathway or as means to focus primary investigative tools.

N = not usually appropriate as an investigative tool for vapor intrusion assessment.

Table D-5. Pros and cons of various investigative strategies

Measurement	Relative Advantages	Relative Disadvantages	Comments
Deep soil gas (>5 feet below slab)	<ul style="list-style-type: none"> Existing data may already be available for some sites Less chance of short-circuiting by atmospheric air Temporal variations in concentration minimal 	<ul style="list-style-type: none"> 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 attenuation as a function of vertical transport distance. However, deep soil gas sampling is conservative for screening purposes.
Shallow soil gas (<5 feet below slab or basement floor)	<ul style="list-style-type: none"> Standard equipment and approaches have been developed Media most likely to intrude into receptors Data can be collected outside the building 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Provides more representative subsurface data for sites with surface releases (e.g., spills and leaks) Gives concentrations immediately below building and receptors 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Measure actual contaminant emissions from subsurface Takes into account all subsurface processes such as biodegradation, advection, sorption Eliminates interpretation using attenuation factor or model 	<ul style="list-style-type: none"> 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 Not considered by most regulatory agencies 	This approach is best suited for evaluating future-use scenarios on undeveloped land, houses with dirt floor basements or crawl spaces, and to confirm bioattenuation in shallow vadose zone (<3 feet bgs).
Soil gas attenuation (α) factors	<ul style="list-style-type: none"> Quick and very easy 	<ul style="list-style-type: none"> Attenuation factors used for this purpose tend to be very conservative (e.g., <50th percentile) Empirical attenuation factors may be biased high due to sources other than vapor intrusion 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.

Measurement	Relative Advantages	Relative Disadvantages	Comments
Slab-specific attenuation factor determination (from subsurface tracer)	<ul style="list-style-type: none"> Naturally occurring compounds (e.g., 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 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Relatively simple to collect samples Direct measurement of contaminant concentrations in buildings May be more convincing to occupants 	<ul style="list-style-type: none"> 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 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 	Time-integrated samples are typically collected (e.g., 24-hour samples for residential sites and 8-hour samples for industrial sites).
Crawl-space air	<ul style="list-style-type: none"> Simple to measure 	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> Relatively simple to measure Can provide evidence of direction of vapor transport (in or out) 	<ul style="list-style-type: none"> Requires subslab port or other subsurface sampling point Temporal variations complicate interpretation and often requires multiple sampling events 	Detection levels down to 1 pascal can be obtained using inexpensive 0–0.25 inch H ₂ O manometric gauge.
Building ventilation rate	<ul style="list-style-type: none"> Very simple to measure (standard ASTM method exists) For many commercial buildings, rate is already known from design specifications Value can be >10 times default parameters allowed in models 	<ul style="list-style-type: none"> 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.

Measurement	Relative Advantages	Relative Disadvantages	Comments
Forensics	<ul style="list-style-type: none"> Can differentiate sources of contaminants 	<ul style="list-style-type: none"> Typically requires a significant amount of data Methods still being developed Background sources can complicate interpretation 	Forensic approaches are not likely to be used until later rounds of an investigation.
Continuous analyzers	<ul style="list-style-type: none"> Provide large amounts of data Can help sort out temporal variations and background scatter 	<ul style="list-style-type: none"> Limited use 	Larger data sets allow correlation to other variables such as pressure differentials, wind speed, and HVAC systems.
Soil physical properties	<ul style="list-style-type: none"> Easy to measure Enable site-specific values to be used in predictive models Values can be >10 times default parameters in models 	<ul style="list-style-type: none"> 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 percentage of water content and permeability.
Groundwater data	<ul style="list-style-type: none"> Monitoring wells already exist for many sites (previous data) Acceptable to most agencies Familiar media to most investigators Temporal effects minimal 	<ul style="list-style-type: none"> Look-up values, attenuation factors, or models tend to be extremely conservative, so VI risk is often overestimated Existing data may be from a well that is not optimally screened for upper water table 	This approach often used as an initial screen.
J&E model with groundwater or soil gas data	<ul style="list-style-type: none"> Quick and easy Model can account for various site-specific factors Potential future scenarios can be evaluated 	<ul style="list-style-type: none"> 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 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 feet 	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).

APPENDIX E

Quality Assurance Considerations

QUALITY ASSURANCE CONSIDERATIONS

Quality assurance and quality control procedures should be implemented in every step of the assessment process to ensure the collection of data of acceptable quality. This appendix discusses some general QA/QC considerations for field and laboratory activities.

QA/QC for Active Sampling

The majority of the soil gas and indoor air sampling conducted for the investigation of the vapor intrusion pathway is for VOCs. This section focuses on USEPA Method TO-15, which uses specially treated, certified clean, leak-free canisters for the collection of air samples in the field. Canisters are shipped to the field under vacuum of approximately –30 inches Hg. Flow controllers, calibrated in the laboratory, are sent with the canisters to allow the canisters to collect the samples over a set time period.

Below are *examples* of QA/QC procedures that should be considered. This list is not meant to be exhaustive:

- Analyte list and reporting limits—Discuss your program-required analyte list and reporting limits with the laboratory to ensure they will be met.
- Determine from the laboratory whether its reporting limit refers to a method detection limit (MDL), practical quantitation limit (PQL), or some other reporting limit.
 - MDL = 99% confidence that data is distinguishable from background noise
 - PQL = an estimated value usually 3–5 times the MDL
 - RL = concentration \geq the lowest calibration standard $>$ MDL

(www.depweb.state.pa.us/landrecwaste/lib/landrecwaste/land_recycling/workshops/usingyourlabwisely.ppt#349,14,How)
- Laboratory certification—Many regulatory agencies across the country require laboratories to be certified to conduct air analysis.
- Certified canisters—The laboratory must certify that the canister is leak-free and clean below the RL for the VOCs of concern.
- Flow controllers—The laboratory provides a flow controller that is clean and calibrated to collect a sample over a specified time frame (e.g., 30 minutes to 24 hours).
- SOPs—Ensure that the sampling crew follows documented, reproducible field procedures.
- System leak checks for soil gas samples—Use a tracer gas to check for leakage around the sampling probe and analytical sampling train.
- Initial and final vacuum readings—The sampler should take the canister vacuum reading before and after sampling to ensure that the canister was leak-free upon receipt in the field and that the flow controller collected the sample over the specified amount of time.
- Precautions should be taken to avoid sample interference such as fueling vehicles prior to sampling or using permanent marking pens in the field.
- Required laboratory QC samples—Mass spectral tuning, initial calibration, continuing calibration verification, laboratory control spike, and method blank.

- Additional QC samples (if needed):
 - Trip blanks refer to canisters sent out with the canister batch to test for the presence of contaminants introduced during transit and storage.
 - Method blanks refer to purified gas (air, nitrogen) samples collected through the sampling system to test for the presence of contaminants introduced by the sampling methods.
- Analytical holding time per USEPA TO-15—Analysis of canister samples for VOCs must be completed within 30 days from collection; check with the state or region to verify holding time requirements.

QA/QC for Passive VOC Sampling

As with any site investigative tool, passive sampling requires adequate QA/QC to provide data of sufficient quality to ensure proper decision making. Modified USEPA Methods 8260 and 8270 may be used for analysis, or USEPA TO-17 using thermal desorption followed by GC/MS may be used. QA/QC requirements are based more on DQOs than on prescriptive procedures. Specific QA/QC procedures vary depending on the manufacturer of the sampler and on the analytical laboratory. Therefore, it is important to understand what procedures will be used and to determine whether they are adequate to meet DQOs.

