DOD VAPOR INTRUSION HANDBOOK

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PREPARED BY
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The Tri-Service Environmental Risk Assessment Workgroup conducted final review and preparation of this document for use by all DoD Components.

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List of Acronyms

AEH	Air exchanges per hour
AFCEE	Air Force Center for Engineering and the Environment
API	American Petroleum Institute
ARAR	Applicable or relevant and appropriate requirement
ASTM	American Society for Testing and Materials
BKG IA	Background indoor air
BKG OA	Background outdoor air
BRAC	Base Realignment and Closure
Cal-EPA	California Environmental Protection Agency
CDPHE	Colorado Department of Public Health and Environment
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
COC	Chemical of concern
CSM	Conceptual site model
CTE	Central tendency exposure
DDE	Dichlorodiphenylethylene
DNAPL	Dense non-aqueous phase liquid
DERP	Defense Environmental Restoration Program
DoD	Department of Defense
DON	Department of the Navy
DQO	Data quality objective
DTSC	California Department of Toxic Substances Control
ECOS	Environmental Council of the States
EPA	U.S. Environmental Protection Agency
EPC	Exposure point concentration
FID	Flame ionization detector
FUDS	Formerly Used Defense Sites
GC	Gas chromatography
GC/MS	Gas chromatography/mass spectrometry
HI	Hazard index
HQ	Hazard quotient
IA	Indoor air
IR	Infrared spectroscopy
IRIS	Integrated Risk Information System
ITRC	Interstate Technology and Regulatory Council
J&E	Johnson and Ettinger
LDPE	Low density polyethylene

LEL	Lower explosive limit
LNAPL	Light non-aqueous phase liquid
$\mu g/m^3$	Micrograms per cubic meter
MassDEP	Massachusetts Department of Environmental Protection
MPCA	Minnesota Pollution Control Agency
NAPL	Non-aqueous phase liquid
NAS	National Academy of Sciences
NIH	National Institutes of Health
NYSDOH	New York State Department of Health
OSHA	Occupational Safety and Health Administration
OSWER	Office of Solid Waste and Emergency Response
OA	Outdoor air
PAH	Polycyclic aromatic hydrocarbon
PCE	Tetrachloroethylene
PDB	Passive Diffusion Bag
PEL	Permissible exposure limit
PID	Photoionization detector
ppbv	Parts per billion by volume
PPRTV	Provisional peer reviewed toxicity value
pptv	Parts per trillion by volume
PA/SI	Preliminary assessment/site inspection
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RfC	Reference concentration
RfD	Reference dose
RI	Remedial investigation
RME	Reasonable maximum exposure
RPM	Remedial project manager
SIM	Selective ion mode
SOP	Standard operating procedure
SVOC	Semi-volatile organic compound
TAGA	Trace atmospheric gas analyzer
TCE	Trichloroethylene
TO	Toxic organic
TSERAWG	Tri-Services Environmental Risk Assessment Working Group
UCL	Upper confidence limit
UST	Underground storage tank
VI	Vapor intrusion

VOA	Volatile organic analysis
VOC	Volatile organic compound

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1 Introduction

Vapor intrusion is the migration of volatile chemicals from the subsurface into the indoor air of buildings located above the contamination. This handbook was developed by the Tri-Service Environmental Risk Assessment Work Group (TSERAWG) to serve as a resource for remedial project managers (RPMs) who may need to investigate the vapor intrusion pathway at Department of Defense (DoD) sites. The Tri-Services of the DoD include the Departments of the Air Force, Army, and Navy, with the Department of the Navy (DON) including both the Navy and the Marine Corps. This handbook was developed to support RPMs working on both active and closed Air Force, Army, Navy, and Marine Corps bases, as well as Formerly Used Defense Sites (FUDS). The handbook is intended to provide a general framework for conducting vapor intrusion investigations under the Defense Environmental Restoration Program (DERP). Both residential and occupational exposure scenarios are discussed since both groups can be affected by vapor intrusion.

Vapor intrusion should be evaluated when volatile chemicals are present in soil, soil gas, or groundwater that underlies existing structures or has the potential to underlie future buildings and there may be a complete human exposure pathway. Due to their physical properties, volatile chemicals can migrate through unsaturated soil and into the indoor air of buildings located near zones of subsurface contamination. The United States Environmental Protection Agency (EPA) defines a chemical as volatile if its Henry's Law constant is 1×10^{-5} atm-m^3/mol or greater (2002). Volatile organic compounds (VOCs) - including such common chemicals as petroleum hydrocarbons (e.g., benzene) and chlorinated solvents (e.g., trichloroethylene [TCE]) - are the class of chemicals of greatest interest for this pathway. Other chemicals of potential interest include mercury (the only volatile metal), various semi-volatile organic compounds (SVOCs), (e.g., polycyclic aromatic hydrocarbons [PAHs]), and certain pesticides. The EPA identified more than 100 chemicals that have sufficient volatility and toxicity to pose a theoretical vapor intrusion hazard (EPA, 2002). Appendix A of this document contains a list chemicals that have sufficient volatility and toxicity that is based on the EPA methodology and with current data. Therefore, if it is known or reasonably anticipated that these chemicals may have been used or released at a site by a DoD entity and there is a potential complete human exposure pathway, they should be included in the vapor intrusion investigation.

If a DoD Component is conducting a response action under DERP in accordance with the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA), the DoD Component will be the lead agency under CERCLA and the National Contingency Plan (NCP), with authority and responsibility to make decisions on necessary response actions in coordination with the support agencies, EPA and/or the appropriate state regulator, and with public involvement. The regulatory coordination and public involvement activities should include addressing the potential for vapor intrusion associated with DoD releases, when appropriate. DoD Components should evaluate the potential for vapor intrusion into overlying or nearby existing structures during site investigation activities conducted under the DERP. If a site-specific vapor intrusion risk assessment indicates the presence of unacceptable risks from DoD releases to the environment, DoD may conduct appropriate response actions to address these risks. All reasonable remedial alternatives will be considered when selecting response actions, including use of ventilation systems or other mitigation measures. The potential for vapor intrusion in future structures should be addressed in the design phase and any necessary and appropriate measures included in the construction costs. Additionally, appropriate notice of the potential vapor intrusion risks from DoD releases should be provided to non-DoD site owners or any future users.

1.1 Current Approaches to Assessing Vapor Intrusion

Until recently, vapor intrusion of subsurface VOC contamination to indoor air was not well understood, and this exposure pathway was rarely evaluated as part of a human health risk assessment at remediation sites. The first guidance document to specifically address vapor intrusion was issued by the EPA Office of Solid Waste and Emergency Response (OSWER), entitled *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* in November 2002. Neither DoD nor EPA consider this 2002 guidance “binding”, yet this DoD Vapor Intrusion Handbook has been developed with consideration of the EPA’s draft guidance and portions of the guidance are cited in this Handbook as providing useful information in evaluating potential vapor intrusion pathways. This Handbook also incorporates several other recently published and relevant vapor intrusion documents, including the following:

- Guide for the Assessment of the Vapor Intrusion Pathway. U.S. Air Force, Air Force Institute for Operational Health. February 2006.
- Draft Navy Guidance for Evaluating the Vapor Intrusion Pathway. Naval Facilities Engineering Command. 15 November 2007.
- Navy/Marine Corps Policy on Vapor Intrusion, 29 April 2008.
- Interim Vapor Intrusion Policy for Environmental Response Actions, Department of the Army, Office of the Assistant Secretary (Installations and Environment). 6 November 2006.
- Vapor Intrusion Pathway: A Practical Guide. Interstate Technology and Regulatory Council (ITRC). January 2007a.

Collectively, these documents represent some of the most up-to-date information available on how to evaluate and (if appropriate) mitigate to interrupt the vapor intrusion pathway. They also provide guidance on how to assess the human health risks associated with the vapor intrusion pathway and incorporate this information into the baseline human health risk assessment used to determine if site remediation is warranted to address chemicals of concern (COCs).

The overall approach used to assess the potential risks posed by the vapor intrusion pathway and possible mitigation and remediation options is summarized below.

- **Evaluate whether exposure to the vapors poses an immediate risk to building occupants:** This can include both acute health risks and the risk of explosion. If such short-term risks are identified due to vapor intrusion, it may be necessary to evacuate the property until the risks are mitigated. If there are no immediate risks, a screening level vapor intrusion evaluation may be conducted.
- **Conduct a screening level assessment of site contaminants:** This evaluation typically involves comparing site soil gas or groundwater data with conservative risk-based screening values. If site concentrations are below the screening levels, it is concluded that the site does not pose a vapor intrusion risk. If exceedances are observed, it may be advisable to re-evaluate the data in a vapor intrusion model using site-specific parameters. In some cases, these site-specific modeling results may be sufficient to determine that the site does not pose a vapor intrusion risk; in other cases, the modeling

results can become one of the multiple lines of evidence used to evaluate whether there is a significant vapor intrusion risk.

- **Conduct a site-specific vapor intrusion pathway evaluation:** This is usually a more data intensive effort and may include collecting near-slab soil gas, sub-slab soil gas, and/or indoor air samples. Multiple lines of evidence may be used to evaluate the magnitude and extent of vapor intrusion. Depending on the results of the investigation and a human health risk assessment, it may be determined that either no further action is necessary or that mitigation or remediation may be warranted.
- **Evaluate mitigation/remediation options, if necessary:** Mitigation involves using techniques that prevent (or minimize) subsurface vapors from migrating into buildings present above the contamination. Common mitigation measures include installation of sub-slab depressurization or pressurization devices, sealing all cracks, sumps and preferential pathways, and installation of vapor-proof membranes. On active bases, land use (or building use) controls may also be an option to control exposure. Remediation is the treatment and removal of chemicals from contaminated subsurface media, such as soil and groundwater. Common remediation options include soil removal, soil gas extraction, and groundwater treatment. Mitigation and remediation may be performed concurrently or individually, depending on site needs.

As awareness and concern over the vapor intrusion pathway has increased, so has the regulatory focus. Many states have developed, or are in the process of developing, their own vapor intrusion guidance. Increasingly, reliance on a single approach or dataset is not considered adequate to support site decision making. The current “state of the science” approach is to collect and evaluate multiple lines of evidence to support decision making regarding the vapor intrusion pathway. These lines of evidence can include such endpoints as those listed below:

- Soil gas data
- Near-slab soil gas data
- Groundwater data
- Background data (from indoor and outdoor samples)
- Building construction and current conditions
- Sub-slab soil gas (or crawl space) data
- Indoor air data
- Outdoor air samples collected concurrently with indoor air samples
- Comparison of constituent ratios of chemicals in soil gas and indoor air
- Impact of site geology
- Results of fate and transport modeling
- Results of the risk assessment
- Site or building ownership and control
- Other site-specific or supplemental data.

It is unlikely that all of these lines of evidence will need to be evaluated in order to investigate the vapor intrusion pathway. More often than not, the lines of evidence considered will include existing information along with datasets defined in advance. In general, the closer to the receptor the data is collected, the more relevant to human health risk it is considered to be. Following this logic, indoor air data would be considered more relevant for a risk assessment than a modeled concentration from groundwater or soil gas.

The findings from some lines of evidence may conflict with others (e.g., indoor air concentrations may be acceptable but sub-slab samples exceed screening criteria), and this should be anticipated in the project planning process.

