Brownfields Technology Primer: Vapor Intrusion Considerations for Redevelopment

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Brownfields Technology Primer: Vapor Intrusion Considerations for Redevelopment

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Notice and Disclaimer

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The document is intended as a primer only, not guidance. EPA recommends that users refer to existing guidance documents (some references are provided herein) regarding vapor intrusion characterization and mitigation techniques. The primer was subjected to the Agency's administrative and expert review and was approved for publication as an EPA document. Mention of trade names or commercial products does not constitute an endorsement or recommendation for use.

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1.0 BACKGROUND

Redevelopment of brownfield sites plays an important role in stimulating the economic revitalization of communities by bringing vacant or underutilized properties into productive use and offsetting the need to develop open land, or “green space.” Along with the normal financial and business risks associated with developing property, brownfields redevelopers must manage environmental risk, including that due to *vapor intrusion*—the migration of chemical vapors from contaminated soil and groundwater into buildings. The core message of this primer is that early consideration of vapor intrusion beginning during the Phase I environmental site assessment will help ensure that redevelopment protects the health of current and future building occupants. In addition, incorporating relatively inexpensive mitigation (prevention) techniques into the construction of new buildings, rather than retrofitting them later, will result in significant cost savings and help avoid the occurrence of vapor intrusion in the future. Because there are many available, cost-effective approaches to mitigation, vapor intrusion need not stand in the way of brownfields redevelopment.

This primer is designed for land revitalization stakeholders[1] concerned about vapor intrusion, including property owners, municipalities, and real estate developers. It provides an overview of the vapor intrusion issue and how it can affect redevelopment. It also summarizes techniques for quickly and cost effectively assessing the potential for vapor intrusion, as well as techniques for mitigating it.

The topics covered will familiarize stakeholders with options for addressing vapor intrusion to help them communicate with their project contractors and consultants. The “Quick Look” box at the beginning of each section summarizes the important points that follow. For reference, a list of acronyms and a glossary are provided in Appendix C. Text boxes throughout the primer and Appendices B, C, D, and E provide additional detail and resources for those readers who would like to know more.

1.1 What Is Vapor Intrusion? Vapor intrusion is an exposure pathway—a way that people may come in contact with environmental contaminants. Vapor intrusion exposes building occupants to potentially toxic levels of vapors when volatile chemicals (those that readily evaporate) present in contaminated soil or groundwater emit vapors that migrate into overlying buildings. It is similar to the more familiar problem of radon, a gas that is emitted naturally from soil and bedrock and enters buildings through cracks and openings in the foundation and through porous building materials. (Text box 1.)

Both volatile chemicals and semivolatile chemicals (those that evaporate more slowly) can pose a vapor intrusion problem. Examples of volatile and semi-volatile chemicals include degreasers, dry-cleaning solvents, gasoline and petroleum (including benzene), naphthalene, polychlorinated biphenyls (PCBs), and certain pesticides. Volatile chemicals are primarily

[1] This primer is not intended for audiences requiring in-depth technical explanations or guidance related to vapor intrusion.

A Quick Look at Vapor Intrusion

- ☞ Determining the potential for vapor intrusion should begin early during the Phase I environmental site assessment.
- ☞ Vapor intrusion exists when volatile or semivolatile chemicals in soil or groundwater migrate toward buildings and enter through cracks and openings in the foundation and walls.
- ☞ Inhalation of vapors may cause chronic and acute health effects.
- ☞ The potential for vapor intrusion exists even though industrial activities may have never occurred on a property.
- ☞ States may have specific vapor intrusion guidance that needs to be considered.
- ☞ The Interstate Technology and Regulatory Council's guidance documents describe a "multiple lines of evidence" approach to assessing vapor intrusion.
- ☞ Contact environmental agencies to ensure that the most up-to-date and appropriate guidance is followed.

organic but also comprise metallic mercury, which is inorganic. For ease of discussion, this primer refers to chemicals that may result in vapor intrusion as volatile organic compounds, or "VOCs." (Other references may refer to "volatile chemicals of concern" or "vapor-forming chemicals.") However, it distinguishes between volatile and semivolatile, as well as organic and inorganic chemicals, where necessary.

As illustrated in Figure 1, VOCs in contaminated soil and groundwater emit vapors that rise through the pore space of the unsaturated zone above the water table. (Where bedrock underlies a property, the vapors move through fractures and openings in the rock.) These vapors, also known as "soil gas," can move laterally as well as vertically from the source of contamination. Lateral movement can increase as groundwater plumes migrate away from the source of contamination or if the ground surface is paved or frozen, preventing escape of vapors upwards.

The movement of soil gas is controlled by the processes of diffusion and advection. Diffusion causes vapors to

TEXT BOX 1: VAPOR INTRUSION AND RADON

Vapor intrusion is similar to the behavior of radon. As a result, the mitigation approaches developed for vapor intrusion are often similar to those for radon. Radon, a colorless, odorless gas, is formed from the decay of radium, a radioactive element that occurs naturally in the bedrock and soil in some areas of the country. Radon poses a threat to the health of building occupants once the gas migrates at high enough levels from soil and rock into homes and the work place. According to EPA estimates, inhalation of toxic radon decay products is the leading cause of lung cancer among non-smokers. For more information and EPA recommended action levels, see: http://www.epa.gov/radon/healthrisks.html.

Today, testing for radon in buildings is common, as is the installation of mitigation systems to prevent entry of radon. Buildings also may be retrofitted to mitigate the problem. As testimony to the effectiveness of these mitigation methods, nearly two million radon retrofits have been installed and more than a half million homes have been constructed using radon reduction techniques. For more information on radon mitigation, read EPA's guide, *Building RadonOut* (EPA, 2001).

spread from the higher concentrations closest to the source of contamination toward low concentrations in uncontaminated areas. Advection is the movement of soil gas from areas of higher to lower pressure.

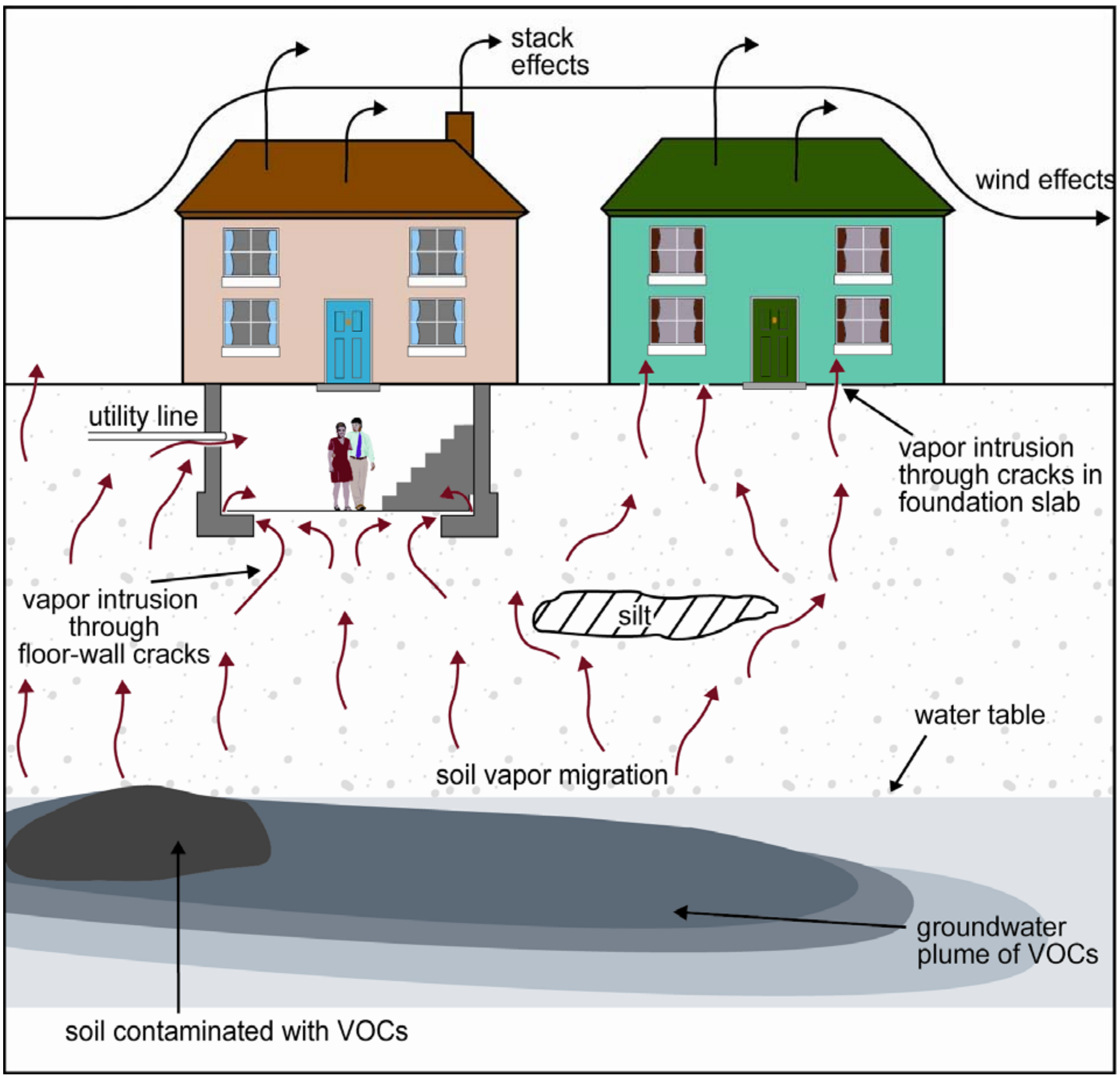
As diffusion causes vapors to rise through soil or bedrock, they tend to accumulate under building foundations and other barriers such as pavement. These barriers create a “capping effect,” which inhibits upward movement of vapors. Because of cracks and other openings in building foundations, these barriers are not impenetrable. Vapor intrusion generally occurs when advection (movement due to pressure differences) draws vapors indoors via these openings. The pressure beneath a building is typically higher than the pressure indoors due to a phenomenon called “building depressurization.” Depressurization causes buildings to draw soil gas indoors. Soil gas that does not pass within the zone of influence of the building will continue to migrate within the subsurface or escape to the atmosphere. Vapors that pass within the zone of influence will be drawn in through cracks in the foundation or through openings associated with utility lines, sump pumps, etc.

Depressurization is caused by “leaky” heating and ventilation systems, exhaust fans, and stack and wind effects (Figure 1) that reduce the pressure indoors. Stack effects cause building depressurization as a result of differences in indoor and outdoor temperatures. As warmer indoor air rises and exits the top of the building, the resulting pressure differences induce vapor flow into the bottom of the building. Stack effects can transport vapors to upper floors of a building via stairwells, elevator shafts, ductwork, etc. Wind currents passing over a building can also cause pressure differences that affect the flow of vapors into the building. For more information on stack and wind effects, consult EPA’s *Indoor Air Guide* at http://www.epa.gov/iaq/schools/tfs/guide2.html.

1.2 Why Is Vapor Intrusion a Concern? Vapor intrusion poses a potential risk to the health of residents, workers, and other occupants who breathe the vapors inside buildings. In the past, cleanup of brownfields and other contaminated sites focused on protecting human health by preventing exposure to contaminants through direct contact (e.g., children playing in contaminated soil) or ingestion (e.g., residents drinking contaminated groundwater from wells). As we have learned more about vapor intrusion, however, it has become clear that the potential for risk of inhaling chemical vapors due to vapor intrusion may still need to be addressed.