At a minimum QA/QC procedures should consider the following:

- Passive sampler installation, retrieval, and handling—To ensure consistency of deployment and sample integrity prior to analysis.
- Units of measure—Concentration or mass (or some other relative) units. If concentration data are to be provided, are there sufficient data to verify sampling rates, indifference to changing air flow, and sampler capacity?
- Detection limit—Are the sampler and analytical method of sufficient sensitivity?
- Cleanliness of sampler—Are procedures in place to verify the cleanliness of the sampler? The sampler background must be sufficiently less than RLs.
- Instrument tuning—Applicable if MS detection is used.
- Instrument calibration—Are target compounds used for calibration and concentration ranges adequate to cover COCs and suspected sample levels?
- Control samples—Method, trip, and field blanks to verify integrity of samples during shipment and potential levels of background.
 - Method blanks are clean adsorbent material analyzed by the applicable analytical method to determine any potential background levels of target compounds contributed by the analytical method.
 - Trip blanks are unexposed passive samplers that accompany samplers during transport to the field and then to the laboratory to determine any potential background levels of target compounds that may have been contributed during transport.
 - Field blanks (for soil gas sampling only) are passive samplers exposed to ambient conditions for the same amount of time field-exposed samplers are exposed to ambient conditions prior to installation in the subsurface, intended to determine the potential

contribution of background levels of target compounds contributed by ambient air and not soil gas.

- Replicate analyses—If replicate analysis is required, does that sampler allow for multiple analyses or do multiple samplers need to be co-located?
- Are matrix spikes required?

Other QA/ QC Considerations

- 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.
- For subsurface applications, the samplers should also have a design that keeps soil, microbes, liquid water, and other contaminants from coming in direct contact with the adsorbent.
- The adsorbent material should be hydrophobic to minimize water vapor uptake.
- Accurate time recording is essential for comparison of results, and all samplers in a given medium should be deployed for a consistent amount of time. The time may vary for different media. For example, if soil gas concentrations are expected to be higher than indoor air concentrations, the soil gas samplers may approach saturation before the indoor air samplers have sufficient mass to reach analytical detection limits, in which case, the indoor air samplers should be deployed for a longer period than the subsurface samplers.

APPENDIX F

Regulator's Checklist for Reviewing Soil Gas Data



REGULATOR'S CHECKLIST FOR REVIEWING SOIL GAS DATA

ITRC Vapor Intrusion Pathway Overview

SAMPLE COLLECTION ISSUES

Active Soil Gas Surveys

- ☐ Did the probe rod have an inert internal tube (stainless steel, Teflon®, nylon)?
- ☐ Was the probe adequately decontaminated between samples?
- ☐ Were at least three dead volumes of the probe purged?
 - ⇒ *Avoid excessive purging, unless field screening (O₂, CO₂, PID, or FID and tracer gas) conducted to demonstrate absence of atmospheric air intrusion.*
- ☐ Were samples collected deep enough to minimize air infiltration?
 - ⇒ *At least 5 feet bgs unless special precautions used to minimize purge volume and confirm absence of atmospheric air.*
- ☐ Did it rain shortly before the sampling event?
 - ⇒ *Soil gas sampling should be avoided following significant precipitation.*
 - ⇒ *Generally, there is no consensus on how much rain can fall or how long you should wait. It depends on soil type, amount of rain, and previous soil moisture content.*
- ☐ Was a reliable method used to ensure the absence of atmospheric air leakage?
 - ⇒ *Probe sealed at the surface and throughout the borehole annulus?*
 - ⇒ *Tracer compound used to demonstrate no leakage down or around probe and at all sample train fittings?*
- ☐ Were samples collected close to the surface (<3 feet bgs) repeated?
- ☐ Were small sample volumes collected?
- ☐ Were samples collected in appropriate containers for the COC(s)?
- ☐ If canisters were used, was each canister certified clean or batch-tested?
- ☐ Were flow controllers and sample trains reused?
 - ⇒ *If yes, they should be cleaned between samples.*
- ☐ Were vacuum pumps used in the sample collection?
- ☐ Were excessive vacuums required to obtain a sample?
 - ⇒ *>10 inches of H₂O should be avoided.*
- ☐ Were samples collected upstream of the vacuum pump?
- ☐ Were samples analyzed on or off site?
- ☐ For canisters, were samples stored at ambient air temperature?
- ☐ Were samples analyzed within recommended holding times?
- ☐ If both on-site and off-site analyses were performed, do the results generally agree?

Passive Soil Gas Surveys

- Were method and trip blanks analyzed?
 - ⇒ *Needed to show absence of contaminants from laboratory or transportation back and forth to site.*
- Were samplers left in the ground for consistent and sufficient time?
 - ⇒ Generally a few days to two weeks.
 - ⇒ Collect in same sequence as deployed.
- Were duplicate samples collected, and how do they compare?
- Are data used appropriately?
 - ⇒ For what purpose?
 - ⇒ Were active soil gas samples collected for comparison?
 - ⇒ How well do passive and active samples compare?
- Could measured values be from infiltration of contaminated atmospheric air or from an overlying surface (e.g., asphalt, dirty soil)?
- Are relative concentrations of compounds detected consistent with expectations from other media (soil gas, groundwater, bulk soil)?

Flux Chamber Surveys

- Were the sample locations representative?
 - ⇒ Near vapor migration routes?
 - ⇒ Open ground, covered ground, cracked ground covers?
- How long was the deployment time? Was it long enough to average temporal variations?
 - ⇒ Match indoor air default collection times.
- Was a sweep gas used? Was the outflow balanced to the inflow to ensure no leaks?
 - ⇒ If outflow lower than inflow, sweep gas exiting bottom.
 - ⇒ Pressure measurements not adequate to test this.
- Did the chamber concentration reach high enough values to influence the flux?
 - ⇒ Should be no more than 20% of risk-based maximum flux value.
- What volume of vapor was collected from the chamber?
 - ⇒ Volume collected should be less than 20% of chamber volume.
- How fast was it collected? Did it create advective flow from the subsurface or sides?
 - ⇒ Flow should be less than 200 mL/min.
- Was the chamber subjected to temperature extremes?
 - ⇒ Shield from direct sunlight.
 - ⇒ Chamber surface must stay above dew point.

SAMPLE ANALYSIS ISSUES

The following questions should be asked when examining the analysis of any type of soil gas sample—active, passive, or flux chambers.

- ☐ What methods are being used? Can they detect the target compounds at the required levels of sensitivity?
- ☐ Have the method required calibration standards been analyzed?
- ☐ Are the reported values within the documented calibration range of the instrument?
- ☐ Are any compounds coeluting on a non-halogen-specific detector?
- ☐ Have the method required QA/QC samples been analyzed (blanks, duplicates, etc.)?
- ☐ Are the calibration standards within method-required holding times and traceable to a certified source?
- ☐ In what units are the data reported (μL , $\mu\text{g}/\text{m}^3$, ppbv, ppmv)?
- ☐ For high concentrations, have large dilutions been performed?

Passive Soil Gas Samples

In addition to the analytical issues summarized above, the following issues should be examined with passive soil gas samples:

- ☐ How are the samples desorbed from the collector?
- ☐ Is the desorption process quantitative, and does it fractionate?
- ☐ What units are the data reported in (mass, concentration in headspace, etc.)?

Surface Flux Chamber Samples

In addition to the analytical issues summarized above, the following issues should be examined with surface flux chamber samples:

- ☐ Is the method detection limit low enough to reach the expected chamber concentrations for the acceptable flux?