Vapor Intrusion Considerations for DoD Facilities

For the most part, federal and state vapor intrusion guidance has been developed to evaluate exposures in a civilian residential setting. This has allowed for the development of a fairly standardized set of exposure assumptions that are widely recognized and used. However, DoD has a number of exposure settings that differ from standard default exposures, including the following:

- **Residential exposures both on-base and off-base:** Some contaminated sources (e.g., groundwater plumes) may extend both on-base and off-base. While the DoD can control land use and exposures on-base, its ability to control off-base exposure is generally more limited. Additionally, residential receptors on DoD sites are typically enlisted individuals and their families. Due to duty rotations, these DoD residents typically live at any one particular site for less time than the civilian population. Exposure factors should be specific to the installation rather than generic default values.
- **Occupational exposure settings:** DoD facilities may have industrial and commercial buildings located over subsurface volatile contamination. Military workplace exposure scenarios and standards should be considered when evaluating the vapor intrusion pathway. Different criteria may affect workers who knowingly work with volatile chemicals and workers whose jobs do not involve contact with volatile chemicals.
- **Vapor intrusion concerns on undeveloped property:** Subsurface contamination from DoD facilities may be present on undeveloped property both on-base and off-base. For off-base properties, vapor intrusion concerns may warrant design and construction considerations for future development at the site. In many cases, the public has expressed concern regarding possible vapor intrusion risks with the off-base contamination and site development.
- **Potential indoor sources:** DoD facilities may have multiple uses and thus there may be volatile chemical sources from equipment, finishes, operations or activities inside a building.
- **Property transferred to other entities:** DoD and its associated service branches routinely transfer property to other federal and non-federal entities. Use and development of these sites may be affected by vapor intrusion.

Vapor intrusion concerns have been investigated at active bases and former bases where buildings (both on- and off-base) are present over subsurface contamination. In addition, evaluation of this pathway is often used as a screening tool to evaluate the potential risks that could arise if buildings were to be constructed over areas of subsurface contamination.

1.2 Objectives of the DoD Vapor Intrusion Handbook

This handbook discusses various technical approaches associated with evaluating the vapor intrusion pathway and provides perspective for RPMs (and associated consultants) regarding the development and interpretation of vapor intrusion investigations. By considering project needs and the pros and cons of the various approaches, the RPM can make a more informed and cost-effective determination of the best way to evaluate vapor intrusion at its site. This handbook was developed to be relevant for CERCLA and Resource Conservation and Recovery Act (RCRA) sites.

As mentioned previously, the EPA issued draft vapor intrusion guidance in 2002, that at the time of this Handbook has not been finalized. While DoD does not consider the EPA's draft 2002 guidance to be binding, it includes information that is still appropriate for consideration and VI investigations and may serve as a useful reference. For example, the EPA's draft vapor intrusion guidance used a three-tiered approach to provide a method to assess human health risks related to the vapor intrusion pathway. This tiered approach moves from a generic screening level approach (Tier 1) to a conservative fate and transport model (Tier 2) and finally to a site-specific approach (Tier 3). This tiered approach allows sites with minimal risk potential to be screened out (eliminated from further evaluation due to low risk potential from this pathway) without expending significant time and effort.

Not all state health agencies follow EPA's draft three-tiered modeling-based guidance. For example, some states recommend conducting indoor air sampling if volatile chemicals are present in the subsurface at levels exceeding threshold concentrations, with no contaminant transport modeling required. Other states have guidance that suggests indoor air sampling in lieu of subsurface investigations (e.g., soil gas sampling) and contaminant transport modeling. Readers of this handbook will need to coordinate with their regulators and identify the technical approach that is most appropriate for their site.

1.3 Organization of the Handbook

This handbook is organized into eight sections. Following this introduction, Section 2 discusses the screening level assessment of the vapor intrusion pathway. Section 3 discusses the steps necessary to conduct a site-specific vapor intrusion study. Section 4 addresses health risk assessment issues at vapor intrusion sites. Risk management and mitigation approaches are discussed in Section 5, and risk communication is addressed in Section 6. Section 7 presents the summary and recommendations, and Section 8 identifies additional technical resources. A bibliography containing cited references and other sources of information follows Section 8.

Appendix A contains a list of chemicals that are considered sufficiently volatile and toxic and thus may require evaluation in a vapor intrusion study if complete exposure pathways potentially exist. This table is similar to a table in the EPA's 2002 draft guidance of chemicals of potential vapor intrusion, however the Table in Appendix A is based on updated toxicity factors and has additional chemicals unique to DoD sites. Appendix B contains the supporting data and information used to develop the table in Appendix A and also includes data for a broad list of chemicals. This information is provided to ensure transparency and that reevaluation could be conducted if and when new information becomes available. Appendix C presents a list of state regulations, guidance, and other publications on vapor intrusion. Appendix D summarizes sampling and analytical methods available for evaluating the vapor intrusion pathway. Appendix E contains EPA's "Occupied Dwelling Questionnaire," which can be used as an indoor air assessment survey (EPA, 2002). Appendix F describes possible sampling and analysis costs associated with a vapor intrusion assessment. Appendix G discusses how to assess and control background chemicals at vapor intrusion site, while Appendix H describes how to evaluate the building envelope in vapor intrusion investigations. Finally, Appendix I describes a number of air-flow modification mitigation measures for vapor intrusion projects that can be implemented at buildings with high levels of risk.

2 Screening Level Assessment of the Vapor Intrusion Pathway

The objective of a screening level assessment is to get an initial understanding of the level of possible risk posed by vapor intrusion in an efficient and cost-effective manner. Once the screening level assessment has been done, the RPM can decide whether to conduct a more site-specific evaluation, to mitigate or remediate, or whether no further action is needed. The screening level assessment is often done in a tiered or step–wise approach, similar to the approach described in the ITRC guidance (ITRC, 2007a).

The first step in any vapor intrusion assessment is to confirm that chemicals of sufficient volatility and toxicity are present in the subsurface and that a potentially complete human exposure pathway exists (for example, a building overlying a contaminated groundwater plume or that may exist in the future). Appendix A contains a list of chemicals having sufficient volatility and toxicity to be included in a vapor intrusion assessment. Very few of these chemicals will be present at most sites, and the selection of chemicals for sampling should be based on current and past site conditions and uses. Another important preliminary step is identifying the regulatory program governing the site and ensuring that all decisions are in accordance with regulatory requirements. RPMs should strive for stakeholder agreement on the screening approach to be used and the decisions that can be made based on the screening data, recognizing, however, that under CERCLA the Components have the responsibility initially to make remedy selection decisions (with EPA concurrence for facilities listed on the National Priorities List). Appendix C presents a listing of state regulations and guidance documents related to vapor intrusion.

This section summarizes techniques for an initial evaluation of vapor risks and conducting an initial screening evaluation at vapor intrusion sites. Figure 2-1 provides a visual example of possible approaches that can be used in the screening level assessment of a vapor intrusion site.

2.1 Potential Exposure Indicators

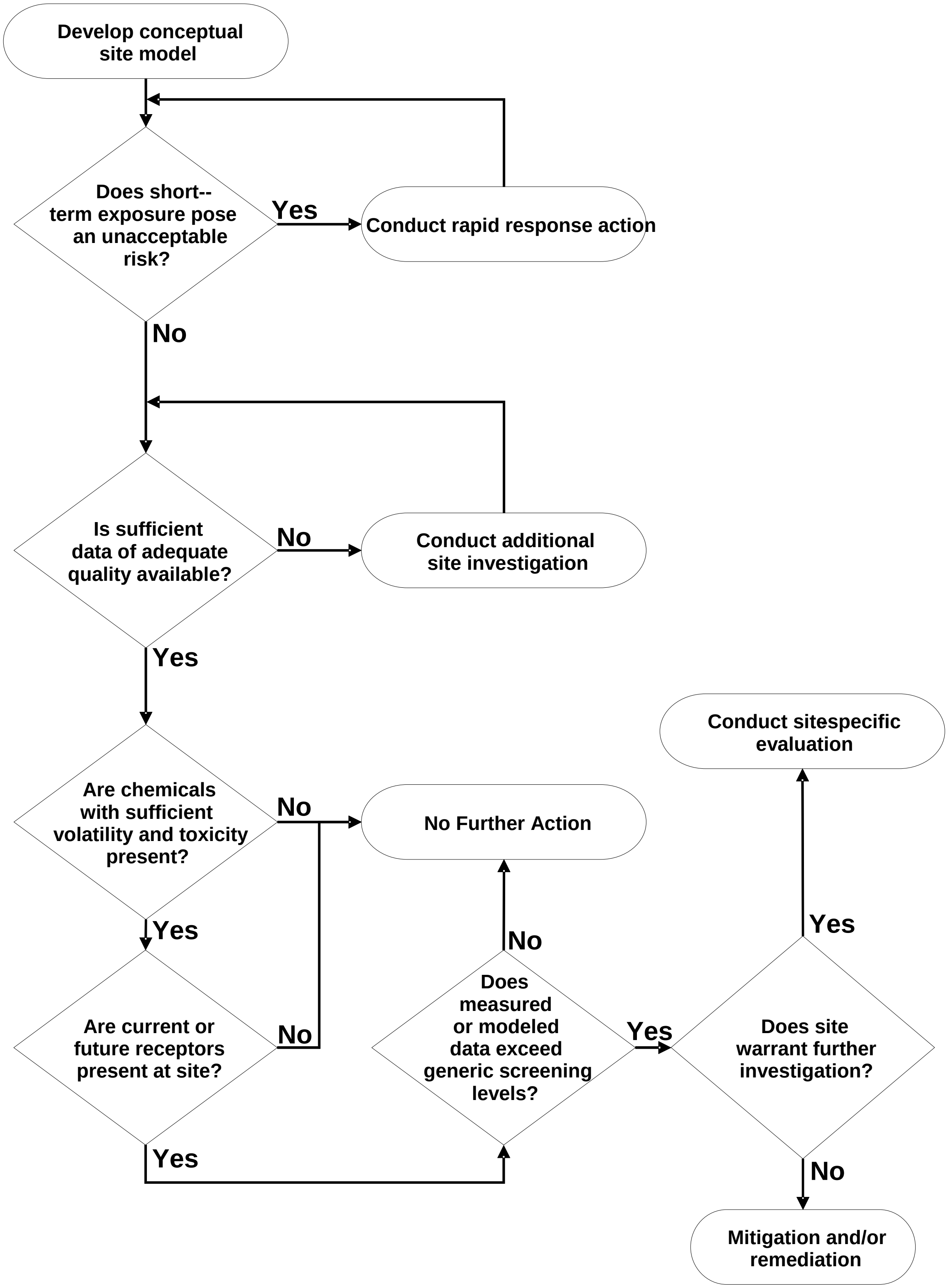
At sites where buildings are present above contaminated soil or groundwater, the first step is to determine if you have, or may have, a potentially dangerous vapor intrusion problem currently in the building. Several indicators that this pathway may be complete are listed below:

- Elevated levels of chemicals in soil, soil gas, and groundwater that have sufficient volatility and toxicity to pose a potential vapor intrusion risk
- Noticeable odors, particularly in the basement, that could indicate a vapor intrusion problem
- Elevated soil gas measurements, particularly in the space just below the slab
- Cracks or other preferential pathways, as indicated by wet areas or signs of water seeping into the basement or ground floor of a building
- Indoor air data that may indicate the presence of chemicals that cannot be accounted for by household materials and activities.