If vapor intrusion is a concern at a property to be developed, we recommend that a risk assessment by qualified personnel be conducted to evaluate the degree of risk to future building occupants. The question of risk posed to building occupants by vapor intrusion will depend on the toxicity of the chemical, the concentration of the chemical vapor in the indoor air, the age and health of the occupants, the amount of time the occupants spend in the building, and other variables. In rare instances, and in extreme cases, significant buildup of vapors from a nearby highly contaminated source (e.g., gasoline from leaking underground storage tanks or methane from landfills) may pose an immediate risk of fire or explosion. In other cases, at concentration levels often associated with a detectable odor, short-term exposures may cause acute health effects such as headache, nausea, and eye and respiratory irritation. But more commonly, the potential risk to building occupants comes from inhaling, over time, lesser amounts of chemical vapors that have accumulated indoors. The contamination may not have a detectable odor; however, long-term exposure to even low-levels of certain vapors may increase the risk of chronic health effects, such as cancer and other diseases.

Figure 1. Migration of Soil Vapors to Indoor Air. Three conditions must exist for environmental-contaminant vapors to reach the interior of buildings: vapors from contaminated soil or groundwater must migrate to the subsurface near the building foundation, entry routes into the building must be present, and there must be driving forces (e.g., stack and wind effects) present that can move the vapors through these entry routes (ASTM, 2005).



1.3 Where Is Vapor Intrusion a Concern? Vapor intrusion is a potential concern at any building–existing or planned–located near soil or groundwater contaminated with VOCs. EPA's draft guidance for evaluating the vapor intrusion pathway defines "near" as contamination within 100 feet (laterally or vertically) of buildings, unless there is a conduit that intersects the soil gas migration route that would allow soil gas to migrate further than 100 feet (EPA, 2002). A conduit is any passageway, such as a sand or gravel layer, buried utility line, or animal burrow, that facilitates the flow of soil gas. The guidance further notes that vapor intrusion is associated with contamination found in the unsaturated zone (the soil above the water table) or in the uppermost portion of the saturated zone (just below the water table) as opposed to deep within the saturated zone. Fluctuations in the water table level due to seasonal precipitation changes or pumping may increase soil gas concentrations where contamination exists.

Properties with potential VOC contamination are common in industrial and commercial areas. They include current and former manufacturing and chemical processing plants, warehouses, landfills, coal gasification plants, train yards, dry cleaners, and gas stations. Improper use, storage, or transport of chemicals at these facilities may have resulted in a release of contaminants to the environment creating the potential for future vapor intrusion issues. In addition to industrial and commercial activities, roadside dumping, pesticide spraying, or even improper disposal of household chemicals via a septic field may also release contaminants to the environment. Therefore, the potential for vapor intrusion should be considered at all types of properties considered for redevelopment.

Even "greenspace" properties that have not previously been occupied or developed may contain VOC contamination. Because groundwater plumes and soil gas can migrate laterally, the contamination source need not be on the property to be redeveloped to pose a vapor intrusion problem. The actual source(s) of vapor intrusion (e.g., landfill wastes, contaminated soil, or buried drums) may be present on a neighboring property or on a property some distance away. Depending on the degree of contamination and geology, contaminants dissolved in groundwater plumes can flow beneath a property from sources located a mile or two upgradient (in the direction opposite groundwater flow and plume migration). Because of the large size of migrating groundwater plumes, they may be the greatest contributor to the vapor intrusion problem.

1.4 How Does Vapor Intrusion Impact Brownfields Redevelopment? Awareness of vapor intrusion as a potential for exposure to soil and groundwater contamination has raised concerns about public health risks and liability during property transactions. However, if vapor intrusion is considered along with other potential exposure pathways commonly evaluated (e.g., ingestion of or direct contact with soil and groundwater), land revitalization stakeholders can eliminate potential health risks and facilitate transactions. Early proactive evaluation of vapor intrusion can make available more options for the mitigation and redevelopment. In addition, preconstruction mitigation measures are less expensive than post-construction remediation and structure retrofits.

The potential for vapor intrusion should be considered during the Phase I or the follow-on Phase II environmental site assessment for any brownfield property transaction. This would include looking at the past history of the property, neighboring properties, site geology and hydrogeology, and the condition of existing buildings for conditions conducive to vapor intrusion. If the potential is found to exist, then an appropriate sampling and analysis plan for site characterization can be developed in Phase II so that vapor intrusion can be evaluated and mitigated. (These topics are discussed further in Sections 2.0 and 3.0, respectively.) Subsequent changes in the use of a property, such as converting an industrial building to loft apartments, may require reevaluation of the vapor intrusion pathway (EPA, 2002).

The American Society for Testing and Materials (ASTM) is developing a standard to address vapor intrusion as it can impact real estate transactions (Buonicore, 2006). The standard will supplement the Phase I environmental site assessment process and can be designed to help decide whether or not there is a reasonable probability that vapor intrusion could present an environmental risk or liability.

1.5 How Is Vapor Intrusion Regulated and What Guidance Is Available? Vapor intrusion is an exposure pathway, and as an exposure pathway, it should be considered by environmental practitioners when evaluating potential health risks from soil or groundwater contaminated with VOCs. Both EPA and state agencies recognize the importance of this pathway and have issued guidance documents to guide practitioners in their assessment of the vapor intrusion pathway. In addition, several state documents also provide guidance for evaluating and mitigating the potential health risks. At the time of this writing, however, neither EPA nor the states regulate how assessments and mitigation must be performed.

Guidance Documents: EPA issued the *OSWER*[2] *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* in 2002. The premise of the OSWER draft guidance is to use sampling data collected from outside the building, such as soil gas, sub-slab, and/or groundwater samples discussed in Section 2.2, to estimate indoor air concentrations of vapors. These estimates are compared to risk-based concentrations for indoor air in residential settings. The guidance also allows evaluation of non-residential settings through use of the Johnson and Ettinger or “J&E” model (See Section 2.3). Use of the OSWER draft guidance is not recommended typically for sites with petroleum-related contamination, such as former gas stations (Text box 2).

The draft guidance (EPA, 2002) suggests beginning assessment with the development of a conceptual site model (CSM; a depiction of site conditions, see section 2.1) and leads the user through a series of questions arranged in a three-tiered approach. If at any time in the three-tiered approach insufficient data are available to answer the questions posed, the EPA (2002) draft guidance recommends the collection of additional samples and site information. An indication of a complete pathway requires an assessment of the risk resulting from breathing the indoor air. If at any time during the approach the vapor intrusion pathway can be ruled “incomplete,” there is no need to proceed further. However, if site conditions or uses change in the future, the site would be re-evaluated to determine if a complete pathway has developed and mitigation is now necessary. For more information on this guidance, see: http://www.epa.gov/correctiveaction/eis/vapor.htm.

[2] OSWER is EPA’s Office of Solid Waste and Emergency Response.

The Interstate Technology & Regulatory Council (ITRC)─ a coalition of states, the District of Columbia, tribal and industrial representatives, and several federal partners─recently published *Vapor Intrusion Pathway: A Practical Guideline* (2007a), which is a framework intended for use with existing state and federal guidance or policy. This framework incorporates multiple lines of evidence and follows a 13-step approach to evaluating the potential for vapor intrusion. Lines of evidence include the locations of sources, distribution of groundwater contaminants and soil gas at the site, sub-slab concentrations (soil gas beneath building foundations), indoor and outdoor air concentrations, background concentrations, presence of conduits, and building construction plans or details. This approach helps determine whether a site warrants no further action, additional investigation, or mitigation. ITRC emphasizes the importance of developing an accurate CSM that is representative of site conditions, so that it can be used to assist with planning and make sure the site data is used properly. This guidance also provides detailed information on site investigation and mitigation approaches.

ITRC's companion document, *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios* (2007b), walks users through using the guidance for varying scenarios, such as different contaminated properties (e.g., service station, dry cleaner, and industrial facility) and different receptors (e.g., residential neighborhood, commercial building, and a vacant lot with proposed brownfields development).

EPA has also published *Guidance for Evaluating Landfill Gas Emissions from Closed or Abandoned Facilities* (EPA, 2005a). This guidance provides procedures and a set of tools for evaluating landfill gas emissions to ambient air, soil gas migration due to landfill-gas pressure gradients (differences in pressure), as well as vapor intrusion into buildings. The risks of inhaling vapors can be evaluated, in addition to the hazards of both on-site and off-site methane explosions and landfill fires.

TEXT BOX 2: THE DRAFT EPA GUIDANCE AND PETROLEUM-CONTAMINATED SITES

Available scientific literature suggests that petroleum contamination *biodegrades* more readily than most other types of VOCs; in other words, microbes found naturally in the soil can break down petroleum into less harmful compounds relatively quickly. Although the OSWER draft guidance allows observations of the effects of biodegradation to be considered in its approach, it does not predict the effects of biodegradation. As a result, application of the draft guidance to petroleum compounds may *overestimate* the impact of vapor intrusion, if observations are not considered. As a result, as mentioned in Section 1.5, the guidance recommends using the approach documented in *Use of Risk-Based Decision Making in UST Corrective Action Programs* (EPA, 1995a) to assess vapor intrusion at petroleum-contaminated sites.

Additional technical information is available from ITRC (2007a, b) and API (2005), while some state guidance documents, California's and New Jersey's, for example (Appendix B), provide more specific direction about how to evaluate biodegradation as a factor in reducing vapor intrusion at petroleum sites.

States: As of this writing, at least 21 states have issued guidance documents dealing with vapor intrusion. State guidance, where it exists, supersedes the existing EPA guidance documents. The specific state documents and the URLs for finding them on the Internet are listed in Appendix A. As is evident by the titles, state guidance documents range in scope and address varying issues related to vapor intrusion. Several state documents, like Ohio's *Methodology for Vapor Intrusion Assessment,* base their approach to assessing vapor intrusion on the OSWER draft guidance, but have modifications. Therefore, it is recommended that relevant state agencies be contacted concerning vapor intrusion issues to ensure appropriate guidance is followed.

Because awareness and concern for vapor intrusion continues to grow and the science and technology behind it continues to improve, new documents are likely to be published soon and existing ones replaced. Therefore, stakeholders should contact appropriate state agencies to ensure that the most up-to-date and appropriate guidance is followed. A list of contacts can be found at: http://www.itrcweb.org/vaporintrusionresources/4_2_07VI_contact_list.xls. Stakeholders also may contact their EPA Regional Brownfields Coordinator, listed in Table 1, for information on brownfields and assistance with their vapor intrusion questions.

TEXT BOX 3: ITRC'S SURVEY OF STATES ON VAPOR INTRUSION

In 2004, the ITRC conducted a survey regarding vapor intrusion regulations. A total of 41 state agencies and Canada responded. The survey results, which include responses to questions on the contaminated media, evaluation of risk, sampling procedures, and mitigation approaches, are available to view or download at http://www.itrcweb.org/vaporintrusion/ITRC_VI_Survey_8-17-05/ITRC_1_VI_Survey_Index.htm.