APPENDIX G

Indoor Air Sampling Questionnaire

**NEW YORK STATE DEPARTMENT OF HEALTH
INDOOR AIR QUALITY QUESTIONNAIRE AND BUILDING INVENTORY
CENTER FOR ENVIRONMENTAL HEALTH**

This form must be completed for each residence involved in indoor air testing.

Preparer's Name _____ Date/Time Prepared _____

Preparer's Affiliation _____ Phone No. _____

Purpose of Investigation _____

1. OCCUPANT:

Interviewed: Y / N

Last Name: _____ First Name: _____

Address: _____

County: _____

Home Phone: _____ Office Phone: _____

Number of Occupants/persons at this location _____ Age of Occupants _____

2. OWNER OR LANDLORD: (Check if same as occupant ____)

Interviewed: Y / N

Last Name: _____ First Name: _____

Address: _____

County: _____

Home Phone: _____ Office Phone: _____

3. BUILDING CHARACTERISTICS

Type of Building: (Circle appropriate response)

Residential
Industrial

School
Church

Commercial/Multi-use
Other: _____

If the property is residential, type? (Circle appropriate response)

Ranch	2-Family	3-Family
Raised Ranch	Split Level	Colonial
Cape Cod	Contemporary	Mobile Home
Duplex	Apartment House	Townhouses/Condos
Modular	Log Home	Other: _____

If multiple units, how many? _____

If the property is commercial, type?

Business Type(s) _____

Does it include residences (i.e., multi-use)? Y / N If yes, how many? _____

Other characteristics:

Number of floors _____ Building age _____

Is the building insulated? Y / N How air tight? Tight / Average / Not Tight

4. AIRFLOW

Use air current tubes or tracer smoke to evaluate airflow patterns and qualitatively describe:

Airflow between floors

Airflow near source

Outdoor air infiltration

Infiltration into air ducts

5. BASEMENT AND CONSTRUCTION CHARACTERISTICS (Circle all that apply)

- a. Above grade construction: wood frame concrete stone brick
- b. Basement type: full crawlspace slab other _____
- c. Basement floor: concrete dirt stone other _____
- d. Basement floor: uncovered covered covered with _____
- e. Concrete floor: unsealed sealed sealed with _____
- f. Foundation walls: poured block stone other _____
- g. Foundation walls: unsealed sealed sealed with _____
- h. The basement is: wet damp dry moldy
- i. The basement is: finished unfinished partially finished
- j. Sump present? Y / N
- k. Water in sump? Y / N / not applicable

Basement/Lowest level depth below grade: _____ (feet)

Identify potential soil vapor entry points and approximate size (e.g., cracks, utility ports, drains)

6. HEATING, VENTING and AIR CONDITIONING (Circle all that apply)

Type of heating system(s) used in this building: (circle all that apply – note primary)

Hot air circulation	Heat pump	Hot water baseboard	
Space Heaters	Stream radiation	Radiant floor	
Electric baseboard	Wood stove	Outdoor wood boiler	Other _____

The primary type of fuel used is:

Natural Gas	Fuel Oil	Kerosene
Electric	Propane	Solar
Wood	Coal	

Domestic hot water tank fueled by: _____

Boiler/furnace located in: Basement Outdoors Main Floor Other _____

Air conditioning: Central Air Window units Open Windows None

Are there air distribution ducts present? Y / N

Describe the supply and cold air return ductwork, and its condition where visible, including whether there is a cold air return and the tightness of duct joints. Indicate the locations on the floor plan diagram.

7. OCCUPANCY

Is basement/lowest level occupied? Full-time Occasionally Seldom Almost Never

Level General Use of Each Floor (e.g., familyroom, bedroom, laundry, workshop, storage)

Basement	<hr/>
1 st Floor	<hr/>
2 nd Floor	<hr/>
3 rd Floor	<hr/>
4 th Floor	<hr/>

8. FACTORS THAT MAY INFLUENCE INDOOR AIR QUALITY

- | | |
|--|------------------------------------|
| a. Is there an attached garage? | Y / N |
| b. Does the garage have a separate heating unit? | Y / N / NA |
| c. Are petroleum-powered machines or vehicles stored in the garage (e.g., lawnmower, atv, car) | Y / N / NA
Please specify <hr/> |
| d. Has the building ever had a fire? | Y / N When? <hr/> |
| e. Is a kerosene or unvented gas space heater present? | Y / N Where? <hr/> |
| f. Is there a workshop or hobby/craft area? | Y / N Where & Type? <hr/> |
| g. Is there smoking in the building? | Y / N How frequently? <hr/> |
| h. Have cleaning products been used recently? | Y / N When & Type? <hr/> |
| i. Have cosmetic products been used recently? | Y / N When & Type? <hr/> |

- j. Has painting/staining been done in the last 6 months? Y / N Where & When? _____
- k. Is there new carpet, drapes or other textiles? Y / N Where & When? _____
- l. Have air fresheners been used recently? Y / N When & Type? _____
- m. Is there a kitchen exhaust fan? Y / N If yes, where vented? _____
- n. Is there a bathroom exhaust fan? Y / N If yes, where vented? _____
- o. Is there a clothes dryer? Y / N If yes, is it vented outside? Y / N
- p. Has there been a pesticide application? Y / N When & Type? _____

Are there odors in the building?

Y / N

If yes, please describe: _____

Do any of the building occupants use solvents at work? Y / N

(e.g., chemical manufacturing or laboratory, auto mechanic or auto body shop, painting, fuel oil delivery, boiler mechanic, pesticide application, cosmetologist)

If yes, what types of solvents are used? _____

If yes, are their clothes washed at work?

Y / N

Do any of the building occupants regularly use or work at a dry-cleaning service? (Circle appropriate response)

Yes, use dry-cleaning regularly (weekly)

No

Yes, use dry-cleaning infrequently (monthly or less)

Unknown

Yes, work at a dry-cleaning service

Is there a radon mitigation system for the building/structure? Y / N Date of Installation: _____

Is the system active or passive? Active/Passive

9. WATER AND SEWAGE

Water Supply: Public Water Drilled Well Driven Well Dug Well Other: _____

Sewage Disposal: Public Sewer Septic Tank Leach Field Dry Well Other: _____

10. RELOCATION INFORMATION (for oil spill residential emergency)

a. Provide reasons why relocation is recommended: _____

b. Residents choose to: remain in home relocate to friends/family relocate to hotel/motel