None of these factors by themselves provides conclusive evidence that vapor intrusion is occurring or that acute or short-term risks are present. However, if one or more of these indicators are present, there is a possibility that vapor intrusion is occurring and the potential for risks should be further evaluated. Portable screening devices such as a photoionization detector

(PID) or a flame ionization detector (FID) may be useful to determine whether volatile gases are present at concentrations that may pose an immediate threat to life and health. If high levels of volatile gases are detected, it is recommended that the area be evacuated and trained professionals (e.g., the fire department) be contacted to determine how best to address the problem and when occupants can safely reenter the building.

Figure 2-1: Example of a Screening Level Evaluation at a Vapor Intrusion Site



2.2 Initial Steps of the Screening Assessment

At the early stage of a vapor intrusion assessment, it should be confirmed that chemicals with sufficient volatility and toxicity have been detected at or near the site, there is the potential for a complete exposure pathway, and that acute risks to local building occupants have been evaluated. The EPA and most states recommend using two criteria to evaluate whether to include a chemical in a vapor intrusion study—volatility and toxicity. Appendix A includes more than 100 chemicals that meet this definition of volatility, including common VOCs such as benzene and TCE, but also pesticides (such as chlordane and dichlorodiphenylethylene [DDE]) and several PAHs. Appendix A also shows chemicals whose vapor concentration of the pure component poses an incremental cancer risk greater than 1 in a million (i.e., 1E-06 or 1×10^{-6}) or a non-cancer hazard index greater than 1. Those chemicals that have both sufficient volatility and toxicity—and are known or reasonably suspected to be present—should be included in a vapor intrusion screening assessment if there is a potential complete exposure pathway. It is also important to confirm whether the detected chemicals are associated with DoD operations and are not due to the activities of other entities that may have used the site or other sources of release inside the building. The DoD does not respond to releases from sources other than DoD at property not under DoD accountability, but DoD may determine if other parties have responsibility for known or suspected contaminated indoor air at a location where DoD is responding.

The list of chemicals in Appendix A provides a reasonable starting point for a vapor intrusion study. However, at most sites, there will only be a few chemicals that will be of interest. If any of the chemicals listed in Appendix A are detected in the environment within approximately 100 feet—horizontally or vertically—of an existing building, EPA recommends that a vapor intrusion study be conducted. Not all state health agencies agree that 100 feet is sufficient to prevent vapor migration and intrusion, so it is important to check with the local regulatory agency. Additionally, if preferential pathways exist in the subsurface that could facilitate the migration of chemicals towards a building, then the guideline of 100 feet may not be appropriate. Some states focus on a limited number of chemicals, with the emphasis directed towards the most volatile. For example, Minnesota (MPCA, 2005) includes 57 chemicals on its list of target chemicals for vapor intrusion, while Colorado (CDPHE, 2004) includes 22 chemicals on its list. The determination of chemicals to investigate at a specific site should be based on site specific facts of known or suspected chemicals released or used at the site with potential to be found in indoor air.

2.3 Conceptual Site Model

An important step in assessing the vapor intrusion pathway is to develop an understanding of the site setting, the fate and transport properties of the contaminants, and the ways by which people could be exposed to site-related chemicals through the development of a conceptual site model (CSM). This CSM is typically represented by a diagram that provides a visual portrayal of site conditions and illustrates the contaminant sources, the movement of these contaminants in the environment, and potential receptors and exposure pathways. The CSM links the source(s) of contamination, such as a leaking tank, with potential environmental transport pathways that may ultimately lead to exposure of a receptor. This information is useful for identifying which exposure pathways are complete, potentially complete, or incomplete, thus allowing the risk assessor or RPM to focus the investigation appropriately. The CSM can be as comprehensive or as simple as necessary depending on site-specific conditions and management requirements. As the understanding of the site conditions evolves, the CSM should be updated so it always reflects the most current and comprehensive understanding of the site.

Understanding the chemical and physical properties of volatile contaminants is critical to developing a good CSM for possible vapor intrusion sites. The critical aspect of these contaminants that makes them a concern in indoor air is their volatility. Depending upon their toxicity, contaminants with Henry's Law Constants as low as 10^{-5} atm-m^3/mol may pose a risk; therefore this Henry's Law Constant is often used as one of the criteria for determining whether a contaminant is sufficiently volatile to justify a vapor intrusion evaluation.

The vapor intrusion pathway is often only one of multiple exposure pathways at a site, and the CSM will need to describe these other pathways as well. If there are multiple exposure pathways for the contaminants, it may be necessary to include the vapor intrusion risk results in the baseline risk assessment. The CSM should be discussed in the text of the document and should be supported by data, maps, and other relevant information.

The following factors should be identified in the CSM developed for a screening level vapor intrusion assessment:

- **Source(s) of Contamination**: The primary source(s) of contamination may include leaking tanks (above and below ground), pipelines, floor drains, landfills, fire-training areas, spills, and discharge areas. Secondary sources may include free phase product in the ground, contaminated soil, and contaminated groundwater.
- **Transport Pathways**: Volatile contaminants can be found in various media under environmental conditions. A single site could contain VOCs in 1) a non-aqueous phase liquid (NAPL) phase, 2) dissolved in groundwater and pore water, 3) in a vapor phase, or 4) in a sorbed phase attached to soil particles or organic matter in the soil matrix. The phase and matrix will influence contaminant transport, with vapor phases being of greatest interest in vapor intrusion investigations. Vapors can migrate through several transport mechanisms, including diffusion in the unsaturated zone, diffusion in shallow groundwater, horizontal and vertical migration via preferential pathways (e.g., utility corridors, pipelines, cracked clay), and advective/convective transport in the soil. Advective and convective transport is generally most active beneath or directly adjacent to buildings, where there can be a negative pressure differential between the building and the surrounding soil that tends to pull soil gas upwards towards the building (often referred to as building or stack effects). Gravity can drive NAPL and dissolved phase contaminants downward through preferential pathways in the vadose zone. Preferential pathways can be even more important for vapor phase migration; minor pressure differentials are all that is necessary to drive soil gas transport. However, it is also important to remember that contaminant migration is retarded by sorption and other processes.
- **Receptors and Land Use**: The primary receptors of interest would be anyone living or working in an enclosed space above soil or groundwater that is contaminated by VOCs. This includes residential settings (e.g., single-family homes, townhouses, and trailers), industrial and commercial workplaces, office buildings, and educational and recreational settings (e.g., schools and gyms). Trailers enclosed at the bottom by a skirt have greater potential for vapor intrusion than do non-enclosed trailers. Air movement between the ground surface and the trailer bottom of the non-enclosed trailer would tend to minimize

vapor buildup and associated vapor intrusion. Similarly, the existence of a basement, underground parking, or other modifications to the foundation should be considered in the vapor intrusion evaluation. The CSM should incorporate receptor and land use factors and building types.

- **Exposure Routes**: In general, the only exposure route of interest for vapor intrusion is the inhalation of vapors migrating from the subsurface into indoor air. Other possible exposure routes that may be considered during other investigations at the site may include ingestion, dermal contact, and inhalation of particulate material. At most sites, vapor intrusion will be one of several possible exposure routes that will need to be evaluated in the risk assessment.

CSMs for vapor intrusion studies often need to consider two distinct exposure situations. At some sites, buildings are present and there are concerns as to whether vapor intrusion may pose a risk to current occupants. For this situation, there will be site- and building-specific information available to support the assessment, including information such as the size and volume of the building, depth of construction, thickness of floor, air turnover rates, and activities of the occupants. These factors may require consideration in the vapor intrusion assessment. The second situation is where contaminant fate and transport models are used to predict whether vapor intrusion may occur in hypothetical future buildings built on the site. In this case, a hypothetical building is placed anywhere over the subsurface contamination and modeling is used to estimate the migration of contaminants into the indoor air of the hypothetical overlying buildings. This approach allows the risk assessor to evaluate a range of construction factors (such as thickness of floor and ventilation issues) that may affect building design. These situations should be considered as part of the development of the CSM and the identification of complete, potentially complete, and incomplete exposure pathways. A variation on this future exposure situation is when a building has been designed but not built. Modeling can be used to predict indoor air concentrations and any necessary or desired mitigation measures incorporated into the building design.

The ITRC guide (2007a) presents a detailed list of information that should also be considered when developing the CSM, including the following:

- The location and nature of the source of volatile chemicals in the subsurface
- Chemical properties, including degradation products, solubility, vapor pressure, diffusivity in air and water, and Henry’s Law constant
- Chemical target concentrations in indoor air and other media, as applicable
- A basic understanding of lithology and stratigraphic features that influence the occurrence and movement of groundwater, NAPL (if any), and vapors
- Depth to groundwater and groundwater flow directions (including vertical gradients or recharge that might lead to a clean groundwater lens at the water table)
- General nature and extent of volatile chemicals in groundwater and/or soil gas
- Locations and depths of major underground utilities (particularly storm sewers)
- Potential background sources of volatile chemicals and typical indoor/ambient air concentration ranges
- Locations, ownership, and general use of buildings within the area potentially impacted.

2.4 Assess Quality of Existing Data

Another important consideration to evaluate early on is whether there is sufficient data of adequate quality to support a vapor intrusion assessment. Data quality factors to consider include media sampled, proximity of samples to buildings of concern, and the quality of the data (especially reporting limits). Since many bases have done environmental investigations for a number of years, a large amount of data may be available. Most commonly, these data would have been collected during a preliminary assessment/site inspection (PA/SI), a remedial investigation (RI), or various monitoring activities. These data will often be limited to soil and groundwater sample results; when used alone, the data may not be adequate to address vapor intrusion concerns. Given that vapor intrusion historically was not a primary pathway of interest, many older sites may not have sufficient data to evaluate this pathway. Additional data (such as soil gas) may be required to define the site in its current conditions. It should be noted that using soil concentration data alone to evaluate the vapor intrusion pathway is generally not recommended, and most agencies will not recognize using only soil data for this purpose. Older soil data can be particularly unreliable because prior to the use of EPA's Sampling Method 5035 (Encore Sampling), loss of volatile contaminants during soil sampling was a common problem.

The existing data should be compiled and reviewed by a risk assessor before any additional data is collected. Older data may be of limited usefulness and may not accurately represent the current nature and extent of contamination. Some questions should be considered when reviewing historical data:

- How old are the data? Are they likely to reflect current conditions or are the contaminant concentrations likely to have changed significantly due to natural attenuation processes?
- How were the samples collected? Are the collection methods considered reliable by today's standards?
- Were analyses conducted for all known or suspected chemicals?
- Were analyses conducted for degradation products?
- Were the reporting limits sufficiently low for comparison with vapor intrusion screening criteria?
- Has the contamination migrated beyond the original study boundaries?
- Has the land use changed or have additional buildings been constructed on the site?

The EPA has developed guidance for evaluating data usability in risk assessment (Guidance for Data Usability in Risk Assessment, EPA, Part A, 1992). This guidance is specifically designed to provide a clear and consistent process for determining whether data meets the requirements and intended use of the risk assessment. As such, it is a good tool for evaluating the quality and usefulness of historical data collected at a site. It describes what factors to consider when reviewing data and identifies minimally acceptable performance objectives for a dataset. The basic data quality factors that may affect the risk assessment include data sources, reporting limits, use of qualified data, and consistency in data collection. A review of the EPA's data usability guidance can help determine whether available data is of sufficient quality to meet the requirements of a vapor intrusion project.

The DoD also has guidance on how to assess and evaluate data quality. It is recommended that the DoD Quality Systems Manual for Environmental Laboratories (2006) and the Uniform

Federal Policy for Quality Assurance Project Plans (2005) be reviewed when considering data quality issues.