Table 1. EPA Regional Brownfields Coordinators

EPA Region	States/Territories in Region	Brownfields Coordinator	Phone	E-mail
1	Connecticut, Massachusetts, Maine, New Hampshire, Rhode Island, Vermont	Diane Kelley	(617) 918-1424	kelley.diane@epa.gov
2	New Jersey, New York, Puerto Rico, Virgin Islands	Ramon Torres	(212) 637-4309	torres.ramon@epa.gov
3	District of Columbia, Delaware, Maryland, Pennsylvania, Virginia, West Virginia	Tom Stolle	(215) 814-3129	stolle.tom@epa.gov
4	Alabama, Florida, Georgia, Kentucky, Mississippi, North Carolina, South Carolina, Tennessee	Mike Norman	(404) 562- 8792	norman.michael@epa.gov
5	Illinois, Indiana, Michigan, Minnesota, Ohio, Wisconsin	Deborah Orr	(312) 886-7576	orr.deborah@epa.gov
6	Arkansas, Louisiana, New Mexico, Oklahoma, Texas	Monica Chapa Smith	(214) 665-6780	smith.monica@epa.gov
7	Iowa, Kansas, Missouri, Nebraska	Susan Klein	(913) 551-7786	klein.susan@epa.gov
8	Colorado, Montana, North Dakota, South Dakota, Utah, Wyoming	Dan Heffernan	(303) 312-7074	heffernan.daniel@epa.gov
9	American Samoa, Arizona, California, Guam, Hawaii, Majuro, Nevada, Trust Territories	Debbie Schechter (Acting)	(415) 972-3093	schechter.debbie@epa.gov
10	Alaska, Idaho, Oregon, Washington	Susan Morales	(206) 553-7299	morales.susan@epa.gov

Also found at: http://www.epa.gov/swerosps/bf/corcntct.htm

2.0 ASSESSING THE POTENTIAL FOR VAPOR INTRUSION

There are many tools available to environmental practitioners for assessing the potential for vapor intrusion. This section summarizes several of these tools─conceptual site models, sampling and analysis equipment, and predictive models─to familiarize land revitalization stakeholders with common terminology and to understand the state of the science and technology behind vapor intrusion assessments.

A Quick Look at Assessment

- ☞ Gathering sufficient information for an accurate conceptual site model is important for assessing vapor intrusion and determining the appropriate mitigation approaches.
- ☞ The upfront cost of an early thorough site characterization can be offset by the ultimate cost savings of installing proper mitigation early and the resulting protection of the health of building occupants.
- ☞ Information gained from environmental sampling (e.g., groundwater, bulk soil, soil gas, sub-slab soil gas, and indoor air) and predictive modeling can be used together to build and evolve a conceptual site model.
- ☞ There are many sampling tools available for assessing vapor intrusion.
- ☞ Evaluation of vapor intrusion can be complicated by background sources of vapors commonly found in homes, businesses, and industry.
- ☞ Predictive model results involve a certain amount of uncertainty, which can be minimized by using as many site-specific measurements as possible.

2.1 Developing the Conceptual Site Model: Developing a conceptual site model (CSM) is an important first step for assessing contaminated sites and the potential for vapor intrusion. Briefly, a CSM is a picture and narrative of the site contamination: how it got there, whether or not it is migrating or degrading, its distribution across the site, who might be exposed to it, and what risk-reduction strategies are most feasible. CSM development actually begins during the Phase I environmental site assessment with collection and evaluation of site history and reconnaissance information. During subsequent site characterization activities, the CSM can be augmented and refined, as necessary, with site-specific information on source areas, contaminant properties, stratigraphy, hydrogeology, exposure pathways, and potential receptors.

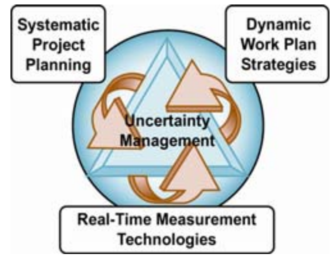
Building and refining a thorough CSM may involve a combination of techniques and tools to understand the subsurface, but specifically, investigations for vapor intrusion often include collecting samples of soil, groundwater, soil vapor, and/or indoor air. Investigators may use sampling in combination with predictive models. These topics are discussed further in Sections 2.2 and 2.3. Gathering sufficient information for a CSM is important for assessing vapor intrusion and determining cleanup and mitigation approaches. Developing a CSM by aggregating this information helps focus attention on areas where uncertainties in site information exist, and direct further information gathering and sampling efforts to where they may be needed most. Reducing these uncertainties and developing a robust CSM can provide more reliable results when implementing the appropriate approaches to assessing vapor intrusion, or the predictive models in Section 2.3.

Sample collection and analysis as well as other site assessment activities used to develop the CSM can be expensive; however, the expense of thorough, upfront characterization can be offset by the ability to plan for proper mitigation. Decisions regarding the number and types of samples to collect, where to collect them, and how to analyze them while minimizing costs can be improved using EPA's Triad approach. (See Text box 4.) Consistent with the Triad, ITRC (2007a) describes CSM development as an iterative sampling process where additional data is collected only when it is necessary to meet the needs of "making informed decisions." EPA encourages Triad in developing a CSM and managing uncertainty.

More information on development of CSMs can be found in the draft OSWER (EPA, 2002) and ITRC (2007a) (includes a checklist) guidances.

TEXT BOX 4: WHAT IS TRIAD?

Triad is a collaborative approach that helps land revitalization stakeholders work toward faster, better, and cheaper site characterization and cleanup, setting the stage for appropriate redevelopment.



Triad uses these guiding principles:

- A systematic planning process, which includes participation of all stakeholders to determine the types of data required and to develop a dynamic work strategy that guides the project but maintains the flexibility to make decisions and adapt as data are analyzed.
- Transparent discussion of uncertainty management, data representativeness, and end goals.
- An evolving CSM that can be updated and used at all stages of the project and is updated through a dynamic work strategy.
- Innovative sampling and data management technologies to help manage uncertainty involved in taking and analyzing samples
- Project teams that have effective communication, trust, and diverse expertise in appropriate fields.

This framework allows all stakeholders to have the opportunity to review the same information as they participate in the decision-making process. Early Involvement by regulators is important for success.

EPA's Triad Resource Center (www.triadcentral.org) has resources to guide stakeholders through the Triad approach.

2.2 Sampling and Analysis: Collecting samples for chemical analysis is the primary way in which a CSM is augmented and refined with site-specific data. Sampling not only helps evaluate the amount of contamination present beneath or inside a building, it can help environmental practitioners identify the source and extent of contamination, possible receptors, and risk levels. The sampling tools and analytical techniques selected for an investigation will depend, in a large part, on the current CSM.

Table 2 summarizes the advantages and disadvantages of the various options for sampling: groundwater, bulk soil, soil gas, sub-slab soil gas, and indoor air. The following subsections briefly describe some of the tools available for collecting these samples. Additional information on these tools as well as common laboratory and field-based analytical methods for soil gas and air samples, is contained in Appendix B. Readers seeking more information on sampling tools and sampling strategies can find it in Appendix B of ITRC's guideline (ITRC, 2007a). Although not discussed here, supplemental data for the multiple-lines-of-evidence approach, including differential pressure measurements, meteorological data, and chemical fingerprinting (ITRC 2007a), may provide valuable information to refine the CSM.

Groundwater and Bulk Soil Sampling: Groundwater sampling helps indicate whether a source in the unsaturated zone is contaminating groundwater, which may result in vapor intrusion occurrences downgradient (in the direction of groundwater flow) of the source. The OSWER draft guidance (EPA, 2002) allows the use of groundwater sampling results to estimate the vapor concentrations expected inside a building due to vapor intrusion.

The guidance does *not* recommend that bulk soil samples be used, because it is not possible to rule out a potential vapor intrusion problem based on soil sample data. However, it may be possible to show a problem does exist, particularly when the contamination is limited to semivolatile organic compounds (SVOCs). In any case, both soil and groundwater sampling are critical in the development of a CSM by helping to locate and delineate potential sources and plumes, identify potential receptors of contamination, and choose a cleanup approach. Guidelines for choosing groundwater sampling locations are included in Appendix B.

Soil Gas Sampling: Like groundwater samples, soil gas samples are used in the OSWER draft guidance to estimate expected indoor air concentrations. Soil gas sampling and analysis results tend to be most reliable where the contaminant concentrations are high and soils are more permeable (in other words, they allow for freer movement of soil gas). Soil gas sampling is limited to the unsaturated zone above the water table and cannot be performed at sites directly underlain by bedrock or having less than five feet of soil depth.

Soil gas samples collected near a known source of contamination best represent source vapor concentrations. Collecting soil gas samples that most closely represent the vapor intrusion to a building often requires collecting soil gas samples close to the building. However, sampling too close to the building could potentially damage the building or lead to inaccurate results. Vertical profiling─taking samples at several depths in one location─is recommended to get a sense of vertical distribution of vapors near the building, although sampling at shallow depths (less than five feet) is to be avoided due to possible influence of atmospheric or "ambient" air on the sample (EPA, 2002). For buildings constructed slab on grade, deep soil gas samples should be collected to offset any bias due to ambient air that could occur by sampling too close to the ground surface.

Because of the complex distribution of contaminants and soil layers beneath a site, soil gas concentrations may vary widely across a property. Because soil gas samples are collected outside the footprint of the building, they may not accurately represent the contaminant concentrations present under the building as a result of the capping effect. Properties to be developed with no existing buildings present an additional problem because soil gas samples

Table 2. Sampling Options for the Assessment of Vapor Intrusion

Option	Pros	Cons
Groundwater sampling	• Indicates whether or not a contaminant source in the unsaturated zone is contaminating groundwater. Helps assess potential downgradient impacts of vapor intrusion. • Can be performed at properties having no existing buildings.	• Does not represent vapor concentrations at the source. • Requires utility clearance to drill boring for monitoring well. • Requires legal access agreement and permit.
Bulk soil sampling	• Search and delineate extent of contamination in the unsaturated zone. • Can be performed at properties having no existing buildings.	• VOC loss on sampling may be significant. • Vapor concentrations may be underestimated. • Requires utility clearance to drill boring. • Requires legal access agreement and permit.
Soil gas sampling	• Near the source, it provides an estimate of source vapor concentration. • Near buildings, it can be performed without entering the structure. • Can be performed at properties having no existing buildings.	• Significant lateral and vertical spatial variability. • Results may not be representative of vapor concentrations under buildings. • Requires utility clearance to advance probe. • Requires legal access agreement.
Passive soil gas survey	• Can cost-effectively identify hot spots or areas of needing additional investigation. • Easy to perform. • Works better than other soil gas sampling methods in low-permeability soil. • Can be performed at properties having no existing buildings.	• Yields semi-quantitative results. • Data reported in mass, not concentration. • There is a two- to three-week delay in results.
Sub-slab sampling of vapors beneath buildings	• Establishes vapor concentration directly below indoor air space. Closest subsurface sample to receptors.	• Method is intrusive. • Requires legal access agreement and entry into buildings. • Cannot be performed at properties having no existing buildings.
Indoor air sampling	• Indoor air concentrations directly measured.	• Indoor contaminants and lifestyle sources may bias the data. • Method is intrusive. • Requires legal access agreement and entry into buildings. • Cannot perform at properties having no existing buildings.

Table adapted from EPA, 2007.