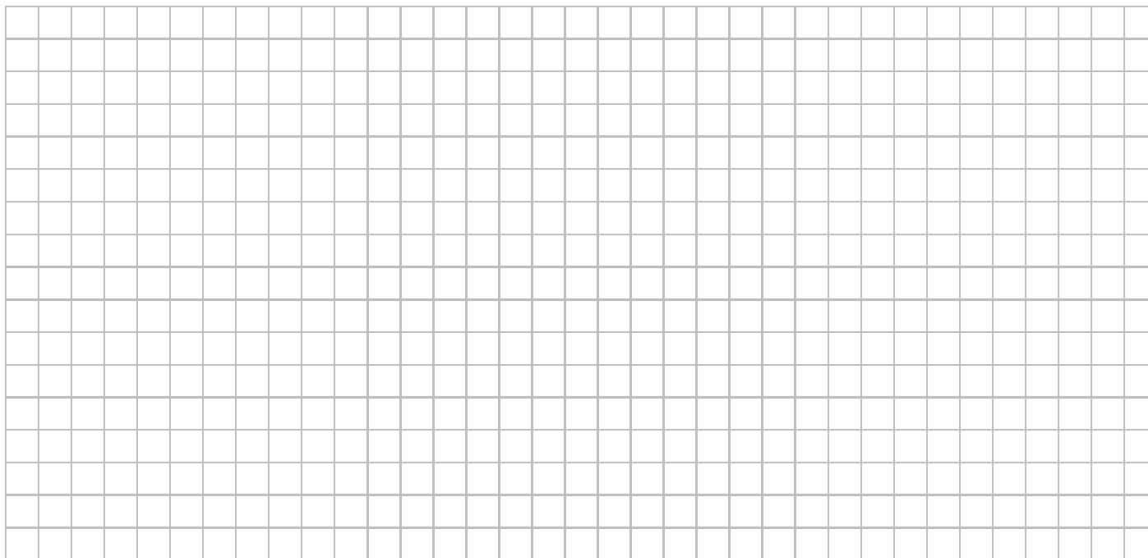
c. Responsibility for costs associated with reimbursement explained? Y / N

d. Relocation package provided and explained to residents? Y / N

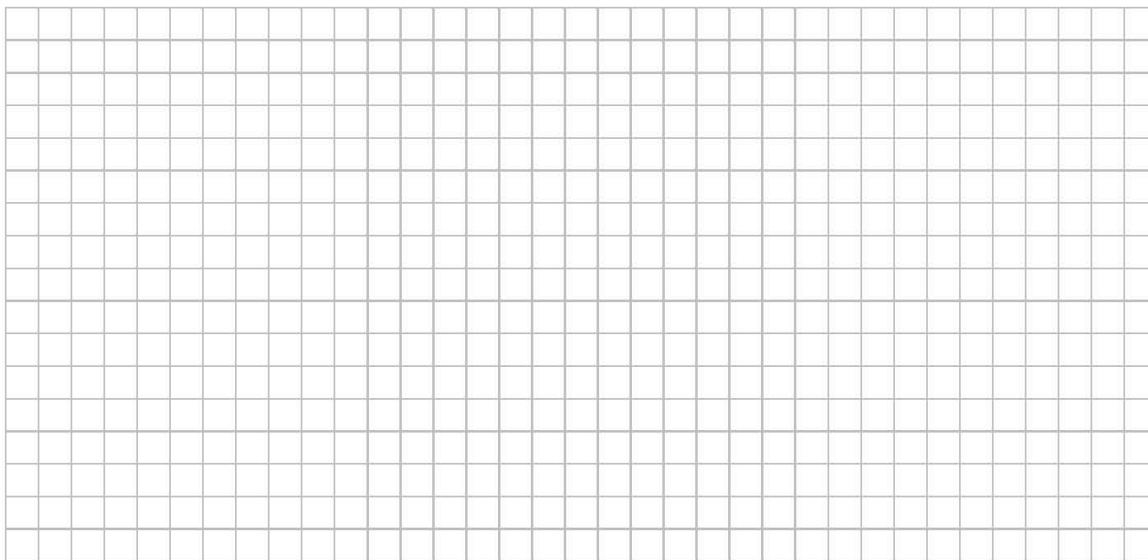
11. FLOOR PLANS

Draw a plan view sketch of the basement and first floor of the building. Indicate air sampling locations, possible indoor air pollution sources and PID meter readings. If the building does not have a basement, please note.

Basement:



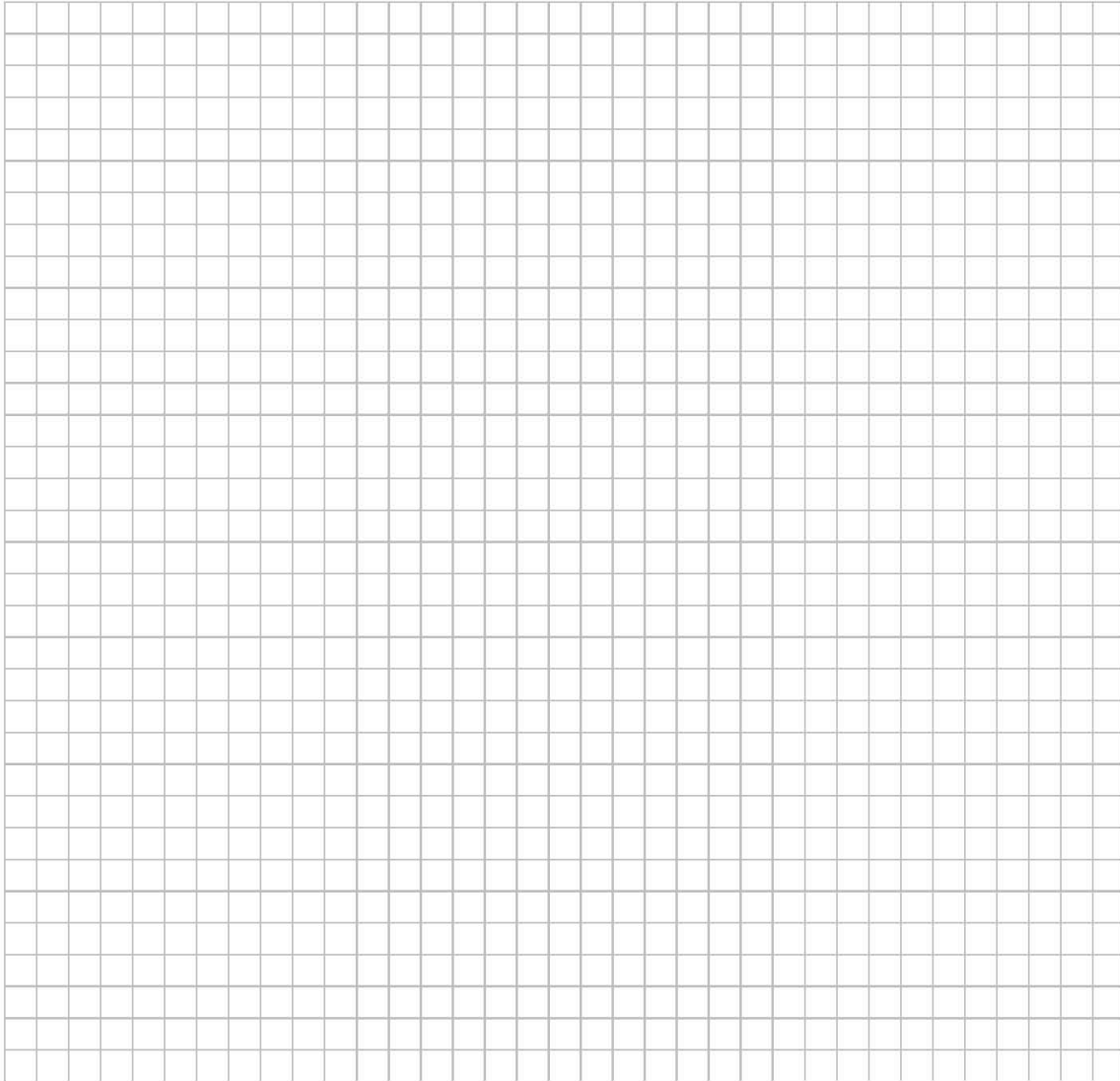
First Floor:



12. OUTDOOR PLOT

Draw a sketch of the area surrounding the building being sampled. If applicable, provide information on spill locations, potential air contamination sources (industries, gas stations, repair shops, landfills, etc.), outdoor air sampling location(s) and PID meter readings.