2.4.1 Data Quality Objectives for Collection of Additional Data

Prior to collecting any additional data that may be needed, site-specific data quality objectives (DQOs) should be developed. DQOs are quantitative and qualitative statements that describe what data are needed to support decision making (EPA, 2000a, 2006). DQOs are a set of site-specific statements that describe, in detail, exactly how the data will be used and what decisions need to be made using the data. The DQO process is a planning tool that is designed to prevent collection and use of data that do not contribute to decision-making and to ensure that a sufficient quantity and quality of data are acquired so that informed decisions can be made. DQOs are typically developed collectively by the stakeholders associated with the project, which may include DoD, EPA, state health departments, local homeowners, and other potentially affected groups.

The EPA has developed a seven-step process for developing DQOs, which steps are listed below along with a brief example:

1. State the problem (e.g., groundwater contaminated with volatile chemicals may pose a risk via the vapor intrusion pathway)
2. Identify the decision to be made (e.g., do soil gas measurements suggest there will be a vapor intrusion risk at locations where future buildings may be constructed?)
3. Identify the inputs to the decision (e.g., soil gas sampling data, site geology, screening criteria)
4. Define the study boundaries (e.g., all locations above groundwater plume)
5. Develop decision rules (e.g., whether a single detection above risk-based criteria is sufficient to trigger action or whether a more representative concentration [such as the 95% upper confidence limit (95%UCL)] should be used for this comparison)
6. Specify the acceptable limits on decision error (e.g., identify size of hot spot area that can be missed during sampling without compromising overall results)
7. Optimize the sampling design (e.g., determine if proposed sampling will adequately characterize the site, revise accordingly if necessary).

All vapor intrusion data collection projects should have site-specific DQOs to help define what data will be collected and how they will be used. Examples of issues that need to be considered when developing DQOs include the types of decisions to be made, the type and number of samples needed to support these decisions, and the necessary reporting limits (analytical sensitivity). Identifying these objectives prior to sampling will facilitate decision making after the data are collected. Additional details on the development of DQOs can be found in EPA's DQO guidance documents (EPA, 1994, 2000a, 2006). The U.S Army Corps of Engineers also has guidance for the development of DQOs (Engineer Manual 200-1-2, Technical Project Planning).

2.5 Generic Data Screening for Vapor Intrusion

After it is determined that contaminants of sufficient volatility and toxicity are present and the potential exists for a complete exposure pathway, there are two basic approaches to evaluating whether vapor intrusion may be occurring at a site or building. These approaches, while distinctly different, are complementary and can be used in conjunction with each other. The first approach uses a contaminant fate and transport model to estimate the indoor air concentration of chemicals of interest, while the second approach relies on direct measurement of chemicals present in indoor air. The EPA and many state health agencies start with an assessment of the contaminant transport model and, if potential risks are high enough, may progress to collection of indoor air samples. The resulting measured or modeled concentration of chemicals is then "screened" by comparing them with generic risk-based concentrations.

Once the data has been determined to be of sufficient quality and quantity and a preliminary CSM has been prepared, the site can undergo a generic screening evaluation. Screening is often done on a building-by-building basis, so that decisions can be made for each building of interest at a site. The generic screening step typically compares site data (most commonly soil gas or groundwater data) with conservative health-protective screening concentrations. These generic screening levels are deliberately conservative to allow for relatively quick and efficient initial site decision making. For example, generic screening levels may not take into consideration such site-specific parameters as soil type, building construction, or land use patterns at the site. Typically, the maximum concentration of a chemical detected in soil gas or groundwater is used as the value representative of the site for screening purposes. The EPA presented generic screening levels for chemicals in soil gas, groundwater, and indoor air in its 2002 draft guidance. A number of states have developed (or are in the process of developing) generic screening levels for different media. The appropriate regulatory agency should be consulted to identify the appropriate screening level for the site in question.

The primary purpose of the generic screen is to separate those sites that clearly do not pose a significant risk from those sites that may or are likely to pose an unacceptable risk. At sites where none of the data exceeds the generic screening levels, the decision is often made that no further investigation or action is needed. If some samples exceed generic screening levels, this generally indicates that some additional site-specific study is warranted. However, significant exceedances of generic screening levels (subjective, but on the order of a hundred- or a thousand-fold) may suggest that a site-specific evaluation is unlikely to reduce the calculated risk estimates to acceptable levels, and the project should proceed directly to mitigation. The effort and cost associated with a site-specific evaluation may be significant, and proceeding directly from the screening assessment to mitigation or land/building use controls based on feasibility and life cycle cost may be a more cost-effective approach than conducting an extensive study.

2.6 Contaminant Fate and Transport Modeling

Contaminant fate and transport modeling is often used to predict indoor air concentrations in evaluating the potential impacts of vapor intrusion. The use of predictive modeling in EPA and state guidance documents varies due to the accuracy of modeling vapor fate and transport. Predictive modeling is discussed in greater detail in the ITRC document (ITRC, 2007). Modeling utilizes both analytical data collected from soil, groundwater, or soil gas from the contaminated area in the vicinity of a building and site characterization data that influence vapor transport. The most commonly used model to estimate human health risks from subsurface vapor intrusion into buildings was developed by EPA and is based on the work of Johnson and Ettinger (1991) (often referred to as the Johnson and Ettinger [J&E] model). The EPA's version of the J&E model is revised periodically to incorporate different assumptions about soil properties as well as new human health criteria developed by EPA. This model combines the analytical data with a variety of soil and building parameters in an algorithm that predicts the emission of chemicals through cracks in the slab of the foundation and, ultimately, the indoor air concentration of volatile chemicals.

The J&E model, fact sheet, and user's guide are presented at: http://www.epa.gov/oswer/riskassessment/airmodel/johnson_ettinger.htm. The EPA has periodically revised and updated specific parameters and recommendations as new information becomes available. Based on discussion with EPA staff, at the time of the publication of this handbook it is not anticipated that EPA will finalize its vapor intrusion guidance; rather the staff have indicated that they will recommend use of the ITRC vapor intrusion guidance as an alternative.

Some regulators are concerned about the accuracy of the J&E model and thus some agencies restrict the types of decisions that can be made about the vapor intrusion pathway based on modeling alone. Results of studies comparing J&E modeling results with actual indoor air concentrations are mixed. While the J&E model usually over-predicts indoor air concentrations (as a conservative model should), several agencies have reported that validation sampling indicated that the J&E model underestimated indoor air concentrations for a number of volatile chemicals. Although modeling results may provide one of the lines of evidence used to assess vapor intrusion, not all regulatory agencies agree that modeling results alone are sufficient to screen out a site from further consideration. Some of the potential advantages and limitations associated with contaminant fate and transport modeling for a vapor intrusion investigation are presented in Table 2-1.

Table 2-1: Advantages and Limitations Associated with Contaminant Fate and Transport Modeling

Advantages of Modeling	Modeling Limitations
Can use available data as a starting point for the evaluation	If model inputs are not representative of site conditions or data quality is questionable, then the modeling results will also be questionable (i.e. garbage in, garbage out)
Can be used as a desktop tool for screening sites and prioritizing any additional investigation needs	Poorly trained practitioners may use the model in situations where its use is inappropriate
Collecting site-specific data can improve model performance	If site characterization data is insufficient to identify preferential pathways for vapor migration and these pathways are not evaluated by the model, then the default parameters of the model may underestimate vapor intrusion risk.
Can be refined to incorporate a wide variety of site-specific parameters	Modeling is complex and some regulators may resist accepting results based on site-specific data because they are unfamiliar with how the model functions
Can be performed without disrupting building occupants	The modeling results are only estimates of indoor air concentrations, so they may not be accepted as definitive proof that vapor intrusion does or does not pose a risk.
Can use different types of analytical data (e.g., groundwater, soil, and soil gas)	Modeling soil and groundwater data requires the use of more assumptions than modeling soil gas data
Can be used for future land use and building analysis	Recognize that future land use and building design may differ from that modeled. Future building design used in the model should result in a conservative risk estimate but also reflect normal building practices for the area in question.
Some models can account for attenuation over time	Accounting for attenuation requires additional model inputs. Some of the inputs may not be well understood for the *in situ* conditions
Provides an estimate of a building-specific attenuation factor	Not accepted by all regulatory agencies as a definitive screening tool

In general, it is recommended that contaminant fate and transport modeling be conducted as part of the generic screening process. It is non-invasive to local residents, is relatively cheap and efficient, and can be designed to incorporate site-specific parameters. While not all regulatory agencies will accept the results of the modeling as a sufficient screening step, it can provide valuable information to consider as part of a vapor intrusion investigation.

2.7 Indoor Air Sampling

An alternative to fate and transport modeling is the direct measurement of indoor air in buildings located above subsurface contamination. Indoor air sampling is not typically performed as part of the initial screening phase of a vapor intrusion project. However, some regulatory agencies seek indoor air sampling when volatile chemicals are detected in soil gas or groundwater below buildings. For example, the Massachusetts Department of Environmental Protection (MassDEP) "generally recommends direct measurement as preferable overall for evaluating conditions in existing buildings associated with current groundwater concentrations" (MassDEP, 2002).

If indoor air samples are taken it is generally recommended that they be taken on at least two separate occasions, typically during the summer and winter seasons. This will account for some of the seasonal variability that may affect vapor intrusion. There is no clear consensus on how to average the data collected over multiple seasons. A reasonable approach would be to evaluate the potential risk for each individual sample. This would allow for an evaluation of the range of risk associated with the indoor air data. Sampling methods for conducting an indoor air investigation are discussed in greater detail in Section 3 and in Appendix D. Appendix E presents EPA's "Occupied Dwelling Questionnaire", which may be useful when preparing for an indoor air investigation.

Indoor air sampling can be a useful method for identifying the actual concentrations of chemicals to which a receptor may be exposed. However, it is important to control for background levels of chemicals that may be present in the building or in outdoor air. Evaluating the impacts of background chemicals on indoor air quality is discussed in greater detail in Section 3.3.4. It may also be useful to collect several sub-slab soil gas samples concurrently with the indoor air samples to evaluate the attenuation associated with the migration of the chemicals from below the slab into the indoor air of the building.

2.8 Evaluating the Results of the Screening Level Assessment

Risk conclusions for the screening level assessment are based on the results of the comparison of site concentrations (either measured or modeled) with the generic screening concentrations referred to in Section 2.5. The results of this conservative evaluation should be considered to be indicative of potential site risk rather than an accurate predictor of risk. The screening level assessment is typically used to distinguish between sites or buildings that pose little or no vapor intrusion risk and those with potential risk that require further study. Sites or buildings where a single sample exceeds the screening criteria but the majority does not, may not be a candidate for additional investigation. It is preferable to seek agreement with stakeholders beforehand regarding how screening data can be used to make risk management decisions, if possible.

For sites that have chemicals that exceed screening values, there are two options that can be pursued. One option is to conduct a site-specific vapor intrusion study, as discussed in Section 3. This approach will result in a better definition of the vapor intrusion pathway. The second option is to proceed directly to mitigation. It is important to note that mitigation is not a substitute for adequately characterizing and understanding potential vapor intrusion pathways, and the health risks potentially associated with vapor intrusion pathways. A certain level of characterization of the vapor intrusion pathway is necessary in order to select appropriate mitigation measures and to demonstrate their effectiveness. Also, it is important to note that merely detecting contaminants in indoor air at concentrations above risk-based screening levels is not by itself an indication of a vapor intrusion pathway that warrants mitigation. If all chemical concentrations are below their respective screening concentrations, the site will generally be considered not to pose a vapor intrusion risk and no vapor mitigation is warranted. However, if there are multiple exposure pathways for site contaminants, it may be necessary to include the vapor intrusion risk results in the baseline human health risk assessment. It is important that the stakeholders collectively discuss in advance how the results of the study will be interpreted and how risk management decisions will be made.