Figure 2. Installation of Soil Gas Probe Near a House. Soil gas probes are a primary method of collecting samples to measure soil-gas chemical concentrations.
Photo Courtesy of H&P Mobile Geochemistry in Carlsbad, CA.

collected from an open field will under-predict concentrations that collect under buildings due to the capping effect.

Soil gas probes are the primary tools for collecting soil gas samples (Figure 2). Where sub-slab sampling is impractical, probes can be installed adjacent to a structure at an angle to sample underneath a building. Care should be taken to avoid significant disturbance of the soil when installing probes. The installation and use of soil gas probes are explained in Appendix B.

Passive Soil Gas Survey: A passive soil gas survey is another line of information that can be used to evaluate soil gas for vapor intrusion. These surveys are often used to direct other sampling. Passive soil gas samplers consist of an adsorbent material in a container that is placed in a small-diameter boring in the unsaturated zone, typically at a depth of less than three feet (Figure 3). The device is left underground for a set period of time─usually one to two weeks─before the adsorbent material is retrieved and analyzed for masses of contaminants.

Passive soil samplers estimate the total mass of each contaminant (essentially the total amount measured in grams) accumulated over the time they are left underground─typically one to two weeks. This approach does not yield concentrations of soil gas contaminants (the amount per a given volume); thus, the results are not directly comparable to those from soil gas probes.

Figure 3. Examples of Passive Soil Gas Samplers. Passive samplers measure total mass of contaminant that accumulates over the time they are left in the ground. These samplers can add a line of evidence to the CSM that can help identify hot spots and preferential pathways.

Top two photos courtesy of Beacon Environmental Services, Inc. Bel Air, MD. Bottom three photos courtesy of W.L. Gore & Associates, Inc. Elkton, MD.

Because the adsorbent material irreversibly accumulates contaminants and over a longer period of time than active sampling, short-term variations in soil gas movement will have less of an impact on detecting contaminants, and smaller amounts of contaminants can be detected.

Use of passive soil gas samplers can help confirm the presence of contaminants in soil gas. However, the absence of a detection of contaminants in a sampler does not necessarily mean a complete absence of contaminants in the soil gas, as soil gas distribution in the subsurface typically is not uniform and the sampler may not be located in an optimal area to intercept the gases.

However, many of these samplers are usually deployed at once, often in a grid pattern over the area of concern; and by comparing contaminant masses measured across a property, passive soil gas sampling can augment a CSM by helping to identify the location of sources, “hot spots” (areas of high concentrations), and preferential pathways. Unlike soil gas probes, passive soil gas samplers can also be used to detect some SVOCs.

Sub-Slab Sampling: Sub-slab samples are samples of soil gas collected just beneath the building foundation, whether a basement floor or slab-on-grade. Soil gas probes designed specifically for sub-slab sampling are used to collect samples (Appendix B).

Sub-slab samples should be located beneath areas of the slab where there are no cracks or openings nearby. Avoiding cracks and openings is important for calculating the attenuation factor[3] that is used in predictive models and vapor intrusion guidance. This may not be easy because cracks and openings may not be obvious, and furniture, appliances, utilities, etc. may

[3] The attenuation factor is a measure of how soil and building properties limit the intrusion of organic vapors into overlying buildings. It is defined as the concentration of the contaminant in the indoor air divided by the concentration of the contaminant in soil gas or groundwater.

limit access to certain desired sampling points. In addition, care must be taken to avoid structural damage and drilling holes through rebar, utilities, etc.

Sub-slab samples are thought to better represent potential vapor intrusion concentrations and potential risk than soil gas samples collected outside the building footprint. Additionally, investigators may use sub-slab samples to distinguish the contribution of vapor intrusion to indoor concentrations, because sub-slab sampling is generally not biased by indoor sources of contaminants the way indoor air sampling can be. However, the primary obstacle to obtaining sub-slab samples, is that they require access to the building and drilling ⅜-inch-diameter holes in the foundation, which may not be allowed by the building owner.

ITRC's guideline (ITRC, 2007a) includes a rule of thumb that if sub-slab concentrations are 1,000 to 10,000 times greater than the target indoor levels, then the probability of unacceptable vapor intrusion is sufficient to warrant proactive mitigation without further characterization. This scenario may not be valid for all sites, but it points out that the property owner will have to decide when costs of further site characterization are more than mitigation.

Indoor Air Sampling: Where possible, samples of the indoor air should be collected to aid in the assessment of vapor intrusion. Deciding where and when to collect samples is important as indoor air and ambient air (the surrounding outdoor air) samples tend to exhibit considerable degree of variability over time. Concentrations of vapors can vary from home to home on the same block by a couple of orders of magnitude, and concentrations may rise and fall seasonally, with higher concentrations during cold months when windows and doors stay shut and heating systems stay on. During warmer months when windows and doors are open, vapors are ventilated to the outdoors.

Concentrations within a building are typically higher in the lower level near the sub-slab. Therefore, indoor air samples should be collected in the basement, if present, or on the first floor. Elevated concentrations may also be present in upper stories, however, as a result of circulation by heating, venting, and air-conditioning (HVAC) systems or if a conduit such as a bathroom pipe connects the lower and upper levels.

Evaluation of indoor air concentrations can be complicated by the presence of contaminant vapors from "background" sources present in most households and office buildings, such as cleaning products, hobby supplies, paints and solvents, carpet, cigarette smoke, dry-cleaned clothing and a host of other common items. Thus, an inventory should be conducted prior to indoor air sampling to identify potential indoor sources of VOCs and SVOCs that may affect the evaluation. To minimize the impact of background sources, it

TEXT BOX 5: IMPACT OF BACKGROUND SOURCES ON EVALUATING VAPOR INTRUSION

The evaluation of vapor intrusion is often complicated by contaminant vapors from other sources present in most households or businesses. These sources include cleaning products, hobby supplies, paints and solvents, carpet, cigarette smoke, and a host of other common items. Evaluation can also be complicated by outdoor sources such as emissions from gas stations, dry cleaners, and smokestacks, which can enter the building through open windows and doors. As a result, indoor air samples should be considered in conjunction with sub-slab samples from below the foundation and ambient air samples to help distinguish vapor intrusion from these background sources.

Figure 4. Air/Soil Vapor Sample Collection Devices: Canister, Sampling Bags, and Sorbent Tubes. These devices are used to collect air samples so they can be transported to a laboratory (either on site or off site) for chemical analysis. Some devices may be left on site for several days or weeks, and some sampling techniques may require property access. Engaging stakeholders early on is important so they understand the procedure, space, and time requirements of the sampling/monitoring events that may be required even after redevelopment and occupancy.

Photos Courtesy of EPA's Raymark OU2 Photo Gallery (http://www.epa.gov/Region1/superfund/sites/raymark/ou2photos.htm) and Environmental Supply Company, Inc.

is recommended that a building survey be conducted and obvious sources of indoor air vapors be removed from the building prior to sampling. All indoor sources may not be immediately apparent; less-obvious indoor sources such as non-functioning vapor traps on waste lines to sewer may contribute to indoor air contamination (ITRC 2007a).

In addition to indoor source identification and removal, indoor measurements should be considered in conjunction with sub-slab measurements to help distinguish vapor intrusion from background sources within the building. Differences in the ratios of contaminant concentrations in the sub-slab and the indoor air may suggest which is the primary source of vapors. Sampling of the outdoor air should also be considered in conjunction with indoor air sampling to assess the contribution of possible outdoor sources of air pollution, such as a nearby gas station, highway, or industries.

Figure 4 illustrates some of the sampling devices used to collect indoor air samples. The same devices are also used to collect soil gas samples from soil vapor probes and sub-slab probes. These devices are explained further in Appendix B. Appendix B also summarizes the analytical methods and real-time measurement devices used in the assessment of vapor intrusion.

2.3 Using Predictive Models: Predictive computer models are useful tools for assessing the potential for vapor intrusion to occur at a property, particularly when limited field measurements can be collected. However, the results should be used with caution as their uncertainty increases with the uncertainty of the data input. In the absence of adequate field measurements, models require that data input be based on assumptions made about the CSM (e.g., concentrations of contaminants, complexity of the site geology/hydrogeology, and characteristics of the building). Models can yield a wide range of results depending on these assumptions.

Data uncertainty is an issue when interpreting the results of any model—particularly when making risk-based decisions. Uncertainty in model results can arise from uncertainties in both data input (i.e., How well do they represent field conditions?) and the model itself (e.g., Does the conceptual basis for the model adequately represent the site? And, is there sufficient knowledge to make this determination?) (EPA, 2005b). As described by ITRC (2007a), other lines of evidence can also be considered. Uncertainty in model results can be minimized by using as many site-specific measurements as possible for data input to the model. Although site-specific data are highly recommended, sufficient field measurements are not always practical or possible at a site due to site access issues. As a result, most models allow for using estimated values of input parameters or default values based on typical averages cited in the literature.

A commonly used, screening-level model for assessing vapor intrusion is the Johnson and Ettinger or "J&E" model (J&E, 1991; Johnson et al., 1998, 1999). (Use of the J&E model may be suggested in the second and third tiers of the vapor intrusion assessment approach described in the OSWER draft guidance.) This model simulates one-dimensional diffusion of soil gas through unsaturated soil and both diffusion and advection through the building foundation. The J&E model is based on a number of simplifying assumptions regarding contaminant distribution and occurrence, subsurface characteristics, vapor transport, and building construction. The J&E model should be used only when site conditions match the model assumptions using reasonable, site-specific, or regulator-approved input (EPA, 2004a).

The J&E model can be used to calculate the expected contaminant concentration in indoor air given a measured or estimated concentration in soil gas or groundwater. Or, it can be used to calculate the allowable building concentration given for a specified increased cancer risk or hazard quotient (used to define non-cancer risks) for a residential scenario. For ease of use, EPA incorporated the J&E model into Excel spreadsheets (available for download at: http://www.epa.gov/oswer/riskassessment/airmodel/johnson_ettinger.htm. Click on "3-Phase System Models and Soil Gas Models.")

TEXT BOX 6:
TYPES OF PREDICTIVE MODELS

EPA's paper, *Review of Recent Research on Vapor Intrusion* (EPA, 2005c), summarizes and provide sources for further information on several of the predictive models and equations used to evaluate the vapor intrusion pathway. More recently developed numerical models allow for three-dimensional movement of soil gas (Abreu and Johnson, 2005).

3.0 MITIGATION OF VAPOR INTRUSION

Whether existing structures will be renovated or new buildings constructed, vapor intrusion can be mitigated at brownfield sites. Eliminating the source of contamination can be more protective of human health and the environment than mitigation alone, but it may not be technically feasible, cost effective, or well suited to site redevelopment (EPA, 2004b). Depending on the nature of contamination present, source elimination may involve a combination of activities, such as excavating contaminated soil for treatment and disposal, pumping and treating groundwater plumes, or soil vapor extraction to remove vapors. There also are a number of remediation technologies available to treat soil and groundwater in place, which avoids the hazard and added expense of handling and disposing large volumes of waste (http://www.cluin.org/techfocus/).