Also indicate compass direction, wind direction and speed during sampling, the locations of the well and septic system, if applicable, and a qualifying statement to help locate the site on a topographic map.



13. PRODUCT INVENTORY FORM

Make & Model of field instrument used: _____

List specific products found in the residence that have the potential to affect indoor air quality.

Location	Product Description	Size (units)	Condition *	Chemical Ingredients	Field Instrument Reading (units)	Photo ** <u>Y / N</u>

* Describe the condition of the product containers as **Unopened (UO)**, **Used (U)**, or **Deteriorated (D)**

** Photographs of the **front and back** of product containers can replace the handwritten list of chemical ingredients. However, the photographs must be of good quality and ingredient labels must be legible.

APPENDIX H

Development of Screening Levels

DEVELOPMENT OF SCREENING LEVELS

H.1 GENERIC SCREENING LEVELS

In general, generic screening levels are used to determine whether the potential exists for subsurface contaminants to be present in indoor air at levels that could result in adverse health effects to exposed receptors. If the screening levels for the selected medium are not exceeded, then it is possible that no further evaluation of the vapor intrusion pathway is necessary. A screening approach should be protective of human health, while limiting unnecessary investigative cost. This appendix describes methodologies for the development of generic screening levels for various environmental media, including indoor air, crawl-space air, subslab soil gas, soil gas, groundwater, and soil.

Typically, the development of a screening level begins with a target concentration in indoor air. Indoor air target concentrations can be risk-based indoor air concentrations derived using USEPA consensus toxicity criteria, indoor air literature background values, or other agency-established values. Target indoor air concentrations can be used as a basis to establish screening levels in soil, soil gas, and groundwater. Indoor air target levels can be developed for residential and nonresidential exposure scenarios. For industrial sites, the OSHA-acceptable workplace levels (e.g., permissible exposure levels [PELs]) or other acceptable workplace levels may be applicable as indoor air target concentrations, depending on the circumstances and established policies of the regulatory agency. (As previously stated, the oversight regulatory agency should be consulted when determining any value or other actions at sites within their oversight.)

Next, an allowable concentration in a subsurface medium is calculated from a target indoor air concentration, assuming a certain amount of attenuation and dilution through the vadose zone and the building floor slab. The amount of vapor attenuation/dilution from the subsurface media concentration to the indoor air concentration, known as the “attenuation factor,” can be based on either a model or empirical data. Generic attenuation factors derived using a vapor intrusion model—primarily the USEPA version of the Johnson and Ettinger model (USEPA 2004b) or variations—incorporate default soil and building parameters. In addition, specific considerations may be applicable to petroleum hydrocarbons due to biodegradation.

Existing numerical criteria developed by various federal and state agencies to evaluate potential indoor air impacts were reviewed. While this appendix focuses on the development of values to be used in a screening-level evaluation of the vapor intrusion pathway, it is important to note that the existing numerical criteria are developed to serve different purposes. More conservative assumptions are included in screening levels that, when exceeded, indicate the potential for risk and a need for further evaluation (USEPA 2002b). More realistic assumptions specific to an exposure scenario may be made in the development of risk-based cleanup standards (CTDEP 2003) or action levels (CDPHE 2004) that, when exceeded, trigger remedial action or mitigation. A point-by-point comparison (in other words, comparison of maximum site data) may be appropriate for a screening-level evaluation using generic screening levels, while cleanup standards are typically compared with an exposure point concentration (such as an average concentration or 95th percentile upper concentration limit of the mean). Some agencies conduct

screening-level evaluations using vapor intrusion models instead of or in addition to numerical screening levels. Other agencies provide generic attenuation factors (discussed below), which are used with subsurface media concentrations to predict indoor air concentrations (Cal DTSC 2004). In addition to a generic screening phase, some agencies have a more site-specific or semi-site-specific screening phase in which generic numerical criteria can be modified using site-specific soil and building parameters and the J&E model (Health Canada 2004, MassDEP 2004, USEPA 2002b).

H.1.1 Attenuation Factors

The attenuation factor represents the ratio of the target indoor air concentration within a building to the vapor-phase concentration in subsurface media underlying or adjacent to a building. Attenuation factors are used by a number of agencies to calculate media-specific screening levels or predict indoor air concentrations. These attenuation factors can be derived either empirically or through the use of vapor intrusion models.

An alpha factor is a unitless empirical attenuation factor relating the indoor air concentration to either a subsurface soil gas concentration (α_{sg}) or to a groundwater concentration (α_{gw}) as follows:

$$(\alpha_{sg}) = C_{indoor}/C_{soil\ gas}$$

and

$$(\alpha_{gw}) = C_{indoor}/(C_{water} \times H) ,$$

where H = the compound's unitless Henry's law constant.

In a more practical sense, the attenuation factor is the measure of how soil and building properties can limit the intrusion of organic vapors as they migrate into a structure (Gerrard 2006).

Generic screening levels and attenuation factors generally assume the following conditions for use in evaluating the potential for vapor intrusion into an existing, or in some cases, future building:

- The site is adequately characterized.
- The subsurface is reasonably homogeneous.
- No significant fractures exist in the subsurface.
- Groundwater is greater than a certain depth (varies by agency).
- There is no standing water inside the building.
- NAPL is not present on the water table.
- Preferential pathways for soil gas migration do not exist.
- Biodegradation of soil gas contaminants is not occurring.
- Contaminants are homogeneously distributed.

- The building does not have a dirt floor.
- Contaminant vapors enter a building primarily through cracks in the foundation and walls.
- Building ventilation rates and the indoor-outdoor pressure differentials are constant.
- Model assumptions are representative of site conditions.

USEPA has conducted some testing of the reliability of the attenuation factors to estimate indoor air concentrations (Dawson 2005). Selected data sets of indoor air, groundwater data, and subsurface soil gas concentrations were compared, and an attenuation factor calculated. It was found that for volatile chlorinated hydrocarbons, an attenuation factor of 1000 is a conservative estimate of actual indoor air concentrations from calculated soil gas concentrations derived from volatilization from groundwater. This attenuation factor may not be applicable for very shallow groundwater (<5 feet below foundation) or shallow groundwater (<feet below foundation) if there are significant openings to the subsurface (e.g., earthen floors, crawl spaces, sumps), preferential pathways, low building air exchange rates, or very high sustained indoor/outdoor pressure differentials. It was also found that there are insufficient data to draw definite conclusions about generic soil gas–indoor air attenuation factors.

H.1.2 Key Differences

Key differences in the numerical screening levels used to evaluate the vapor intrusion pathway may include the following:

- receptor-specific screening levels (some agencies have developed residential screening levels only, so levels specific to nonresidential exposure scenarios can be derived)
- toxicity values (some states have approved toxicity value that differ from the approved federal toxicity values)
- use of modeled or empirical data to develop attenuation factors and numerical screening levels
- incorporation of background quantitatively into screening levels
- consideration of hypothetical future buildings (California specifies different modeling or exposure point concentrations assumptions depending on whether the building being evaluated is an existing or future structure)

Target indoor air concentrations can vary by several orders of magnitude due to differences in target carcinogenic and noncarcinogenic risk levels, toxicity values, indoor air background values, odor thresholds, analytical quantitation limits, exposure factors (e.g., exposure duration, inhalation rate, body weight), and not-to-exceed ceiling values, if used. Target indoor air concentrations serve as an input in the development of screening levels for subsurface media. In addition to the variability in target indoor air concentrations, groundwater-to-indoor air, soil gas-to-indoor air, and soil-to–

Application of Screening Levels

- There may be state-specific screening levels, as opposed to defaulting to federal values
- Screening levels are promulgated values in some states, so there is little or no ability for site-specific revision.
- States may have different hierarchies for media preference.
- Consideration of possible future land use changes may be required when identifying the most appropriate receptor-specific screening levels.

indoor air numerical screening levels can vary for a number of other reasons. Regional geology, hydrogeology, climate, and building construction vary and therefore affect default assumptions and model input parameters regarding depth to groundwater, soil type, building air exchange rate, building-outdoor pressure differential, building size, and other variables. Some agencies include a dilution or degradation factor for certain petroleum hydrocarbons to account for the biodegradation in the vadose zone.