3 Site-Specific Assessment of the Vapor Intrusion Pathway

This section discusses the information that needs to be collected and evaluated to support a site-specific assessment of the vapor intrusion pathway. Some of this information is the same as that described for EPA's Tier 3 assessment (2002). However, more detail is presented here describing the development of a vapor intrusion investigation work plan and the sampling and analysis that must be done to support the study. Some of the information presented in this section draws on that presented in the 2007 ITRC guidance document *Vapor Intrusion Pathway: A Practical Guideline* and its companion document *Vapor Intrusion Pathway: Investigative Approaches for Typical Scenarios*.

The first step of a site-specific vapor intrusion study is to determine the regulations which govern the conduct of response actions at the site, as well as those that may be appropriate to consider. All DERP hazardous substance response actions are required to be conducted pursuant to CERCLA and the NCP. Other State promulgated standards may be applicable or relevant and appropriate, and guidance may be considered if reliable and useful to the DoD Components. DoD Components should confer with the regulators and stakeholders to establish the objectives of the study, including the development of clear and defined risk management objectives. An example of a flowchart for a site-specific vapor intrusion investigation is shown in Figure 3-1. This flowchart serves as a visual example of the decision logic that can be used for a site-specific vapor intrusion study.

3.1 Development of a Vapor Intrusion Work Plan

Developing a site-specific vapor intrusion work plan includes:

1. Reviewing the CSM developed for the screening level assessment and updating it as appropriate
2. Reviewing and updating the DQOs
3. Identifying data gaps
4. Identifying sampling and building locations
5. Considering potential background sources of contaminants
6. Preparing the sampling and analysis plan.

3.1.1 Conceptual Site Model

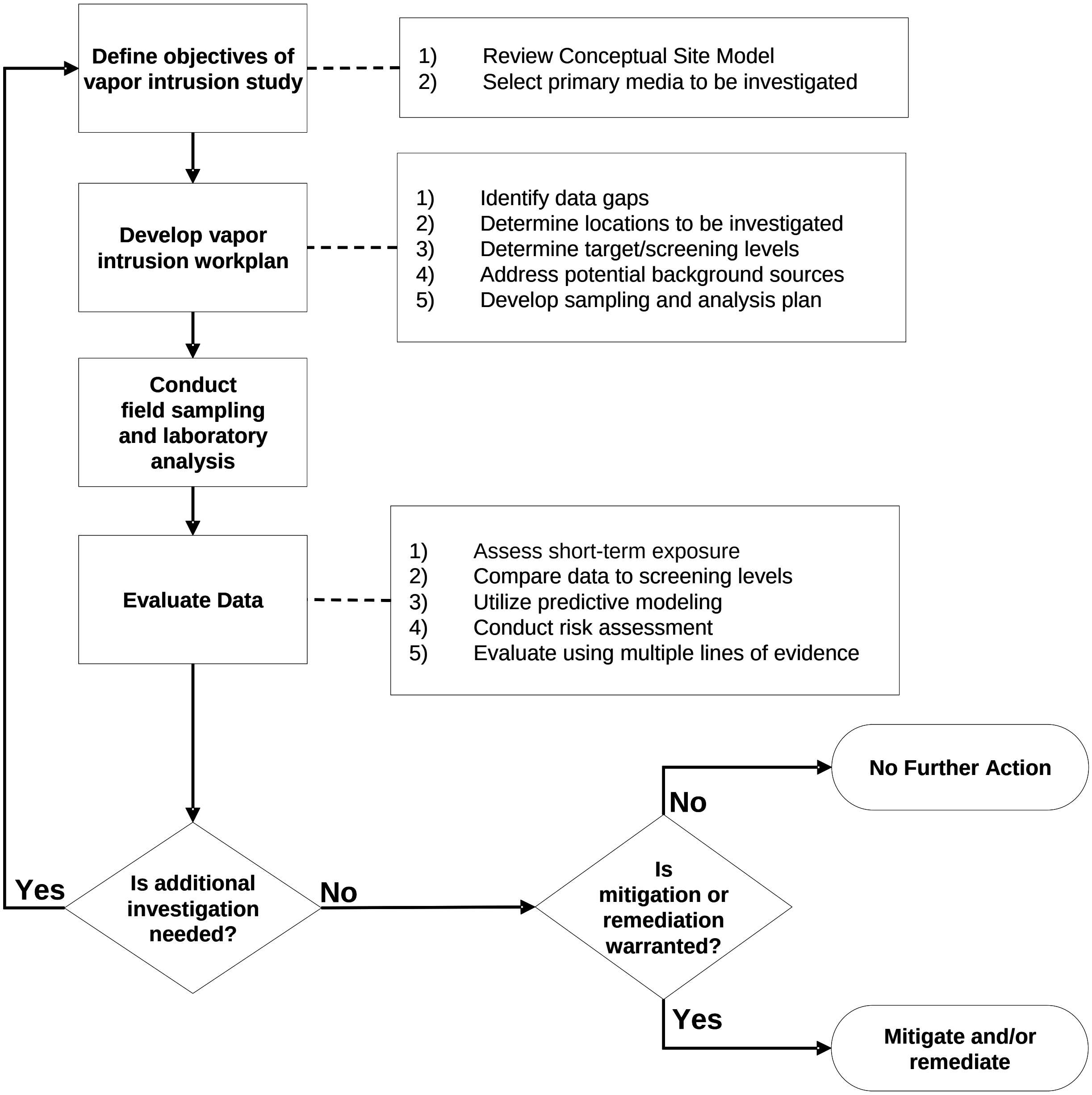
The CSM, developed as part of the screening level assessment described in Section 2, should be reviewed to evaluate whether changes need to be made based on any new information obtained for the site (e.g., the presence of unexpected chemicals). Possible changes in building or land use should also be evaluated.

3.1.2 DQOs

The DQOs developed for the screening level assessment should be reviewed and updated as needed to ensure that they are adequate for the level of investigation being proposed. In addition, any data gaps noted in the screening level assessment or identified during the work plan development should be stated. For example, if a primary focus of the study is the collection of indoor air, it may be useful to collect sub-slab soil gas and background air data concurrently.

In many cases, additional groundwater or soil gas data may be needed to narrow down the area with the highest concentrations before selecting individual properties or buildings for site-specific evaluation.

Figure 3-1: **Example of the Decision-Making Process for a Site-specific Vapor Intrusion Study (after ITRC 2007a)**



3.1.3 Locations to be Investigated

Specific properties or buildings that require investigation should be identified in the work plan. It can be a relatively straightforward decision when only one property or building is of concern (e.g., see Scenario 1 in the ITRC [2007b] companion document). However, when a large number of buildings is potentially impacted, selection of the property or building for initial investigations can be more challenging (e.g., see Scenario 3).

Historically, groundwater and soil gas samples collected as part of the PA/SI or RI may not have been intended to support a vapor intrusion analysis. A review of the chemical data, the location of the samples, and the results of the screening will indicate whether sufficient sampling of an adequate quality was performed and whether additional samples or locations are needed to evaluate the vapor intrusion pathway.

To account for some of the inherent uncertainty, several buildings should be selected for the initial investigation to ensure that the varying factors potentially affecting vapor migration are addressed. A statistically based approach might also be appropriate for some bases or sites to help select unbiased sampling locations. This method is most appropriate when concentrations are fairly consistent over a relatively large area and there is little to distinguish the most susceptible homes or area to sample.

3.2 Development of a Vapor Intrusion Sampling and Analysis Plan

It may be necessary to sample multiple media during the course of a vapor intrusion study. Soil gas, groundwater, indoor air, and outdoor air may all be sampled, depending on the phase of the study and the concerns and regulatory requirements at the site. As previously discussed, to adequately sample and analyze these various media, it is necessary to develop DQOs, determine the needed reporting limits, and select the appropriate analytical techniques. Important issues related to the sampling and analysis of chemicals within these different media are discussed in this section.

Current versus future land use is an important factor to consider when selecting sampling locations at a site. For current site uses, sampling should be done in the immediate vicinity of the building(s) in question. It is generally recommended to sample around any buildings located within 100 feet of documented subsurface volatile contamination. For future land use, the samples should be taken in the area at a site where the maximum chemical concentrations are located. This location may be adjacent to a building (e.g., near a leaking chemical storage tank) or may be taken from the location with the maximum groundwater contaminant concentration. This approach provides a worst-case type of assessment for vapor intrusion risks. Because of the mobility of volatile chemicals, concentrations of chemicals in both groundwater and soil gas can change over time. Hence, additional sampling may be needed in the future to confirm the status of site conditions at the time of development if information existing at that time (for example, decreasing groundwater contaminant concentrations) is not sufficient for assessment purposes. While DoD Components can control sampling and development on active bases, they may not have full control regarding future sampling or development at closed bases or FUDS properties.

These additional samples may include groundwater, soil gas, near-slab, sub-slab soil gas, or indoor air. Soil gas data, be it near-slab, sub-slab, or more remote from the building, provides more appropriate information regarding the migration of volatile chemicals through the subsurface and through the building foundation than groundwater data, which requires the use of additional fate and transport modeling.

3.3 Sampling

The density, number, and locations of the sampling depend on several factors including: nature and extent of subsurface contamination, size and construction of the building(s) being investigated, site-specific geology, and location of potential preferential pathways. These factors need to be considered in the development of project DQOs and the sampling plan and associated Quality Assurance Project Plan (QAPP). The QAPP is a document that describes the necessary quality assurance, quality control, and other technical activities that must be implemented to ensure that the results of the investigation will satisfy the stated performance criteria. The results of the sampling can then be compared with the appropriate screening criteria or used in a site-specific risk assessment. Appendix F presents sampling and analysis costs associated with different endpoints for evaluating the vapor intrusion pathway.

3.3.1 Soil

Sampling of bulk soil is not a preferred approach for vapor intrusion studies. Accurately measuring concentrations of VOCs in soil samples can be problematic for several reasons. The chemicals may volatilize or escape either during collection or from the sample container prior to analysis. If soil is sampled for VOCs, it is recommended that discrete (rather than composite) samples be collected using sampling methods designed to minimize loss of volatile chemicals. Modeling and partitioning equations needed to predict indoor air concentrations of VOCs from soil samples are greater in number and often more uncertain than those needed for either soil gas or groundwater. Notwithstanding, there are mathematical techniques that can estimate a soil gas concentration from soil data; the resultant soil gas concentration can then be input into a fate and transport model. Hartman (2002) noted that calculated soil gas values can differ from measured soil gas values by several orders of magnitude. As a result, the error introduced by using calculated soil gas data may be substantially greater than that associated with all of the other modeling parameters. However, as discussed by the California Department of Toxic Substances Control (DTSC) (2005), bulk soil data (and groundwater data, where appropriate) may be collected and used as the basis for modeling at sites with very low soil permeability where it is difficult to collect soil gas. It is recommended that a number of soil properties be analyzed concurrently with any soil collection, including soil moisture content, bulk density, and porosity. If default soil parameters (rather than site-specific values) are used for J&E modeling at sites with low permeability soil, the contaminant transport rates are likely to be overestimated.