Eliminating the source of contamination is unlikely to immediately protect building occupants from vapor intrusion, however. Because remediation can take years, institutional controls (Text box 7) may be required to prevent or limit development of certain parcels until cleanup has sufficiently reduced risks. In addition, mitigation may be necessary. For example, existing buildings may need to be retrofitted with vapor mitigation systems, and new construction may require design elements that incorporate the mitigation of vapor intrusion. This section focuses on both passive and active mitigation methods for vapor intrusion. Treatment of the indoor air itself is not considered here because this approach is not common, and treatment systems are expensive to install and operate as well as difficult to maintain.

A Quick Look at Mitigation

- ☞ Mitigation approaches should be considered during the development of the CSM (See Section 2).
- ☞ Eliminating the source of contamination can be the best way to prevent vapor intrusion, but source elimination may not be technically feasible, abate immediate risks, or affordable.
- ☞ Early awareness and consideration of the potential for vapor intrusion facilitates use of mitigation strategies before building occupants can be exposed to harmful vapors.
- ☞ Proactively incorporating mitigation strategies into new construction provides more options for mitigation.
- ☞ Mitigation strategies used in construction of new buildings are more cost effective and tend to function better than retrofits.
- ☞ Institutional controls may be required to inform owners and occupants of the vapor intrusion mitigation measures and to ensure ongoing operation of those systems.

> **TEXT BOX 7:
> WHAT ARE INSTITUTIONAL CONTROLS?**
>
> Institutional controls are legal or administrative actions that help minimize the potential for human exposure to contamination by ensuring appropriate land or resource use. Examples include restrictive covenants, zoning restrictions, and special building permit requirements.

Note that mitigation methods for vapor intrusion are similar to those for radon gas (EPA, 1994), but due to the much lower target vapor concentrations the design and performance assessment of such systems requires a more robust approach.

3.1 Passive Mitigation Methods: Passive mitigation methods to vapor intrusion generally prevent vapor intrusion by blocking entry through the building foundation. It is usually simpler and more cost-effective to prevent the entry of soil vapor than remove soil vapors using active approaches, although active mitigation methods are generally more effective at meeting regulatory standards for the vapor intrusion pathway. Selection of approach will depend on site circumstances, including the amount of contaminant reduction in the vapor required. The primary passive approaches are to seal cracks, install a passive barrier, and install a passive venting system.

Sealing Cracks: Cracks and openings in the building foundation are the primary routes of vapor entry. Thus, sealing cracks in the floors and walls as well as gaps around utility conduits is an important first step in preventing vapor intrusion. Similarly, gaps around utilities, sumps, and elevator shafts also should be properly sealed. Sealing cracks and gaps may also be necessary when used with other mitigation strategies, such as sub-slab depressurization to ensure efficiency.

In existing buildings, cracks may be difficult to find, and as buildings age, more cracks tend to appear and seals tend to fail. Buildings that are in seismically active areas may be particularly prone to additional cracking and compromising of existing seals. And despite sealing cracks, walls made of porous cinder blocks may still allow vapor entry.

In studies of radon gas, a thorough job of sealing cracks and openings typically only results in a 50-70 percent reduction in radon entry (EPA, 1988). As a result, EPA does not recommend radon mitigation solely by sealing cracks because this approach has not been shown to lower levels significantly or consistently (EPA, 2003). Thus, additional mitigation also may be needed to prevent vapor intrusion.

Passive Barriers: Passive barriers are materials or structures installed below a building to block the entry of vapors (ITRC, 2007a). Barriers are usually installed during construction, but they can be installed in existing buildings with a crawl space, if needed. Typically, a passive barrier comprises a sheet of polyethylene plastic or equivalent geomembrane installed beneath a slab-on-grade foundation and sealed to the foundation walls or footings. The seams created by the overlapping sheets must be completely sealed as well. Passive barriers are only effective if they are not compromised by holes, tears, or a poor seal around the foundation, so their integrity must be tested after installation. Passive barriers without an underlying venting layer are not likely to be effective unless the subsurface conditions are conducive to natural venting (ITRC, 2007a).

Passive Venting: Where vapor intrusion may be anticipated in new construction, passive venting systems may be used to safeguard against vapor intrusion. These systems are often combined with passive barriers. Typically, perforated collection pipes are installed in a layer of permeable sand or gravel to direct vapors to the edges of the foundation. Often, such collection pipes are connected to a main header point that runs up through or along the building's inner or outer wall and exhausts above the roofline. If the permeable layer is vented directly to the atmosphere, no exhaust pipes are needed.

Because passive systems rely on wind currents to induce vapor flow through the pipes, they are ineffective at removing vapors on days that aren't windy. If the wind blows toward the exhaust pipe at the roof line, it may blow vapors back down to the sub-slab region. Thus, active systems (Section 3.2), which use electric fans to induce vapor flow, are more consistently effective at mitigating vapor intrusion. Passive venting systems can be converted to an active depressurization system when needed.

3.2 Active Mitigation Methods: Active approaches to mitigating vapor intrusion remove the driving force behind vapor migration, which is the higher pressure that exists in the sub-slab area relative to indoors. By lowering the pressure beneath the sub-slab or passive barrier or inducing a higher pressure in the building, vapor flow is neutralized or reversed.

Depressurization: There are several types of depressurization systems, including sub-slab depressurization (also called sub-slab suction), sub-membrane depressurization, block-wall suction, and drain-tile suction. In most instances, mitigation of residential structures requires a sub-slab depressurization system (Mosley, 2005), which can be installed in houses with basements or slab-on-grade construction. They are similar to passive venting systems, except that they include a fan to induce a level of sub-slab depressurization that compensates for the depressurization of the building. In practice, these systems often operate by sweeping contaminated soil vapor from the sub-slab region (Figure 5). Installed properly, these fans should operate quietly without disruption to building occupants. Depressurization systems offer the added benefit of reducing radon concentrations, moisture, and mold (Mosley, 2005).

In existing buildings, holes are drilled into the sub-slab for installation of 4-inch diameter vertical PVC pipes. The optimum location for the pipes is near the center of the sub-slab; however, this location is often inconvenient to building occupants. Therefore, pipes are more likely to be installed at the perimeter of a room, but should not be too close to the building footing to avoid short circuiting of ambient air down the exterior wall. The pipes are connected by manifold and equipped with a fan (typically made of PVC to prevent corrosion) to draw vapors up the pipe, or

**TEXT BOX 8:
FOR MORE INFORMATION ON MITIGATION…**

A more detailed discussion of mitigation methods, including pros and cons of each method and a comparison of typical applications and costs, can be found in Section 4 of ITRC's recent guideline (ITRC, 2007a) and in Table 1 of EPA, 2007. Appendix X2 of ASTM E 2435-05 also details design, installation, and maintenance for engineering controls (i.e., mitigation technologies).

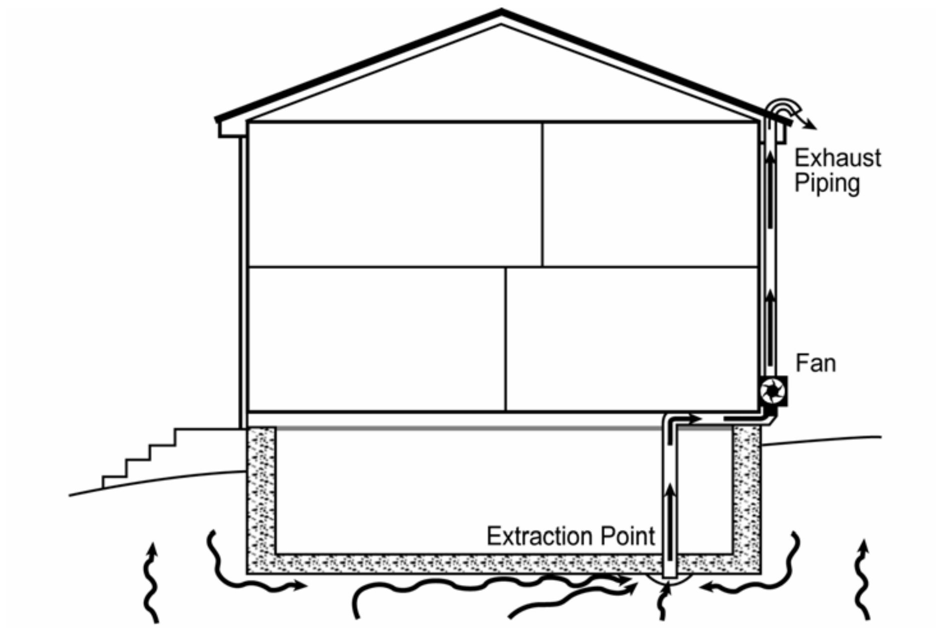


Figure 5. Schematic of Active Soil Depressurization System. This system provides a pathway for the vapors to vent to the outside air, instead of migrating into the building. Consideration of possible mitigation processes should be considered before the characterization process so that key design parameters can be evaluated during the field investigations. For more information see ASTM E2435-05, 2005.

Figure Source: New Jersey Department of Environmental Protection fact sheet on Subsurface Depression Systems (www.nj.gov/dep/srp/community/factsheets/subsurface01.pdf.)

stack. The stack is vented to the outdoors at the top of the building in accordance with ASTM 2121. Although the location of the stack vent is usually at the discretion of the owner, care should be taken to position it so that it is not near a window, deck, or other location where air can be inhaled or drawn back into the building or neighboring buildings. If the soil beneath the building is not very permeable or if the gravel subbase is discontinuous, additional suction points may be needed. After installation, a demonstration of a negative pressure under the entire slab can be used to confirm the performance of the system.

Submembrane depressurization systems are similar to sub-slab depressurization systems except that they are installed below the passive barrier during construction, or can be retrofitted in buildings with crawl spaces. The vertical pipes that penetrate the passive barrier should be well sealed. *Block-wall suction systems* involve the removal of vapors that accumulate in basement walls constructed of hollow blocks. *Drain-tile suction systems* apply suction to existing water drainage systems that circle a building, in order to remove vapors.

Sub-slab Soil Pressurization: A sub-slab soil pressurization system is similar to a depressurization system except that the fan is reversed to pressurize the sub-slab and divert flow away from the foundation. This approach is only used for high permeability soil and when other options fail. It is generally not recommended because it can exacerbate vapor intrusion in some situations.

Building Pressurization: Building pressurization involves adjusting the building's heating, ventilation, and air-conditioning (HVAC) system or installing a new system to maintain a positive pressure indoors relative to the sub-slab area. This approach is more common for large commercial buildings and can be the most cost effective if the existing HVAC system already maintains a positive pressure (ITRC, 2007a). Having to increase the pressure will result in larger energy costs, particularly if significant heating and cooling is required. Replacing an HVAC system will be significantly more expensive.

Modifications to an HVAC system should be designed to avoid condensation of water resulting from excessive humidity. Excess moisture can foster the growth of mold, which has significant negative impacts on indoor air quality and potentially the health of building occupants. Conversely, in some climates HVAC modifications might lead to uncomfortably low levels of humidity (EPA, 2007b).

3.3 Strategies for New Construction: New construction affords the opportunity to plan a redevelopment according to the CSM. For example, new building construction could be targeted to the portions of the site that are least prone to vapor intrusion, such as those areas furthest from the contaminant source or upgradient of a groundwater plume. In addition, construction could incorporate strategies that minimize vapor intrusion induced by stack and wind effects and ventilate vapors. Such strategies include using a raised building design or including an open-air parking garage on the lower level of the building. Plans for new buildings could also proactively consider the potential for vapor intrusion by incorporating mitigation strategies into construction.