H.2 INDOOR AIR TARGET VALUES

Risk-based concentrations are concentrations of chemicals within a building that are not expected to cause adverse health effects from long-term exposure. Risk-based indoor air concentrations are generally developed for chronic exposures to generally low-level vapor concentrations. This appendix does not specifically address acute hazards.

Target indoor air screening levels are generally risk-based and are derived using standard risk assessment equations and the following input parameters:

- acceptable target risk thresholds for individual chemicals or cumulative effects
- appropriate toxicity values (federal or state toxicity values for carcinogenic and noncancer toxicity endpoints)
- exposure assumptions such as inhalation rate, exposure duration, and exposure frequency

Standard risk assessment equations and typical default assumptions are identified in various USEPA and state risk assessment guidance such as USEPA 1989, 1996a, 1996b and 2002d. The following equations generally apply:

- For noncarcinogens:

$$\text{target indoor air concentration } (\mu\text{g}/\text{m}^3) = \frac{\text{THQ} \times \text{RfD} \times \text{BW} \times \text{AT} \times 1000 \mu\text{g}/\text{mg}}{\text{EF} \times \text{ED} \times \text{IRA}},$$

where

THQ = target hazard quotient (see Section 2.1)
 RfD = reference dose (mg/kg-day, see Section 2.2)
 BW = body weight (kg)
 AT = averaging time (days)
 EF = exposure frequency (days/year)
 ED = exposure duration (years)
 IRA = inhalation rate (m³/day)

- For carcinogens:

$$\text{target indoor air concentration } (\mu\text{g}/\text{m}^3) = \frac{\text{TR} \times \text{BW} \times \text{AT} \times 1000 \mu\text{g}/\text{mg}}{\text{EF} \times \text{ED} \times \text{IRA} \times \text{CSF}},$$

where

TR	=	target incremental lifetime cancer risk (see Section 2.1)
BW	=	body weight (kg)
AT	=	averaging time (days)
EF	=	exposure frequency (days/year)
ED	=	exposure duration (years)
IRA	=	inhalation rate (m ³ /day)
CSF	=	cancer slope factor ([mg/kg-day] ⁻¹ , see Section 2.2)

Alternatively, the indoor air target concentration may be established as the practical quantitation limits using standard methods or indoor air literature background values. For buildings regulated under OSHA, the indoor air target concentrations may be OSHA-derived screening levels (PELs). Consideration of background concentrations is important in the evaluation of potential subsurface media contributions to indoor air given the presence of other sources of VOCs inside buildings. Some agencies use literature or agency-collected indoor air background values as target indoor air concentrations (NYSDOH 2006), while others use a background value if it exceeds a risk-based concentration on a compound-specific basis (CTDEP 2003, MassDEP 2004). Most agencies set the target indoor air concentration at the PQL if it is higher than a risk-based concentration. Some agencies evaluate PQLs on a chemical-specific basis, while others select one value to represent the PQL for all compounds for a specific medium. For example, the Connecticut Department of Environmental Protection sets a “floor” for the soil gas volatilization criteria at 0.5 ppb (CTDEP 2003).

H.2.1 Acceptable Target Risk Thresholds

Cancer risk is generally described as an incremental lifetime cancer risk (ILCR), and noncancer risk is generally described as a hazard quotient (HQ) or total hazard index (HI), which is the sum of HQs for evaluating noncancer effects for multiple chemicals. Acceptable ILCR values are also identified as individual chemical risk or multiple (cumulative) chemical risk. There is some variability in acceptable target ILCRs established by various regulatory agencies, although the acceptable target level for HQ or total HI is less ≤ 1.0 . Most target cumulative ILCRs considered acceptable lie within the risk range of 10^{-6} – 10^{-4} .

A total HI of less than 1.0 indicates that it is unlikely that adverse human health effects will occur during a lifetime in an exposed population, including sensitive subpopulations (USEPA 1989). Cumulative ILCRs of 10^{-6} – 10^{-4} correspond to theoretical probabilities of 1 chance in 1 million to 1 chance in 10 thousand in addition to or in excess of the background cancer risk. It is generally widely accepted in the regulatory community that cumulative ILCR estimates that are equal or less than 10^{-6} do not require remediation or mitigation measures. Risk estimates that are greater than 10^{-4} generally require remediation or mitigation to reduce potential exposures. Under the Resource Conservation and Recovery Act Corrective Action Environmental Indicators (EI) program (USEPA 2005), USEPA indicates that “For the purposes of making Current Human Exposure under Control EI determinations with respect to vapor intrusion, EPA generally

recommends the use of 10^{-5} levels for carcinogens (incremental individual lifetime cancer risk), and a Hazard Quotient (HQ) of 1 for noncancer risk.”

H.2.2 Toxicity Values

Commonly, the equations that are used to calculate risk, screening levels, or acceptable concentrations use the inhalation cancer slope factor, CSF $(\text{mg/kg-day})^{-1}$ and the inhalation reference dose, RfD (mg/kg-day) as the main indicators of potency or toxicity. Some years ago the Integrated Risk and Information System (IRIS) and the USEPA Office of Air Programs began using, and advocating the use of, a reference concentration (RfC) in $\mu\text{g}/\text{m}^3$ to describe an acceptable airborne concentration protective of the general public and sensitive subpopulations and a unit risk factor (URF) in $(\mu\text{g}/\text{m}^3)^{-1}$ is to represent the risk of exposure from $1 \mu\text{g}/\text{m}^3$. RfCs and URFs are toxicity values developed assuming only an adult receptor. Adult exposure assumptions are included in their derivation, whereas RfDs and CSF may be used to estimate risk or develop screening levels for adults or children.

H.2.3 Receptors and Exposure Parameters

USEPA 1989 provides general guidance on how to characterize exposures and risks when conducting risk assessments. Characterization of potentially exposed populations involves the identification of the current populations at the site in question, activity patterns of these populations, consideration of future land usage at the property, and an evaluation of sensitive populations (i.e., potentially at an increased risk from exposure to a contaminant due to activity and/or behavioral patterns). The following land use categories may be applicable for the development of screening levels for generic exposure scenarios:

- residential
- nonresidential (e.g., commercial/industrial)
- recreational

The exposure assumptions for different exposure scenarios can change, for example in terms of hours per day, days per year, and years of exposure as well as inhalation rates and body weights, depending on the applicable receptor(s). Screening levels for a residential receptor is generally considered to be the most conservative and thus protective of sensitive populations as well as adults and children in a residential land use scenario. The exposure assumptions for nonresidential receptors (e.g., commercial and industrial workers) are generally less conservative than those in a residential exposure scenario since for nonresidential exposure scenarios only adult receptors with lesser exposure durations are typically considered. Exposure assumptions may be modified to account for regional conditions.