3.3.2 Groundwater

Contaminated groundwater is often the primary media acting as a source for vapor intrusion at many sites. Contaminant plume migration can bring VOCs into close proximity to occupied structures, so it is important to characterize groundwater concentrations and the potential for plume migration when assessing current and future vapor intrusion risks at a site. The depth to groundwater and the fate and transport properties of the contaminants will influence vapor intrusion risks.

Groundwater samples should be collected from wells screened at or across the top of the aquifer, where the volatile chemicals of interest can partition into the vapor phase. It is an accepted component of the CSM for vapor intrusion from groundwater that a clean water lens above VOC contamination can act as a barrier to volatilization of VOCs from deeper ground water and reduce or prevent vapor intrusion into overlying buildings. Field studies and modeling presented in Rivett (1995) suggest that groundwater concentrations one meter below the water table are unlikely to create significant soil gas signatures in the overlying vadose zone. Other studies indicate that because the rate of diffusion of contaminants through the overlying clean ground water is so slow, the overlying ground water can greatly impede or prevent VOCs in deeper ground water from reaching the unsaturated zone, thus possibly preventing a vapor intrusion situation (Fitzpatrick & Fitzgerald, 2002; McAlary et al., 2004). New Jersey's vapor intrusion guidance states that sites with a groundwater lens at least three feet above contaminated groundwater are not likely to be associated with significant offgassing (NJDEP, 2005). Groundwater monitoring from the top of the water-bearing zone is considered appropriate for the purposes of evaluating potential vapor intrusion pathways. Either permanent monitoring wells or temporary direct push wells can be used for accessing the groundwater.

3.3.2.1 Non-Aqueous Phase Liquid

Liquid phase contamination in the subsurface environment may be associated with either dissolved phase contamination or as NAPL. The NAPL can be associated with either light non-aqueous phase liquid (LNAPL; typically small hydrocarbon molecules such as gasoline) or dense non-aqueous phase liquid (DNAPL; typically chlorinated solvents). NAPL occurs when the amount of chemical present exceeds that which can go into solution (i.e., dissolve). LNAPL forms on top of the aquifer (often referred to as "floaters"), while DNAPL ("sinkers") migrates towards the bottom of the aquifer. LNAPL is usually present as a discrete layer; DNAPL often forms small, isolated pools that can be difficult to find. Both LNAPL and DNAPL are essentially reservoirs of chemicals that will continue to contaminate the surrounding groundwater as long as they remain. Thus groundwater concentrations of chemicals are usually highest near NAPL sources. Both groups of NAPLs can be very hard to find and measure accurately. Sampling groundwater at the appropriate depth is often used as a surrogate to determine whether LNAPL or DNAPL are present. However, as noted in Section 3.3.2, any groundwater samples should be taken from the top of the aquifer.

3.3.3 Soil Gas

Soil gas is often the preferred subsurface media sampled for evaluating the vapor intrusion pathway. Using soil gas data instead of soil or groundwater data avoids the modeling needed to predict a gas concentration from soil or groundwater data. Direct measurement of soil gas will capture vapors from all sources that may be present, such as contaminated groundwater, soil, or laterally transported vapors (Hartman, 2002). It is important that the soil gas samples be taken from the appropriate depth, as the site-specific geology and the type and location of the contamination can affect how soil gas behaves in the soil column.

Soil gas can be collected in one of three ways: **active, passive, or by surface-flux chambers. Active soil-gas collection** is probably the most commonly used method. Active methods involve direct collection of soil gas either by driving a tube or rod (often called a "probe") into the earth or by burying a small diameter tube underground. A vacuum is then applied to the collection device to pull soil gas into the collector. There must be a good seal between the probe and the earth's surface to minimize pulling atmospheric air into the collector. In general, the collection system (either probe or tubing) should have a small internal volume (dead space) to minimize the purge volume. Purging is done to remove the clean air present in the system when it is put in place; the system must be fully purged and replaced with soil gas before actual sample collection is done. The number of times the system should be purged prior to sample collection is essentially a matter of professional judgment. Hartman (2002) says that the purge number can range from one to five, depending on the system and regulatory requirements. One of the benefits of active soil-gas collection is that these methods give concentration-based data (e.g., micrograms per cubic meter, $\mu g/m^3$), which can be input directly into contaminant transport models or a risk assessment.

Passive soil gas collection is the burial and subsequent retrieval of an absorbent material designed to collect volatile chemicals. This material absorbs chemicals present in the soil vapor over time; the longer it is there, the more it can absorb. On the plus side, it can be left in the ground for a long enough period to minimize temporal variations in soil gas flux. However, because it measures chemical mass rather than concentration, there is no way to determine the volume of soil gas associated with the chemicals on the absorbent material. As a result, passive soil-gas data is not suitable for quantitative risk assessment. However, passive soil-gas results can be a useful screening tool to target more definitive soil gas sampling in areas where soil gas concentrations or flux are highest. Passive sampling can also help determine which VOCs are present in soil gas.

The third option for measuring chemicals present in soil gas is the **flux chamber**. This is a box placed directly on the ground or building floor that captures the chemicals in soil gas that are leaking through the area of the floor covered by the flux chamber. Flux chambers can be left on the same spot for relatively long periods of time (hours or days), thus yielding a time-integrated sample that will help to reduce temporal variability. There are two basic types of flux chambers: static and dynamic chambers. The static chamber does not use “sweep” gas to maintain a steady-state concentration in the chamber. Dynamic flux chambers, by contrast, have a “gas in, gas out” design that allows their chamber to reach a steady-state condition with regard to the chemical flux from the subsurface. Static chambers are more sensitive than dynamic chambers because the soil gas entering the chamber is not diluted by the sweep gas. However, the disadvantage of the static chamber is that if high concentrations of chemicals build up in the chamber, this will reduce the flux rate from the subsurface (which is directly related to the concentration gradient). Flux chambers can provide useful information regarding the migration of chemicals from the subsurface. However, not all agencies are familiar with them or will approve their use. For example, the California DTSC will accept them as a qualitative screening tool but will not allow their results to be used in a quantitative risk assessment. The use and interpretation of flux chamber results should be determined during the development of the DQOs.

Flux chambers cannot be placed at the slab/wall connection, which is typically considered to be the primary building entry point for vapor intrusion. For more information, Hartman (2003) has a detailed discussion of various issues concerning flux chambers.

3.3.3.1 Sub-Slab Sampling

Sub-slab sampling can be performed to determine if vapors are present directly below a building. Buildings selected for sub-slab sampling should be chosen with full consideration of both the CSM and project DQOs. One approach recommended by some regulatory agencies is to collect several sub-slab samples per building and combine the data with a generic attenuation factor. This yields an estimated indoor air concentration of the chemicals detected below the slab. Other agencies require that both sub-slab and indoor air data be collected concurrently so that a building-specific attenuation factor can be calculated.

There are several technical and logistical difficulties with sub-slab sampling. It can be very invasive to the occupants and may be difficult to get the right equipment in place to drill through the slab, particularly in buildings with basements. California DTSC and MassDEP recommend using either an electric hand-drill or a concrete corer to drill through the slab. The recommended hole size is 1.0 to 1.25 inches in diameter, and the holes should be advanced through the slab and three to four inches into the sub-slab material (DTSC, 2005). Care should be taken to avoid drilling through a slab tensioning cable or rebar in the slab. Utilities also need to be located prior to drilling. It is important that any holes or breaches made in the foundation as part of the sub-slab sampling be properly sealed following the sampling to avoid creating a new preferential pathway for vapor intrusion.

Sub-slab sampling is used for the direct measurement of soil gas that may accumulate immediately below a building's foundation. The DTSC recommends that at least two sub-slab samples be taken per building, with one sample from the center of the building's foundation. For buildings larger than 5,000 square feet, one sample per 1,000 square feet is recommended by DTSC (2005). Other agencies may have different requirements regarding sub-slab sampling locations and density.

Several factors should be considered regarding sub-slab sampling:

- Sensitivity of reporting limits (should meet DQOs and risk-based requirements)
- Seasonal and/or temporal variability
- Presence of shallow groundwater
- Spatial variability (e.g., soil types, preferential pathways, building design, subsurface contamination location, etc.)
- Chemicals that may be formed by the degradation of the primary chemicals of interest.

The results of sub-slab samples may be used for screening predictive modeling, or as one line of evidence, as described by the ITRC guidance (ITRC, 2007a). Sub-slab samples may be compared to generic screening levels to assess potential vapor intrusion. Generic screening levels, as well as attenuation factors that are used to generate the screening levels, are conservative and non-site-specific and thus should be used accordingly. The EPA 2002 draft guidance recommends an attenuation factor of 0.1 be applied to sub-slab soil gas samples to predict indoor air concentrations. Based on updated information, DTSC (2005) recommends that an attenuation factor of 0.01 is appropriate for sub-slab soil gas samples. At the time of this publication, an updated database of attenuation factors is expected to be released from EPA with semi-site-specific criteria. If the site concentrations are below the risk-based criteria, it may be concluded that the pathway does not pose an unacceptable risk and no further study is needed. If the site concentration exceeds the criteria, additional investigation may be needed to evaluate the risks associated with this pathway. Alternately, the soil gas data and selected attenuation can be used to estimate an indoor air concentration, which can then be evaluated in a human health risk assessment. Components are discouraged from quantifying risks using anything but actual indoor air data; results of estimated risk using modeled or estimated air concentrations will be properly qualified and not be construed or presented as actual risk.

3.3.3.2 Near-Slab Soil Gas Sampling

Near-slab soil gas sampling can be another line of evidence to evaluate whether vapor intrusion is occurring at a building. Taking near-slab samples has the advantage of not being as invasive as sub-slab sampling, since they can be taken outside without piercing the foundation. The closer the sample is taken to the ground surface or structure foundation, the greater the chance that surface processes (such as precipitation, atmospheric pumping, and advective flow caused by the building) will affect the soil gas concentration. It be may appropriate to concurrently collect groundwater and indoor air samples to allow a better understanding of contaminant movement at the site. It is generally recommended to avoid taking shallow soil gas samples (i.e., less than five feet below ground surface), since potential infiltration of atmospheric air can potentially dilute the contaminant concentration in soil gas. Other factors to consider in selecting the appropriate depth for soil gas sampling include geologic conditions at the site, source depth, foundation depth, and building area, as these will influence the sub-slab and near-slab soil gas concentrations. When evaluating soil gas data and comparing to target concentrations, it is important to understand the subsurface lithology, preferential migration routes (conduits), and the potential for multiple sources. The sampler should identify whether the source of vapors in the area occurs in the unsaturated zone or whether contaminated groundwater is the only source of the contaminant.

3.3.4 Indoor Air Sampling

Indoor air sampling may be conducted to evaluate the vapor intrusion pathway. Chemicals may have migrated from the subsurface and into the indoor air of structures located above the contamination, or chemicals may be present as a result of indoor sources of air contamination. Attribution to a source cannot be made until other information is gathered of possible external or internal releases of chemicals to the indoor air. It is generally desirable to conduct concurrent sampling of other media, such as sub-slab soil gas, outdoor air, or groundwater. Sampling multiple media concurrently will give a more accurate representation of contaminant migration than that obtained from a single media. At many DoD sites the subsurface contamination is historic (e.g., 10-20 years old) and there is a trend towards decreasing concentrations over time (due to remediation, attenuation, or both). Because the subsurface concentrations exhibit a decreasing trend, indoor air concentrations would also be expected to decrease over time.