Buildings should be designed and constructed to minimize potential entry pathways for vapors and minimize the pressure differences that draw them in. Examples of design elements that can be evaluated include elevator shafts (and drains), utility corridors and penetrations, and basement sumps. HVAC systems in new construction can be designed to limit entry pathways and conduits, and/or create positive pressure inside the building. Incorporating vapor intrusion mitigation strategies into new construction provides more options for mitigation and can save costs in the long run. For example, aggregate placed beneath the foundation slab and the installation of passive ventilation systems can facilitate incorporation of further post-construction mitigation systems. Another possibility is configuring radon mitigation systems, required in high-radon areas, to mitigate vapor intrusion as well.

It is estimated that incorporating mitigation strategies in residential-building (typical single-family home) design costs from $120 to $1000–or only 15-40 percent of the $800-$2500 cost of retrofitting the building later (Mosley, 2006). Not only are they more cost effective, but systems incorporated into new construction tend to function better than retrofits. Thus, it can be beneficial both in terms of costs and functionality to install a passive barrier and passive venting system in the anticipation that vapor intrusion may occur, even if it is not currently a problem.

3.4 Operation and Maintenance of Residential Systems: Land revitalization stakeholders should be involved in helping their consultants develop an operation and maintenance (O&M) plan that identifies who will be responsible for the O&M of residential systems and for how long. Over time, breakdowns in the system can occur. Fans may need to be serviced, leaks may develop, or exhaust stacks may break. When a system is installed, it should be understood by all stakeholders who will be responsible for O&M: e.g., the building owner or lessee, developer, or overseeing regulatory agency. Also, they should decide how long the system may need to operate to meet treatment objectives: e.g., until the groundwater plume is treated, until contaminant concentrations are no longer detected in indoor air, or as long as the building is occupied. Additional considerations include: Will samples be collected to ensure the system is functioning and that venting to the atmosphere does not result in additional risk to people nearby? And, who will collect and analyze the samples?

If the building owner/lessee is responsible for O&M, this should be understood at the time of purchase through, for example, a maintenance agreement along with information about whom to call with questions or problems. Typically, if the property falls under the domain of a regulatory program such as CERCLA, the regulatory agency overseeing cleanup will be responsible for conducting or overseeing monitoring system performance and/or monitoring indoor air to ensure risk levels are not exceeded. This communication about vapor intrusion and the O&M of a mitigation system can be critically important. For example, building owners may be concerned about the electrical costs for operating a system, and decide to turn off the system. However, a typical residential sub-slab depressurization system requires negligible power compared to home appliances and lighting. Therefore, turning off the system may save little in relative costs, and the system will now likely be less consistent and effective in reducing the vapor concentrations inside the building.

4.0 CONCLUSIONS

Vapor intrusion is an exposure pathway that potentially affects thousands of brownfield sites considered for redevelopment, and even sites that have no known history of contamination or industrial activities. It is important for land revitalization stakeholders involved in brownfields redevelopment to recognize the potential for vapor intrusion to avoid liability, construction delays, and expense. The key to cost-effective and comprehensive solutions to vapor intrusion is considering the issue early in the redevelopment process– before final building design and construction. Early consideration makes available more options for cleanup, prevention, and abatement. It also saves money and time in the long run, thus ensuring that the vapor intrusion pathway is not a deal breaker when it comes to redevelopment.

Interest in investigating this pathway continues to grow and development of` new and reliable means for sampling and analysis is occurring at the federal and state levels. Many states have already issued guidance, and others are in the process of developing new guidance regarding sampling, modeling, and risk assessment for vapor intrusion.

A thorough CSM incorporating adequate site characterization is an important tool that can assist decision-makers with ensuring that redevelopment can protect human health. A collaborative, systematic approach that includes all appropriate stakeholders will ensure progress. There are several sampling techniques already available to aid in vapor intrusion investigations, including some real-time measurement technologies that are a key component of Triad. Proven and relatively inexpensive prevention and abatement technologies are available to eliminate vapor intrusion risk.

For more information on addressing vapor intrusion sites, please contact the Brownfields and Land Revitalization Technology Support Center (BTSC). Information on the BTSC and support contacts for both brownfields and Superfund sites are listed on http://www.brownfieldstsc.org/. Updates will be posted as they become available.

Other sources of information include:

- The EPA Ground Water and Ecosystems Research Division's summaries of its vapor intrusion related research at http://www.epa.gov/ada/topics/vapor.html.

- EPA documents related to vapor intrusion, many of which are archived online at the Technology Innovation and Field Service Division's (TIFSD) CLeanUp Information (CLU-IN) website at www.cluin.org.

- The Triad Resource Center (www.triadcentral.org), a website maintained by TIFSD, which is devoted to providing information that hazardous waste site managers and cleanup practitioners need to implement the Triad approach effectively.

- The Indoor Air Vapor Intrusion Database (http://iavi.rti.org), which allows regulators and other stakeholders to submit site-specific vapor-intrusion data to support development of screening-level predictions of vapor attenuation. The website also lists upcoming vapor intrusion workshops and conferences and provides links to guidance documents and other references.

- The references listed in Appendix D of this document.

APPENDIX A: Know Your State! Available State Guidance Regarding Vapor Intrusion

State	Available Guidance[4]
Alaska	*Evaluation of Vapor Intrusion Pathway at Contaminated Sites* (Draft), 16 pp, 2006. http://www.dec.state.ak.us/spar/csp/guidance/draft_vap_intr_tm_6_28.doc *Inhalation of Diesel Vapor in Indoor Air*, Technical Memorandum 02-001, 7 pp, 2002. http://www.dec.state.ak.us/spar/csp/guidance/indoor_air_12_02.pdf
California	*Guidance for Assessing Exposures and Health Risks at Existing and Proposed School Sites*, Excel spreadsheet for calculating risk, updated July 12, 2006. http://www.oehha.ca.gov/public_info/public/kids/schools2604.html *Screening for Environmental Concerns at Sites with Contaminated Soil and Groundwater*, Interim Final, 2005. http://www.swrcb.ca.gov/rwqcb2/esl.htm *Use of California Human Health Screening Levels (CHHSLs) in Evaluation of Contaminated Properties*, 67 pp, 2005. http://www.calepa.ca.gov/Brownfields/documents/2005/CHHSLsGuide.pdf *Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air*, 105 pp, 2004. (Revised February 7, 2005) http://www.dtsc.ca.gov/AssessingRisk/upload/HERD_POL_Eval_Subsurface_Vapor_Intrusion_interim_final.pdf *Advisory – Active Soil Gas Investigations*, 25 pp, 2003. http://www.dtsc.ca.gov/loader.cfm?url=/commonspot/security/getfile.cfm&pageid=94677 CalTOX: A Total Exposure Model for Hazardous Waste Sites http://www.dtsc.ca.gov/AssessingRisk/ctox_dwn.cfm
Colorado	*Policy on an Interim Risk Evaluation and Management Approach for PCE*, 3 pp, 2006. http://www.cdphe.state.co.us/hm/pcepolicy.pdf *Policy on an Interim Risk Evaluation and Management Approach for TCE*, 2 pp, 2006. http://www.cdphe.state.co.us/hm/tcepolicy.pdf *Draft Indoor Air Guidance*, 58 pp, 2004. http://www.cdphe.state.co.us/hm/indoorair.pdf *Guidance for Analysis of Indoor Air Samples*, 9 pp, 2000. http://www.cdphe.state.co.us/hm/airsmpl.pdf Petroleum Storage Tank Owner/Operator Guidance Document, 45 pp, 1999. http://oil.cdle.state.co.us/OIL/Technical/Guidance%20Documents/guidancedoc.asp

[4] List is current as of April 2007.

Connecticut	*Significant Environmental Hazard Condition Notification Threshold Concentrations, Reference Table A: Volatile Organic Substances*, 2005. http://ct.gov/dep/cwp/view.asp?a=2715&q=324964&depNav_GID=1626 *Connecticut's Remediation Standard Regulations Volatilization Criteria: Proposed Revisions*, 50 pp, 2003. http://ct.gov/dep/cwp/view.asp?a=2715&q=325012 http://ct.gov/dep/lib/dep/site_clean_up/remediation_regulations/RvVolCri.pdf
Delaware	*Policy Concerning the Investigation, Risk Determination and Remediation for the Vapor Intrusion Pathway*, 32 pp, March 2007. http://www.dnrec.state.de.us/dnrec2000/Divisions/AWM/sirb/policy%20concern07008.pdf
Idaho	*Risk Evaluation Manual, Appendix C: Evaluation of the Indoor Air Inhalation Pathway*, 2004. http://www.deq.idaho.gov/Applications/Brownfields/download/appx_all.pdf
Indiana	Indiana's pilot program guidance is intended to provide interim guidance, not requirements, for site investigation. *Indiana Department of Environmental Management Draft Vapor Intrusion Pilot Program Guidance*, 90 pp, April 26, 2006. http://www.in.gov/idem/catalog/factsheets/la-712-fs.pdf
Louisiana	Risk Evaluation/Corrective Action Program (RECAP), 119 pp, October 20, 2003 http://www.deq.louisiana.gov/portal/tabid/131/Default.aspx
Maine	*Edited/Adapted Field Guideline for Protecting Residents from Inhalation Exposure to Petroleum Vapors*, 34 pp, 2000. http://www.maine.gov/dep/rwm/petroleum/pdf/inhaexpfg.pdf Guideline for Protecting Residents from Inhalation Exposure to Petroleum Vapors, 271 pp, 1998. http://www.maine.gov/dep/rwm/petroleum/pdf/inhalexp.pdf
Massachusetts	*Indoor Air Sampling and Evaluation Guide*, WSC Policy #02-430, 157 pp, 2002. http://www.mass.gov/dep/cleanup/laws/02-430.pdf *Guidelines for the Design, Installation, and Operation of Sub-Slab Depressurization Systems*, 15 pp, December 1995. http://www.mass.gov/dep/cleanup/laws/ssd1e.pdf *Massachusetts Contingency Plan Numerical Standards: GW-2* http://www.mass.gov/dep/cleanup/laws/gw2.htm

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Minnesota	*Indoor Air Sampling at VOC Contaminated Sites: Introduction, Methods, and Interpretation of Results*, 17 pp, 2004. http://www.health.state.mn.us/divs/eh/hazardous/topics/iasampling.pdf *Vapor Intrusion Assessments Performed During Site Investigations*, Guidance Document 4-01a, 13 pp, 2005. http://www.pca.state.mn.us/publications/c-prp4-01a.pdf
Missouri	*Missouri Risk-Based Corrective Action (MRBCA) Technical Guidance, Appendix H: Measurement of Soil Vapor Levels*, 16 pp, 2006. http://www.dnr.mo.gov/env/hwp/mrbca/mrbca.htm *Missouri Risk-Based Corrective Action (MRBCA) Process for Petroleum Storage Tank Sites, Appendix C: Evaluation of Indoor Inhalation Pathway*, 9 pp, 2004. http://www.dnr.mo.gov/env/hwp/tanks/mrbca-pet/docs/mrbca-pet-appendix-c.pdf
Nebraska	Nebraska has no individual guidance. However, the topic of vapor intrusion is discussed in *Risk-Based Corrective Action (RBCA) at Petroleum Release Sites: Tier 1/Tier 2 Assessments & Reports*, 2004. http://www.deq.state.ne.us/Publica.nsf/a9f87abbcc29fa1f8625687700625436/66fdec793aefc4b286256a93005b8db8?OpenDocument
New Hampshire	*Vapor Intrusion Guidance*, 44 pp, July 2006. http://www.des.state.nh.us/orcb/doclist/pdf/vapor_intrusion.pdf GW-2 Methodology, 2 pp, 2006. http://www.des.state.nh.us/orcb/doclist/pdf/Revised_GW-2_Methodology.pdf