Residential

This category applies if the primary activity of the property is residential in nature and includes single-family dwellings, condominiums, or apartment buildings. Residential screening levels may also apply to facilities deemed to have similar exposure potential as a residence (such as a day care center, school, or elderly care facility). Receptors for the residential land use must

include the general population, including adults and children of various ages. A pregnant female may also be considered a relevant receptor. Default exposure assumptions for the residential scenario are typically 30-year residence time, daily exposure for 350 days/year, with an inhalation rate of 20 m³/day for a 70-kg adult over 24 years and 10 m³/day for a 15-kg child over 6 years.

Nonresidential (Commercial)

Activities and uses are extremely variable within the nonresidential land use category. Nonresidential/commercial land uses may range from more sensitive uses such as day care centers and schools to less sensitive uses such as gas stations and warehouse operations. Potential exposures to children are considered for day care centers and schools. For other commercial scenarios, a commercial worker is considered to be the most sensitive receptor. Default exposure assumptions for the commercial worker are typically 25-year employment time, daily exposure for 250 days/year, with an inhalation rate of 20 m³/day for a 70-kg adult. Some agencies reduce the default inhalation rate per day to reflect a shorter exposure time during the time the worker is in the work place (e.g., from 20 m³/day to 10 m³/day, CTDEP 2003).

Nonresidential (Industrial)

Industrial land use is typically applied when the primary activity at the property is and will continue to be industrial in nature. Inactive or abandoned properties can be included in this category if the use was and/or will be industrial and access is controlled as necessary to ensure unacceptable exposures (i.e., exposures more consistent with a residential exposure setting) do not occur. The industrial category does not typically include establishments where children may commonly be present. For industrial sites, the OSHA-acceptable workplace levels (PELs) or other acceptable workplace levels may be used as indoor air target concentrations. Note: Many regulatory agencies use a risk-based value rather than OSHA PELs when vapor intrusion is occurring and the COC is not being used in the facility.

Default exposure assumptions for the industrial worker are generally similar to a commercial worker: 25-year employment time, daily exposure for 250 days/year, with an inhalation rate of 20 m³/day for a 70-kg adult. However, some agencies may adjust the inhalation rate to account for increased breathing rates during the workday exposure period.

Recreational

Receptors in structures used for recreational purposes may also include adult and child receptors. Default exposure assumptions for the recreational worker are generally similar to a commercial or industrial worker: 25-year employment time, daily exposure for 250 days/year, with an inhalation rate of 20 m³/day for a 70-kg adult. Default exposure assumptions for the child recreator may be similar to those for a residential child with shorter exposure durations. However, as above, some agencies may adjust the inhalation rate to account for increased breathing rates during typical recreational activities.

Sensitive Populations

The potential for sensitive populations at a vapor intrusion site should be considered. Facilities where sensitive populations may be located include day care centers, schools, and elderly care facilities. The target indoor air concentration for a residential scenario, which includes children, is often considered adequately protective for sensitive populations. Some agencies include adjustments to screening levels based on adult receptors for the derivation of appropriate screening levels for children. For example, the Connecticut Department of Environmental Protection includes in its residential volatilization criteria (CTDEP 2003) a twofold adjustment factor for children's increased inhalation exposure rate relative to adults (due to a greater respiratory rate per body weight and lung surface area) and a twofold adjustment factor for children's increased sensitivity when exposed to genotoxic carcinogens.

H.3 CRAWL-SPACE AIR SCREENING LEVELS

Few agencies currently have generic screening levels for air within building crawl spaces. Screening levels for crawl-space air may only be applicable in certain regions of the country where crawl-space construction is common for residential buildings. Based on the preliminary results of the agency's vapor intrusion database review process, USEPA has concluded there is limited empirical data from which to develop an attenuation factor for crawl-space air (Dawson 2004).

The following equation can be used to calculate generic screening levels for crawl-space air:

$$C_{CA} = C_{IA}/\alpha ,$$

where

- C_{CA} = crawl-space air screening concentration ($\mu\text{g}/\text{m}^3$)
- C_{IA} = target indoor air concentration ($\mu\text{g}/\text{m}^3$)
- α = crawl-space air attenuation factor (dimensionless)

The crawl-space air screening levels reviewed are based on empirical attenuation factors and generally range 0.1–1.0. An attenuation factor of 1.0 assumes no attenuation of compound concentrations from crawl-space air to indoor air and is considered to be an upper bound value (Dawson 2004).

H.4 SUBSLAB SOIL GAS SCREENING LEVELS

For both subslab soil gas and soil gas measured at deeper depths beneath a building or outside a building footprint, the soil gas screening levels are the target indoor air concentrations multiplied by an attenuation factor. The attenuation factors should be supported by empirical observations and represent the attenuation of vapors as they migrate from the source through the vadose zone to beneath the floor slab, through the floor slab, or from the exterior into the interior of a building and equilibrating in the indoor air space. Specific considerations may be applicable to petroleum hydrocarbons due to biodegradation.

Several agencies, including USEPA, include soil gas collected from a depth of 5 feet or less (outside a building or below a building floor slab) and subslab soil gas collected below a building floor slab in the same category (typically designated “shallow soil gas”) when evaluating the vapor intrusion pathway.

The following equation can be used to calculate subslab soil gas screening levels:

$$C_{SS} = C_{IA}/\alpha ,$$

where

$$\begin{aligned} C_{SS} &= \text{subslab soil gas screening concentration } (\mu\text{g}/\text{m}^3) \\ C_{IA} &= \text{target indoor air concentration } (\mu\text{g}/\text{m}^3) \\ \alpha &= \text{subslab soil gas attenuation factor (dimensionless)} \end{aligned}$$

Attenuation factors for subslab soil gas are typically based on empirical data and generally range 0.01–0.1 for residential buildings. As part of its ongoing review of the agency’s vapor intrusion database, USEPA has determined that its current OSWER draft subslab attenuation factor of 0.1 may be overly conservative and is reportedly revisiting this number (Dawson 2004).

H.5 SOIL GAS SCREENING LEVELS

As discussed above, several agencies currently include soil gas collected from a depth of 5 feet or less (outside a building or below a building floor slab) and subslab soil gas collected below a building floor slab in the same category (typically designated “shallow soil gas”) when evaluating the vapor intrusion pathway. Due to differences in the nature of sampling, and the need to gain access into a building to conduct subslab sampling, it may be preferable to have soil gas screening levels apply to all soil gas samples collected outside a building at a certain depth below ground surface.

The following equation can be used to calculate soil gas screening levels:

$$C_{SG} = C_{IA}/\alpha ,$$

where

$$\begin{aligned} C_{SG} &= \text{soil gas screening concentration } (\mu\text{g}/\text{m}^3) \\ C_{IA} &= \text{target indoor air concentration } (\mu\text{g}/\text{m}^3) \\ \alpha &= \text{soil gas attenuation factor (dimensionless)} \end{aligned}$$

Both empirical and modeled attenuation factors are available for soil gas. The reported range of attenuation factors, both empirical and modeled, for a residential building scenario is 0.002–0.1. These attenuation factors apply to either shallow (typically <5 feet bgs) or deep (>5 feet) soil gas samples taken at or in proximity to the current structures. Attenuation factors for future

residential buildings are also available for some agencies and typically range 0.0009–0.01. The attenuation factors used by the agencies for nonresidential/commercial buildings typically range 0.0005–0.1. One agency, California Environmental Protection Agency, provides a soil gas attenuation factor for future commercial buildings of 0.0004 (Cal DTSC 2004). Health Canada provides semi-site-specific soil gas attenuation factors for residential and commercial buildings (Health Canada 2004).