Some of the potential advantages and limitations of indoor air sampling are summarized in Table 3-1.

Table 3-1: Issues Associated with Indoor Air Sampling

Advantages of Indoor Air Sampling	Limitations of Indoor Air Sampling
Provides a direct measurement of indoor air concentrations of the chemicals of concern	Like any environmental sample, an individual indoor air sample may not be representative of the long term exposure concentration.
Might provide confirmation that the vapor intrusion pathway is complete (or incomplete)	A number of environmental parameters (e.g., water table variations, temperature, soil moisture, atmospheric pressure) may affect vapor intrusion rates, thus indoor air concentrations can have large temporal variability
Can be used as a validation tool for fate and transport modeling	Samples at different times of year may be required to account for effects of seasonality on vapor intrusion
If collected in conjunction with sub-slab samples, indoor air samples can be used to develop empirical, building-specific attenuation factors	Sampling may be disruptive to building occupants. Normal activities may need to be curtailed to avoid adding volatiles to air. Stored chemicals and cleaning supplies may need to be removed from building.
The direct measurement of indoor air may account for the influence of building-specific parameters that are hard to measure or quantify	Sampling cannot be used to estimate attenuation of contaminants over time (unless long-term monitoring is undertaken)
Can provide data suitable for either qualitative screening level assessment or a quantitative risk assessment if sufficient data is available	Sampling cannot be used to predict vapor intrusion impacts to buildings to be built in the future
Sampling does not require drilling through building foundation and thus does not have the potential to change vapor migration patterns	Volatile contaminants in groundwater may be released directly to indoor air if groundwater is used in the home
	Impact from background chemicals (including indoor sources) may be substantial and must be accounted for (for indoor and outdoor background impacts)
	Sampling design can affect risk assessment

The sampling duration and the number and location of indoor air samples are key parameters for an indoor air sampling study. In general, the sampling duration for each sampling event should be sufficiently long to replicate the anticipated daily exposure duration. For residential receptors, a 24-hour sample collection period is reasonable; for commercial and industrial receptors, an 8-hour collection period is typically used. Sampling canisters and flow regulators should be adjusted to collect an integrated air sample over the exposure duration of interest.

The EPA and a number of states recommend that indoor air samples be collected during at least two different time periods to account for seasonable variability in building parameters and the volatilization of chemicals from the subsurface. One sample should be collected in the summer and the other in the winter. Samples collected in the winter are expected to represent the high end of potential exposures at many locations since there will be less external ventilation (windows closed) and the building heating system will create a pressure differential that pulls gases up from the subsurface.

The number and location of sampling points will likely vary from building to building. In general, several samples should be taken from the basement and from high-trafficked areas in both residential and commercial buildings. DTSC (2005) recommends that residential sampling points include the potential VOC infiltration point (typically the bathroom or kitchen), as well as the primary living area. For multi-storied residential buildings, they recommend taking at least one sample from each floor. For office buildings, DTSC (2005) recommends taking at least one sample from each discrete office.

There are several different techniques that can be used to collect indoor air samples. These include grab sampling, time-integrated sampling, real-time monitoring, passive sampling, and portable direct-measurement sampling. Each of these techniques has advantages and disadvantages that vary depending on the monitoring objectives, required reporting limits, duration of monitoring, and the project goals. Selection of the proper sampling techniques is dependent on how the data will be used and what reporting limits are needed.

The EPA recommends that an "occupied dwelling questionnaire" be completed before conducting indoor air sampling. This questionnaire can aid in the identification of human activities and household chemicals that may contribute to the presence of chemicals in indoor air. This information can be critical for determining whether the source of an indoor air contaminant is coming from vapor intrusion from subsurface contamination or is associated with chemical use or storage within the house. A copy of EPA's occupied dwelling questionnaire from its 2002 draft vapor intrusion guidance is included as Appendix E of this document. Inspection and documentation of equipment, operations, and chemicals present in the building or structure at the time of sampling is needed for subsequent evaluation of the significance of sampling results and for possible attribution of the sources of indoor air contamination.

Grab sampling: This approach involves collecting an air sample at a single point in time. The actual time of sample collection can range from a few seconds to a few minutes. Grab sampling is typically used as a screening technique to identify contaminants present and to determine their approximate concentration range. Compared to other monitoring techniques, grab sampling is easy and quick to conduct, and sampling costs are minimal. There are two primary disadvantages of grab sampling. The first disadvantage is that the sample represents just a "snapshot in time" and may not be reflective of long-term conditions. The second disadvantage is that the sample volume collected is very small, thus making it difficult to achieve low reporting limits.

Time-integrated monitoring: This is the most commonly used technique for indoor air sampling. The sampling is conducted over a sufficiently long period of time to be representative of the population occupying the space, typically over 24 hours for residences and 8 hours for workplaces. Integrated samplers work by trapping the chemicals of interest on either solid absorbent molecules or in specially treated canisters. In general, the longer the sampling period, the more chemical will be collected. Advantages of time-integrated monitoring include achievement of low reporting limits and the ability to conduct the analysis when it is convenient (since the chemicals are absorbed into a matrix). A primary disadvantage related to this method is that it does not provide timely data for short-term decision-making. In addition, the potential time gap between collection and analysis allows for sample loss, chemical deterioration, and contamination of the canister.

Real-time monitoring: This approach uses techniques that provide for rapid collection and analysis within a short period of time (often just minutes). This approach requires hooking up an analysis system directly to the collection device or transporting the sample via heat-trace lines to a central location for analysis. Often, a single analysis device is able to process samples from multiple sampling locations within a building. The EPA's trace atmospheric gas analyzer (TAGA) unit can be used for real-time monitoring and the rapid analysis of air samples. The analysis system for real-time monitoring can use various techniques and detectors, including gas chromatography (GC), GC/mass spectrometry (GC/MS), and infrared spectroscopy (IR), as well as others. Care needs to be taken that the detection and reporting limits are sufficiently sensitive and are able to meet DQOs.

Passive sampling: This is primarily a long-term monitoring technique. It does not require a pump or any kind of active collection device. Passive sampling uses an absorbent material (such as charcoal or organic resins like Tenax®) that absorbs any VOC molecules that come into contact with it. Passive samplers can be either permeation- or diffusion-driven. After the appropriate interval, the absorbent material is removed and the VOCs are extracted and analyzed. This technique provides a means for evaluating the presence of VOCs over extended periods of time. Passive sampling provides an inexpensive and convenient alternative for assessing time-weighted average concentrations of chemicals for personal monitoring. Passive gas collection may be used to provide either qualitative or quantitative results, depending on the project needs and project planning. A disadvantage of this method is that there may be sample degradation if the collection period is too long.

Passive sampling devices have to be developed and calibrated for specific chemicals. They are often used as personal monitoring devices (badges) for industrial hygiene applications to evaluate a worker's exposure during the course of a workday. The absorbent material is an important factor in defining the sensitivity of a passive sampler. When conducting ambient air monitoring for VOCs, organic resin absorbents will yield lower reporting limits than will carbon absorbents. It is important that the choice of absorbent material be selected specifically for the compound of interest. This technique is not commonly used to evaluate residential exposures to VOCs because the reporting limits are not low enough.

Portable Direct-Measurement Sampling Techniques: These screening methods provide rapid analytical results so that on-site decisions can be made regarding worker or community safety. The most commonly used direct-measurement detectors are FIDs and PIDs. These detectors are handheld devices that analyze air samples on-site. The primary analytical output of these instruments is typically given for classes of chemicals, such as VOCs, SVOCs, and total hydrocarbons, rather than for individual chemicals. These techniques are usually used as a screening tool to determine whether chemicals are present at levels of concern, as their lack of analytical sensitivity limits their usefulness. FID or PID devices may be held at specific locations of interest, such as sumps or cracks in the foundation, to determine if VOCs are migrating through them. If chemical groups (total hydrocarbons) exceed a generic trigger concentration, more sensitive and specific sampling and analysis techniques may be needed to provide more accurate data.

Background Issues for Indoor Air Sampling: The contribution of background sources of chemicals to measured concentrations of indoor air must be accounted for in any sampling program. Background indoor air contamination is everything unrelated to the subsurface vapors that migrate into a structure. Background contamination may result from either indoor or outdoor sources and is an important component of the chemicals measured during indoor air sampling. Background chemical sources should be accounted for to ensure that any site management decisions are based on chemicals associated with vapor intrusion and not background chemicals. Concurrent background outdoor air sampling should be considered to allow for evaluation of any possible contaminant contribution from ambient air to the indoor air.

Background indoor air sources of volatile chemicals in residential structures include consumer products, supplies used for personal hobbies, household cleaners, paints, and building supplies. These background sources should be identified and removed prior to indoor air sampling, if practical. As noted by ITRC (2007a), common household products that can cause measurable levels of volatile chemicals in indoor air are presented on the National Institutes of Health (NIH) Household Products Database (http://householdproducts.nlm.nih.gov/) and include:

- Adhesives (automotive, household, craft, plumbing)
- Household cleaners
- Lubricants
- Building materials
- Bonders
- Adhesive removers
- Anti-static aerosols
- Automotive parts cleaners
- Paint strippers
- “Spot removers” for fabrics
- Jewelry polish
- Water repellants
- Spray paints
- Dry-cleaned materials (e.g., clothing containing residual dry-cleaning solvents)
- Caulks and sealants
- Cosmetics including hair spray, nail polish and nail polish remover, perfume, cologne
- Air fresheners and odor eliminators
- Insect repellants.

These products should not be used inside the building at least 24-48 hours before and during the indoor air sampling activities, if practical. It should also be noted that some materials (e.g., carpeting, drapes, upholstery) may absorb and retain VOCs, slowly releasing them to the indoor environment over a long period of time (weeks or more).

Other background sources include outdoor ambient sources such as those related to automotive exhaust, smoking (e.g., benzene) and commonly emitted solvents. Outdoor sources may include gas stations, industrial facilities, agricultural activities, and roadways (along with widespread regional sources such as power plants or refineries). Sub-slab sampling and outdoor ambient air sampling should be conducted concurrently with indoor air sampling to aid in identifying chemicals potentially migrating into the structure.

Indoor air concentrations of chemicals, even at contaminated sites, are often very low - in the parts per billion by volume (ppbv) and parts per trillion by volume (pptv) range. Even small indoor sources - such as paint cans or cleaning bottles - can introduce VOCs into the air at concentrations that can be detected and interfere with indoor air studies. Prior to conducting any indoor air sampling, the contribution from background sources should be defined and distinguished from any input via vapor intrusion to avoid any confusion between different sources of chemicals. All background conditions in or around the building or structure need to be documented at the time of sampling in order to support evaluation of subsequent actions by DoD. Additional information regarding the assessment of background chemicals is included in Appendix G.

Several regulatory agencies, including EPA, Cal-EPA, and MassDEP, have prepared a questionnaire that includes detailed questions regarding possible sources of background chemicals in indoor air. A copy of the EPA's questionnaire from its 2002 draft vapor intrusion guidance is attached as Appendix E. For additional information regarding indoor air sampling, refer to the 2002 publication *Indoor Air Sampling and Evaluation Guide*, WSC Policy #02-430 (MassDEP, 2002).

The Occupational Safety and Health Administration (OSHA) regulates worker health and safety in workplaces subject to their regulation. This includes regulatory authority over indoor air contamination in workplaces under their jurisdiction. See section 4.5.2, below for further information on this subject.