New Jersey	*New Jersey Johnson & Ettinger Spreadsheets*, 2006. http://www.nj.gov/dep/srp/guidance/vaporintrusion/njje.htm Several reports at http://www.nj.gov/dep/srp/guidance/vaporintrusion/ including: *Vapor Intrusion Guidance*, 282 pp, 2005 http://www.nj.gov/dep/srp/guidance/vaporintrusion/vig.htm *Indoor Air VOC Sampling and Analysis Requirements*, 2 pp, 2003 http://www.nj.gov/dep/srp/guidance/vaporintrusion/ia_sampling_req.pdf
New York	Several reports at http://www.health.state.ny.us/environmental/indoors/vapor_intrusion/ including: *Guidance for Evaluating Soil Vapor Intrusion in the State of New York*, 2006 http://www.health.state.ny.us/environmental/investigations/soil_gas/svi_guidance/ Strategy For Evaluating Soil Vapor Intrusion at Remedial Sites in New York (DER-13), 16 pp, 2006. http://www.dec.state.ny.us/website/der/tagms/der13.pdf or http://www.dec.state.ny.us/website/der/guidance/vapor/ Indoor Air Sampling and Analysis Guidance, 4 pp, 2005. http://www.health.state.ny.us/environmental/indoors/air/guidance.htm
Ohio	*Methodology for Vapor Intrusion Assessment*, 4 pp, 2005. http://www.epa.state.oh.us/derr/rules/vapor.pdf
Oregon	Screening Model for Volatilization from Soil to Indoor Air at Heating Oil Tank Sites (Excel spreadsheet to be used with *Risk-Based Decision Making for the Remediation of Petroleum-Contaminated Sites* at http://www.deq.state.or.us/lq/rbdm.htm). http://www.deq.state.or.us/lq/tanks/hot/screeningmodel.htm
Pennsylvania	Section IV.A.4, "Vapor Intrusion into Buildings from Groundwater and Soil under the Act 2 Statewide Health Standard," (26 pp, 2002) in the *Recycling Program Technical Guidance Manual*. http://www.dep.state.pa.us/dep/subject/advcoun/cleanup/2002/BoldedVaporGuidance_100702.pdf
Wisconsin	*Chemical Vapor Intrusion and Residential Indoor Air: Guidance for Environmental Consultants and Contractors*, 16 pp, 2003. [Provides background on vapor intrusion but basically refers readers to EPA guidance and the Johnson and Ettinger model.] http://www.dhfs.wisconsin.gov/eh/Air/fs/VI_prof.htm

APPENDIX B: Additional Sampling and Analysis Information

Groundwater and Bulk Soil Sampling: When collecting groundwater samples for the assessment of groundwater plumes that are suspected to be a cause of vapor intrusion, it is recommended that samples be collected near the source at locations selected to determine representative concentrations under the building. Sufficient sampling should be conducted to understand the extent of the plume. Both traditional drill rig and direct push technologies can be used to install permanent monitoring wells or point-in-time (temporary) groundwater sampling points (EPA, 1991; EPA, 2005d). Similarly both technologies can be used to advance borings to sample soil. Both soil and groundwater samples should be collected so as to minimize the loss of VOCs in the sample due to volatilization. In addition, when collecting groundwater samples for the purpose of assessing the vapor intrusion pathway, samples should be collected from the upper portion of the groundwater column at or near the water table because the soil gas from a groundwater source diffuses from the portion of the contaminant plume nearest the water table.

Confidence in groundwater data can be increased through the use of a short screened interval across the surface of the water table, the use of low-flow sampling procedures, and a variety of other depth-discrete sampling protocols (EPA, 2002). Possible fluctuations in water table elevation would need to be considered when positioning screens in permanent monitoring wells. The possibility of seasonal variations in the water table or plume diving (where a plume is forced progressively deeper with increasing distance from the contaminant source as precipitation recharges the water table) should be considered as well.

Appendix E of the EPA draft guidance provides a list of standards for groundwater sampling, published by ASTM.

Soil Gas Sampling: Soil gas probes are the primary method of collecting samples to measure concentrations of contaminants in soil gas. The American Petroleum Institute (API) also suggests two alternatives to soil gas probes─passive soil gas samplers and flux chambers─for use in instances where probes are not practicable, such as where site access is limited for probe installation or where soil is fine-grained or has high moisture content. These devices measure contaminant mass and mass flux, respectively, rather than contaminant concentration. By using several of these devices to collect samples across an unpaved area, it may be possible to measure the potential or relative potential of vapor intrusion at sites at which development is planned in the future. If the area is paved a small portion of the paving can be removed to allow for installation.

Soil gas probes are narrow-diameter, hollow, copper or stainless steel rods installed vertically into the soil to withdraw soil gas at depth for analysis. The rods can be installed in small augered borings, or by direct push technology or drilling, which is typically quicker and less expensive. In some situations, probes can be installed at an angle to sample underneath a building, rather than adjacent to it. Care should be taken to avoid significant disturbance of the soil when installing probes.

Soil gas probes are most effective at collecting samples in permeable soil having little moisture. Soil gas enters the rods through the bottom opening or a short (6- to 12-inch) screen, which is positioned at a depth of interest. The length of rods is attached to a sampling tube and a sampling device (as described later in this section) near the sampling location. The probe is first purged of standing air to ensure a more representative sample.

The gap between the soil gas probe and sampling tube must be well sealed to prevent dilution of the sample with ambient air (the outdoor air surrounding the property of interest). Tracer gases have been suggested for use as a quality assurance/ quality control (QA/QC) device to verify integrity of the soil gas probe seal and determine if the sample is being diluted by surface air during collection (New York Department of Health, 2005). A container, such as cardboard box or a plastic bag, is placed over the probe and filled with one of many possible tracer gases. A soil vapor sample is collected from the probe and analyzed for the tracer gas. A concentration of more than 20 percent of the tracer is considered evidence of surface air infiltration of the sample.

The American Petroleum Institute (API, 2005) describes and compares the probe installation options, how to collect and analyze soil vapor samples, and how to interpret the results. The discussion is geared toward petroleum-contaminated sites, but much of the information can be applied to other VOC sites as well.

Sub-Slab Sampling: To identify optimum sub-slab sampling locations, a reconnaissance of the building should be performed prior to sampling to locate any cracks or openings in the foundation and to find out if the building owner has any concerns with proposed sampling locations. Due to possible impact of wind on sub-slab concentrations, atmospheric conditions should be monitored at the time of sampling, and sampling should be avoided on unusually windy days. It is also recommended that two or three samples be collected at each building, if possible (EPA, 2006a).

Sub-slab probes are constructed of a brass or stainless steel, narrow-diameter tube inserted into a hole drilled through the foundation and into the underlying soil. The hole can be drilled with a hand-held, rotary hammer drill. The upper few inches of the annulus between the tube and the drilled hole is sealed flush to the floor with grout to prevent extraction of indoor air and dilution of the sample. Between samples, the top of the tube is covered with a threaded cap, which can be installed flush with floor level so it does not protrude into the living space. Soil gas samples are withdrawn and analyzed from the sub-slab probes in the same manner as soil gas probes. These probes can be used to design and assess the performance of mitigation systems, if such systems are needed.

In the absence of a standard sub-slab probe installation and sampling method, EPA’s Office of Research and Development (ORD) and Region 1 recently developed an installation method that was tested in a vapor intrusion investigation at the Raymark Superfund Site (EPA, 2006b). ORD’s probe installation method involves counter sinking a small hole within a larger hole in the foundation. The probe fits flush in the 1-inch-diameter outer hole, which is drilled into the top 1 inch of the slab. A ⅜-inch diameter inner hole penetrated the slab and about 2 inches of the sub-slab material to provide an opening and prevent clogging of the probe. Use of a screen was unnecessary. The annular space between the holes was grouted to ensure a tight seal. EPA's Environmental Response Team subsequently redesigned the probe using chromatographic-grade stainless steel and gas-tight fittings.

Additionally, ORD developed a method to assess vapor intrusion using basement (indoor air) and sub-slab samples that could be used for building-by-building vapor intrusion determinations. Contaminant concentrations in the indoor air were determined to be a result of vapor intrusion if:

(1) a VOC was detected in groundwater or soil-gas samples collected in the vicinity of the building; *and*

(2) statistical testing of the sampling data supported vapor intrusion, which required the use of an "indicator" vapor known to be associated only with subsurface contamination (EPA, 2006c).

Basement/sub-slab concentration ratios of indicator contaminants (known to be associated only with subsurface contamination) were compared with those of other VOCs detected. The results revealed that detections of three indicator VOCs in indoor air consistently were caused by vapor intrusion, but the presence of a fourth occasionally generated false positives and negatives.

Air/Soil Vapor Sample Collection Devices: Air sample collection devices encase air samples so they can be transported to a laboratory (either on site or off site) for chemical analysis. Devices are available to take a "grab" sample at a point in time or a time-integrated sample, which provides a time-weighted average. Selecting an approach will depend on the CSM (e.g., Are vapor intrusion rates expected to be steady or vary throughout the day?) and when access to the building is permitted. The document, *Superfund Program Representative Sampling Guidance Volume 2: Air* (EPA, 1995b), explains a number of devices. Air sample collection devices commonly used at vapor intrusion sites─canisters, sampling bags, and sorbent tubes/cartridges─are discussed here (Figure 4; see Section 2.2):

- *Canisters* collect bulk air samples and measure time-weighted average concentrations. They can be placed in a building for a selected period of time (typically 24 hours) and will provide an average concentration for that period. For typical risk-based measurements, the canisters are placed at sitting height. Canisters can also be attached to soil gas probes to collect soil gas samples over a selected period.

  Canisters vary in size depending on the length of the sampling period. They come equipped with evacuated systems or pressure systems to draw in air samples. The flow meter must be well-calibrated before sampling begins. Evacuated systems, which use the pressure difference between the evacuated canister and ambient air to pull the sample into the canister, are the easiest to use. A critical orifice attached to the canister to draw the sample in at a constant rate over the sampling period until the canister is near atmospheric pressure. Pressure systems use a pump to push air into the canister, but involve a lot of effort to certify that the pumps are clean enough to satisfy data quality objectives.

- *Sampling bags* collect grab samples of bulk air at a point in time. The bags are made of an impermeable material, such as Tedlar™, with a stainless steel or polypropylene fitting to which the sample tube is attached. Samples are generally collected in the bags using a "lung" system, which uses a pump to create a vacuum around the bag in a drum. This, in turn, draws air from the source into the bag without the potential for cross-contamination from the pump. Sampling bags need to be analyzed within a few hours of collection, so field-based analytical methods are recommended.