H.6 GROUNDWATER SCREENING LEVELS

The groundwater screening levels include established groundwater standards, such as maximum contaminant levels, as well as health-based groundwater concentrations calculated to be protective of indoor air quality.

Groundwater screening levels developed for the vapor intrusion pathway are applicable to groundwater concentrations obtained from monitoring wells screened at or near the water table. Groundwater samples collected from deeper aquifers or well screen intervals are not appropriate for evaluating the vapor intrusion pathway and should not be compared with groundwater screening levels for the purposes of site screening since chemical volatilization and subsequent upward vapor migration occur from chemical concentrations in groundwater at the water table. When nonimpacted shallow groundwater lies above an impacted groundwater zone, the shallow groundwater acts as a barrier for volatilization from groundwater at deeper depths. However, the application of groundwater screening levels is state specific. For instance, Michigan requires that groundwater screening levels be compared to concentrations throughout the affected aquifer.

The following equation is often used to develop generic screening levels to evaluate the groundwater-to-indoor air exposure pathway:

$$C_{GW} = C_{IA}/(H \times \alpha \times 1000 \text{ L/m}^3) ,$$

where

- C_{GW} = groundwater screening level ($\mu\text{g/L}$)
- C_{IA} = target indoor air level ($\mu\text{g/m}^3$)
- H = Henry's law constant (dimensionless)
- α = groundwater attenuation factor (dimensionless)

Henry's law constant is used to convert the groundwater concentration in the aqueous phase to a vapor-phase concentration at equilibrium. According to USEPA (2002b), "Field data suggest that this conversion may result in over prediction of the soil gas concentration (by as much as a factor of ten) directly above the contaminated groundwater. However, this is not always the case and consequently Henry's Constant is used [in the USEPA-OSWER Draft Vapor Intrusion Guidance] without a correction factor." Henry's law constants can be obtained from USEPA for many VOCs (USEPA 2004a).

Both empirical and modeled attenuation factors are available from the various agencies for groundwater. Some states calculate chemical-specific attenuation factors using the J&E model

(MassDEP 2004). The range of groundwater-to-indoor air attenuation factors is typically 0.0007–0.0008 (chemical specific) to 0.001 for residential buildings. Generic groundwater attenuation factors are not available for nonresidential/commercial buildings. Health Canada provides semi-site-specific groundwater attenuation factors for residential and commercial buildings (Health Canada 2004). Additional information regarding the use of the J&E model can be found in the EPA 2005.

H.7 SOIL SCREENING LEVELS

Screening levels based on soil concentrations are generally not derived for assessing the vapor intrusion pathway. Most states and USEPA regions do not use or encourage the use of soil-to-indoor air screening levels. The USEPA Office of Solid Waste and Emergency Response draft guidance cites uncertainties related to soil partitioning calculations and analytical limitations when sampling and evaluating VOCs in the soil matrix which reduce the defensibility of soil screening levels (USEPA 2002). Further, nondetect analytical soil concentration results do not necessarily indicate a lack of a soil gas source (due to potential volatilization during sample collection, handling, and analysis) but may be interpreted as such.

Generally, soil gas measurements are recommended as an alternative to bulk soil measurements to evaluate potential vapor migration from a soil medium. There are situations, though, in which it is not feasible to collect a defensible soil gas sample. For instance, the presence of a shallow water table or clay-rich soils may preclude soil gas sampling. In these situations, where contaminants originate from a soil source (as compared to a groundwater source), bulk soil measurements may be used to evaluate the vapor intrusion pathway.

Few states have derived soil-to-indoor air screening levels. Pennsylvania Department of Environmental Protection (PADEP 2004) has developed and promulgated soil screening levels based on the application of the J&E model.

H.8 BIODEGRADABLE COMPOUNDS

Some agencies include a dilution or degradation factor in the development of screening levels for certain petroleum hydrocarbons to account for the biodegradation in the vadose zone. Several apply a dilution/degradation factor of 0.1 (or 10-fold dilution) to petroleum compounds, including BTEX (Health Canada 2004, NJDEP 2005, MADEP 2004). USEPA generic attenuation factors are based largely on data for less-degradable chlorinated compounds (USEPA 2002b). Empirical data suggests that a 3- to 10-fold decrease in the attenuation factor is appropriate for biodegradable BTEX compounds compared with chlorinated compounds (USEPA 2002b, Appendix F, Section 5). Recent American Petroleum Institute guidance suggests 0.01 as a low-end soil gas attenuation factor and that soil gas-to-indoor air attenuation factors of 0.0001–0.00001 may be reasonable for BTEX compounds (API 2004).

APPENDIX I

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APPENDIX J

Acronyms

ACRONYMS

API	American Petroleum Institute
BTEX	benzene, toluene, ethylbenzene, and xylenes
bgs	below ground surface
CAG	Community Advisory Group
CGI	combustible gas indicator
COC	chemical of concern
CSF	cancer slope factor
CSM	conceptual site model
1,1-DCE	1,1-dichloroethene
DQO	data quality objective
EI	environmental indicator
FID	flame ionization detector
GC	gas chromatography
GC/MS	gas chromatography/mass spectrometry
HDPE	high-density polyethylene
HI	hazard index
HQ	hazard quotient
HVAC	heating, ventilating, and air conditioning
ILCR	incremental lifetime cancer risk
IRIS	Integrated Risk Information System
IRM	interim remedial measure
ITRC	Interstate Technology & Regulatory Council
J&E	Johnson and Ettinger model
MassDEP	Massachusetts Department of Environmental Protection
MDL	method detection limit
MIBK	4-methyl-2-pentanone
MTBE	methyl tertiary-butyl ether
NAPL	nonaqueous-phase liquid
NASA	National Aeronautics and Space Administration
NJDEP	New Jersey Department of Environmental Protection
NYSDOH	New York State Department of Health
OM&M	operation, maintenance, and monitoring
OSHA	Occupational Safety and Health Administration
PAH	polyaromatic hydrocarbon
ppbv	parts per billion by volume
PCB	polychlorinated biphenyls
PCE	tetrachloroethene (also called perchloroethene)
PDBS	passive diffusion bag sampler
PEL	permissible exposure limit
PID	photoionization detector
PQL	practical quantitation limit
QA/QC	quality assurance/quality control
RfC	reference concentration
RfD	reference dose

RL	reporting limit
SIM	selective ion monitoring
SMD	submembrane depressurization
SOP	standard operating procedure
SSD	subslab depressurization
SSP	subslab pressurization
SVOC	semivolatile organic compound
TAGA	Trace Atmospheric Gas Analyzer
TCA	trichloroethane
TCD	thermal conductivity detector
TCE	trichloroethene
TPH	total petroleum hydrocarbons
URF	unit risk factor
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VI	vapor intrusion
VOC	volatile organic compound

Soil Gas Unit Conversion Factors		
Unit	To convert to:	Multiply by:
µg/L	mg/m ³	1
µg/m ³	mg/m ³	0.001
ppbv	µg/m ³	MW/24
µg/m ³	ppbv	24/MW
ppmv	mg/m ³	MW/24
ppbv	mg/m ³	MW/24,000
µg/L	µg/m ³	1000
µg/m ³	µg/L	0.001
µg/L	ppbv	24,000/MW
µg/L	ppmv	24/MW
ppbv	ppmv	0.001
ppmv	ppbv	1000

At standard temperature and pressure

µg/L	micrograms per liter
mg/m ³	milligrams per cubic meter
µg/m ³	micrograms per cubic meter
ppbv	parts per billion by volume
MW	molecular weight
ppmv	parts per million by volume