- *Sorbent tubes and cartridges* differ from canisters and sampling bags in that they do not collect bulk air samples for analysis. Instead, a sorbent-filled tube (or cartridge) is opened and connected to a sample pump to draw air in through the tube. Contaminants are trapped onto the surface of the sorbent. The tube is then sealed with caps until the sorbent is analyzed. Depending upon the sorbent material, it can be analyzed using either solvents (solvent extraction) or heat (thermal desorption). Tubes and cartridges are available with a variety of sorbent materials and are generally preferred over canisters and sampling bags when sampling for SVOCs.

Air/Soil Vapor Sample Analyses: Both fixed-laboratory and field-based techniques are available for analysis of soil gas, sub-slab, and indoor air samples. Fixed-laboratory analyses refer to those analyses conducted off site at a certified commercial laboratory. Samples are collected at the site and delivered to the laboratory, which analyzes them within a specified turnaround time. The data undergoes a rigorous QA/QC process to ensure they are useable for their stated purpose. Therefore, it can take weeks to receive the analytical data. An expedited turnaround time can be requested to reduce the wait, but the per-sample cost for expedited analyses can double or triple.

Field-based analytical methods (a key component of the Triad approach) are conducted using portable instruments that can be brought on site for real-time measurements of ambient air, indoor air, soil gas, and sub-slab sample concentrations. Some field-based analyses can provide the same level of QA/QC as fixed-laboratory analyses. However, the faster and often more economical field-based methods allow for higher density sampling of a site. Higher density sampling can help refine the CSM for improved decision making. Typically, a combination of the two types of samples is recommended in a site investigation. Field-based methods include the following analytical devices. Additional information on air sampling tools can be found in the *Superfund Program Representative Sampling Guidance* (EPA, 1995b).

- A *field-portable GC/MS* operated by a trained operator, can be used for on-site analysis of air samples. To run a field-portable GC/MS, the operator must know the range of expected concentrations. The operator runs the GC/MS in different modes to identify the chemicals present in the sample, measure their concentrations, and attain a lower detection limit, if necessary, for chemicals known to be in the subsurface.

- EPA's National Environmental Response Team operates the *Trace Atmospheric Gas Analyzer* (TAGA), a vehicle-mounted laboratory instrument capable of real-time direct air sampling and analysis of organics in indoor and ambient air on site. The 36-foot bus is equipped with analytical equipment to identify and quantify organic compounds.

  Use of equipment like TAGA at vapor intrusion sites can cut the time and costs spent for traditional fixed-laboratory analyses, and can provide the same level of QA/QC. Results of the one-minute TAGA on-site analyses and laboratory analyses of 24-hour Summa canisters for indoor air samples have been shown to be comparable. Furthermore, analyses of Tedlar™ bag grab samples using TAGA were also comparable to Summa canisters (Mickunas, 2005).

> **MORE ON TAGA HARDWARE**
>
> TAGA is equipped with a low-pressure chemical ionization (LPCI) source operating in conjunction with a triple-quadrupole MS/MS to identify and quantify organic compounds. The vehicle also is equipped with several GCs to aid in identification and confirmation analysis. Use of TAGA have been shown to resolve vapor intrusion issues, such as identifying subsurface sources, "lifestyle" sources, atmospheric sources, and ambient sources of contaminants in indoor air (Mickunas, 2005).

- The *MicroGas Analyzer* is a portable instrument that measures and graphs the levels of carbon monoxide, carbon dioxide, methane, hydrocarbons, nitrogen oxides, and oxygen in an air or soil gas sample (nitrogen oxides are measured separately). Such measurements can be useful in monitoring soil gas from landfills and assessing the potential for bioremediation of petroleum contaminants.

- For real-time detection of VOCs for evaluation of possible entry pathways (e.g., cracks or openings in the floor or wall, sumps, elevator shafts, etc.) monitoring with hand-held instruments such as photoionization detectors (PIDs), flame ionization detectors (FIDs), or combustible gas indicators (CGIs) may be appropriate. Most instruments are limited to the parts per million by volume range, however, and would not resolve lower concentrations of contaminants. PIDs and CGIs can be used for field screening to identify immediate dangers due to hazardous levels of VOCs. (ITRC, 2007a).

APPENDIX C: Acronyms and Glossary

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
BTSC	Brownfields and Land Revitalization Technical Support Center
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CGI	combustible gas indicator
CSM	conceptual site model
EPA	U.S. Environmental Protection Agency
FID	flame ionization detector
GC	gas chromatograph(y)
HVAC	heating, ventilation, and air conditioning
ITRC	Interstate Technology and Regulatory Council
J&E	Johnson and Ettinger
LPCI	low-pressure chemical ionization
MS	mass spectrometer (spectrometry)
NAPL	non-aqueous phase liquid
O&M	operation and maintenance
ORD	Office of Research and Development
OSWER	Office of Solid Waste and Emergency Response
PCB	polychlorinated biphenyl
PID	photoionization detector
PVC	polyvinyl chloride
QA/QC	quality assurance and quality control
SVOC	semivolatile organic compound
TAGA	trace atmospheric gas analyzer
TCE	trichloroethene
UST	underground storage tank
VOC	volatile organic compound

Acute health effect – Health problems, such as headache, nausea, and eye and respiratory irritation, caused by short-term exposure (within hours or days) to contaminants. In the case of vapor intrusion, acute health effects are often associated with a detectable odor of chemical vapors.

Advection – the movement of soil gas from areas of higher to lower pressure. Advection due to building depressurization is often the driving force for the movement of vapors from the soil gas in the sub-slab to indoor air.

Ambient air – Air unaffected that surrounds a building and is unaffected by vapor intrusion. Ambient air samples are collected outdoors and away from openings in the building (windows, stacks, etc.) that vent indoor air.

Background sources – Objects within a building (e.g., cleaning products, hobby supplies, paints and solvents, carpet, cigarette smoke, dry-cleaned clothing) that emit chemical vapors not due to vapor intrusion. An inventory of chemicals should be conducted prior to indoor air sampling to identify potential background sources of VOCs and SVOCs that may affect indoor air sampling results.

Biodegradation – The breakdown of harmful chemicals into less harmful ones by microbes found naturally in soil. If the biodegradation of VOCs that readily biodegrade (e.g., petroleum-related compounds) is not considered in the evaluation of vapor intrusion, it may lead to the overestimation of vapor intrusion impacts.

Brownfield – Real property, the expansion, redevelopment, or reuse of which may be complicated by the presence or potential presence of a hazardous substance, pollutant, or contaminant.

Capping effect – Inhibition of the upward movement of soil gas due to the presence of building foundations and other barriers such as pavement.

Chronic health effect – Health problems, such as cancer, liver or kidney disease, and reproductive difficulties, caused by long-term exposure to even low-levels of contaminants.

Conceptual site model – A picture and narrative of the site contamination: how it got there, whether or not it is migrating or degrading, its distribution across the site, who might be exposed to it, and what risk-reduction strategies are most feasible. Development of a conceptual site model begins during the Phase I environmental site assessment and is continually modified throughout the characterization and cleanup process.

Conduit – A passageway in the subsurface (e.g., a sand or gravel layer, buried utility line, or animal burrow) or in the building foundation (e.g., a sump, elevator shaft, or utility line) that facilitates the flow of soil gas.

Depressurization – Phenomenon that causes buildings to draw soil gas indoors─ via cracks in the foundation or through openings associated with utility lines, sump pumps, etc.─when the pressure beneath a building is higher than the pressure indoors. Depressurization is caused by “leaky” heating and ventilation systems, exhaust fans, and stack and wind effects that reduce the pressure indoors.

Diffusion – Movement of vapors from areas of high concentrations closest to the source of contamination toward lower concentrations in uncontaminated areas.

Exposure pathway – A way that people may be exposed to (come in contact with) environmental contaminants.

Green space – Vegetated land separating or surrounding areas of intensive residential or industrial use and devoted to parks, playgrounds, trails, gardens, habitat restoration, and other recreational uses.

Hazard quotient – A number used in environmental risk assessment to define the probability that adverse non-cancer health risks will occur.

Hot spot – Area of high contaminant concentrations.

Institutional controls – Legal or administrative actions that help minimize the potential for human exposure to contamination by ensuring appropriate land or resource use. Examples include restrictive covenants, zoning restrictions, and special building permit requirements.

Lines of evidence – The various ways of proving or disproving the potential for vapor intrusion before drawing conclusions about the risks posed. Lines of evidence include the locations of sources, distribution of groundwater contaminants and soil gas at the site, sub-slab concentrations (if buildings are present), indoor and outdoor air concentrations, background concentrations, presence of conduits, and building construction plans or details. More information on lines-of-evidence can be found in ITRC, 2007a.

Mitigation – Engineering approaches to preventing vapor intrusion to a building.

Phase I environmental site assessment – The process of determining whether or not contamination is present on a parcel of real property for the purpose of identifying potential or existing environmental contamination liabilities. A Phase I assessment does not include collection or analysis of samples.

Phase II environmental site assessment – An investigation following and based on the Phase I environmental site assessment that involves the collection of samples of environmental media (e.g., soil and groundwater) for chemical analysis.

Predictive model – Computer model used to assess the potential for vapor intrusion to occur at a property. Models are used as a line of evidence particularly when limited field measurements can be collected.

Radon – A colorless, odorless gas formed from the decay of radium, a radioactive element that occurs naturally in the bedrock and soil in some areas of the country. Mitigation methods for vapor intrusion are similar to those for radon gas, but due to the much lower target vapor concentrations the design and performance assessment of such systems requires a more robust approach.

Receptors – In the case of vapor intrusion, persons who may be exposed to indoor air contaminants resulting from vapor intrusion.

Risk assessment – Qualitative and quantitative evaluation of the risk posed to human health and/or the environment by the actual or potential presence or use of pollutants.

Screening-level model – Computer software tool often used to determine if a potential indoor inhalation exposure pathway exists and, if such a pathway is present, whether long-term exposure increases the occupants' risk for cancer or other toxic effects to an unacceptable level.

Soil gas – Vapors emitted from volatile and semivolatile organic compounds (and mercury) at contaminated sites and found in the pore space of soil.

Soil gas probe – The primary tool for collecting soil gas samples

Stack effects – Pressure differences inside and outside a building caused by differences in indoor and outdoor temperatures. As warmer indoor air rises and exits the top of the building, the resulting pressure differences induce vapor flow into the bottom of the building.

Sub-slab – Beneath the foundation of a building.

Triad – An innovative approach to decision-making for hazardous waste site characterization and remediation. It offers a technically defensible methodology for managing decision uncertainty that leverages innovative characterization tools and strategies. The primary components of Triad are systematic planning**,** dynamic work strategies**,** and real-time measurement systems.

Upgradient – The direction opposite groundwater flow and plume migration, both of which move downgradient.

Vapor attenuation factor – A measure of how soil and building properties limit the intrusion of organic vapors into overlying buildings. It is defined as the concentration of the contaminant in the indoor air divided by the concentration of the contaminant in soil gas or groundwater.

Vapor intrusion – The migration of chemical vapors from contaminated soil and groundwater into overlying buildings.

Volatile organic compounds – Chemicals that readily evaporate.

Water table – The level below which the ground is saturated with groundwater.

Wind effects – Pressure differences inside and outside a building caused by wind currents passing over and around the building. Wind effects can induce the flow of vapors into a building.

APPENDIX D: References

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