3.3.5 Building Design Parameters

The DoD has a wide variety of building styles that can be impacted in different ways by vapor intrusion. Examples of various buildings used by the military include residential housing, barracks (group housing), industrial buildings, airplane hangars, warehouses, bunkers, munitions igloos, commercial buildings, and office space. Foundation construction and composition will vary among the different types of buildings. Many buildings will be slab on grade, while others will be built slightly off the ground (pier and beam) with a crawl space for accessing utilities located under the building. Still other buildings will have basements, some of which will have sumps for collecting water. All of these factors will influence the emission of vapor through the foundation. The J&E model was developed assuming either slab on grade or a basement construction style. In its current configuration, the J&E model is not designed to accurately model vapor intrusion into buildings with a crawl space.

Air exchange (air turnover) inside a building is also an important parameter in the J&E model. The J&E model's default assumption is 0.25 air exchanges/hour (AEH) for a typical residence. This value is intended to be conservative, and represents a lower bound on air exchange rate for houses nationwide; it does not account for any local or regional issues (e.g., affects of heating or air conditioning). The appropriateness of this assumption would need to be considered for DoD operational buildings, which may have air exchange rates substantially different than residential dwellings. The DTSC (2005) recommends using an air exchange rate of 0.5 per hour for houses and 1.0 for commercial buildings in California. Large military warehouses or hangers are likely to have air turnover rates much greater than typical residential and commercial buildings.

Another factor to be considered in assessing vapor intrusion is preferential pathways that may serve as a channel for entry of vapors into buildings. These preferential pathways may be created by various building entries, such as sewer lines, gas lines, or floor drains and sumps.

Vapor intrusion into a building via preferential pathways cannot be evaluated using the J&E model. Direct measurements taken adjacent to possible preferential pathways may be needed to evaluate whether these pathways are contributing to indoor air contamination. Appendix H contains information on how to evaluate a building envelope and its effects on a vapor intrusion investigation.

3.4 Analytical Methods

The EPA has standardized analytical protocols for many common chemicals detected in soil, soil gas, groundwater, and indoor air. It is outside the scope of this document to describe the analytical techniques available for soil and groundwater sampling. This document is focused on the analysis of chemicals in air, either in soil gas or indoor air.

The EPA has developed a number of techniques for measuring air pollutants to support a range of air programs across the country. The methods for a wide range of airborne pollutants have been published in a series of documents known as *Compendia*. Presently, there are three documents in the *Compendia* series:

- Compendium of Methods for the Determination of Air Pollutants in Indoor Air, EPA/60014-90-010, April 1990.
- Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air, Second Edition, EPA/625IR-96-010b, January 1999a.
- Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air, EPA/625IR-96-010a, June 1999b.

The *Compendia* include methods for many chemicals that are not volatile and are not of concern for the vapor intrusion pathway.

Two methods commonly used to measure VOCs in indoor air (as well as in soil gas) are the EPA's toxic organic TO14 (and TO-14A) and TO15 methods. In general, these methods have the sensitivity needed to provide data with reporting limits that are sufficiently low to support risk assessment. They have similar sensitivities of 0.2–20 ppbv, depending on the chemical and the instrumentation settings. These air samples are collected in canisters, usually Summa® canisters. The TO14A method is used for non-polar VOCs such as toluene, benzene and ethylbenzene. The TO15 method includes both polar and non-polar VOCs, such as methanol, xylene, and nitrobenzene, as well as those previously listed. The TO-15 Supplemental method was developed specifically for collecting and analyzing chlorinated VOCs, such as dichloroethane, TCE, and tetrachloroethene (PCE). The TO-15 Supplemental method can achieve detection limits in the ppbv-pptv range. Both the TO-14 and TO-15 methods use a Summa® canister as a collection device—a canister (often 6 liters in size) that is specially treated to avoid absorbing VOCs—and a combination GC/MS for analysis. Even lower detection limits can be achieved by using these methods in the "selective ion mode," or SIM. Another benefit of TO-14 and TO-15 SIM analysis is the capability to focus on selected organic compounds of interest to DoD at a very low detection limit without interference from other chemicals. SIM analysis may be required when the needed reporting limits or action levels are in the 0.01 $\mu g/m^3$ range.

The California vapor intrusion guidance (DTSC, 2005) discusses the use of several other analytical methods that can be used for indoor air sampling. TO-1 and TO-2 both trap VOCs on a matrix, which can then be stripped and analyzed by GC/MS. Reporting limits for these techniques range from 0.01 to 1.0 ppbv, depending on the chemical.

3.5 Multiple Lines of Evidence

Once the analytical data needs have been identified and appropriate data collected, it will be necessary to evaluate the data for site management decision making. There is a trend away from using just a single data set for decision making and towards using the findings from several different data sets for making site decisions. This approach is termed the "multiple lines of evidence" approach. Considering these multiple findings together rather than relying on a single decision criteria will often give a better understanding of the vapor intrusion pathway.

The ITRC (2007a) identified a number of possible lines of evidence that could be used to assess if the vapor intrusion pathway is complete. These lines of evidence include (in no particular order):

- Soil gas data
- Near-slab soil gas data
- Groundwater data
- Background data (from indoor and outdoor sources)
- Building construction and current conditions
- Sub-slab (or crawl space) soil gas data
- Indoor air data
- Outdoor air samples collected concurrently with indoor air samples
- Comparison of constituent ratios of chemicals in soil gas and indoor air
- Impact of site geology
- Results of fate and transport modeling
- Results of the risk assessment
- Site or building ownership and control.

It should be noted that the various lines of evidence have different degrees of accuracy and relevance associated with them. It is unlikely that all of these lines of evidence will need to be evaluated in order to make site management decisions. It will be important to identify what information is needed for site decision making by working with the regulators before conducting an additional field investigation. Some agencies recommend that indoor air samples be collected as soon as a potential vapor intrusion concern is identified, while other agencies prefer to collect indoor air data as the final data type in a vapor intrusion investigation.

Evaluation of constituent ratios in soil gas and indoor air can provide evidence as to whether a chemical detected in indoor air is associated with vapor intrusion or is a background chemical. For example, if the concentration of TCE is10 times higher than that of PCE in groundwater and soil gas but the PCE concentration in indoor air is higher than TCE, it is possible that there is an indoor or background source of PCE (such as dry-cleaned clothes). This observation will help the investigator better understand the site and make better risk management decisions.

Using groundwater or soil gas data requires fate and transport modeling and the selection of an attenuation factor for the slab in order to predict an indoor air concentration. Modeling from groundwater typically requires very conservative assumptions, and the Henry's Law parameter must be corrected for the aquifer temperature. Modeling from soil gas requires fewer assumptions than from groundwater, but the accuracy and representativeness of the soil gas data may be a factor. Modeling from sub-slab vapor requires the fewest assumptions, but collecting the data is intrusive and the assumed attenuation factor may still be conservative for many buildings. Indoor air sampling avoids the need to make the assumptions required for fate and transport modeling, but can be intrusive and the results may be confounded by background sources and seasonal variability.

Building construction details can also be a line of evidence in a vapor intrusion investigation. If a building's ventilation system creates positive air pressure, this will tend to reduce or prevent soil gas from entering the building. Other building parameters that should be considered include foundation thickness and integrity and the location of utility lines and drains that may pierce the floor and create preferential pathways. Refer to Appendix H for more detailed information about how the building characteristics can impact the vapor intrusion pathway.

In general, the closer to the receptor the data is collected, the more relevant it is considered. Following this logic, indoor air data would be considered more relevant for a risk assessment than an indoor air concentration modeled from groundwater or soil gas. It is important the weighting given to each line of evidence be considered during the development of project DQOs.

It is possible that the findings from some lines of evidence may conflict with others (e.g., indoor air concentrations may be acceptable but sub-slab soil gas samples exceed screening criteria), and this should be anticipated in the project planning process. It is recommended that data collection be targeted to lines of evidence needed for site decision making.

4 Health Risk Assessment at Vapor Intrusion Sites

The objective of a vapor intrusion study is to identify a representative indoor air chemical concentration that can be used to evaluate potential risks at a site. Indoor air concentrations of chemicals are presented as either $\mu g/m^3$ or as ppbv. These concentrations can be compared with screening criteria or can be used in a site-specific risk assessment. Comparison with conservative screening criteria is often done as an initial step in the risk assessment process to prioritize sites and resources. These generic screening criteria typically include a number of conservative assumptions intended to overestimate the actual exposure potential at most sites. However, a screening evaluation may not give an accurate picture of potential risk at a site, since results of a screening assessment do not yield a numerical estimate of risk. Screening can be useful to eliminate sites where the data are below screening criteria and are not expected to pose a risk or to prioritize resources at sites where the data is above screening criteria and there is potential risk present. At sites where the collected data significantly exceeds screening criteria, it may not be necessary (or desired from a risk communication standpoint) to calculate risk; rather it might be more advantageous to proceed directly to mitigation or remediation.

This section of the handbook discusses how results of a vapor intrusion study can be included in a risk assessment. Human health risk assessments are typically conducted at sites that are part of a CERCLA or RCRA investigation. These assessments are used to determine whether a site poses a potential health risk to people who may be exposed to site contaminants and to determine whether remedial action is needed. Generally, the risk assessment is part of the RI; however, other reports may also contain a risk assessment. There are many risk assessment guidance documents available, but the most commonly used is EPA's *Risk Assessment Guidance for Superfund: Human Health Evaluation Manual* (1989).

A risk assessment consists of four distinct phases:

- **Data Evaluation** includes site investigation, collection of data, and identification of chemicals of potential concern.
- **Exposure assessment** includes identification of potentially exposed receptors and exposure pathways, as well as exposure duration, frequency, and exposure point concentration.
- **Toxicity assessment** includes the hazard identification and a dose-response evaluation for the chemicals of potential concern.
- **Risk characterization** combines the results of previous steps and produces quantitative and qualitative evaluations of risk resulting from real or potential exposure to site chemicals; this phase also includes an uncertainty analysis.

This section discusses the primary components of risk assessment within the context of a vapor intrusion study.

4.1 Data Evaluation

The data evaluation phase of a risk assessment encompasses two primary elements: site characterization and identification of chemicals of potential concern. Older sites may not have been well characterized for vapor intrusion; available data should be carefully reviewed in light of the project DQOs to determine how well the site has been characterized or whether the site needs to be re-characterized due to the volatile nature of VOCs. For vapor intrusion studies, the chemicals of interest will typically be those chemicals that meet the criteria for toxicity and volatility (see list in Appendix A). Chemicals of potential concern for other pathways may include these chemicals as well as non-volatile chemicals.

4.2 Exposure Assessment

An exposure assessment includes the CSM and evaluates the pathways and routes by which people may be exposed to site-related chemicals. There may be a number of exposure pathways by which a receptor may be exposed to site-related contamination; however, this document focuses only on vapor intrusion and inhalation exposure. Standard exposure routes not addressed by this handbook include soil exposure via ingestion, dermal contact, and inhalation of dust, and groundwater exposure via ingestion, dermal contact, and inhalation of VOCs while showering. While these exposure routes are not relevant to the vapor intrusion investigation, they will be relevant when assessing overall site risks and making risk management decisions. An important aspect of the CSM is to distinguish between complete and incomplete exposure pathways. Complete pathways are typically quantitatively evaluated in the risk assessment, while incomplete pathways are not. Pathways that are currently incomplete may be complete in future scenarios. The exposure assessment also identifies specific exposure assumptions to be used in the risk assessment, including such parameters as exposure duration, exposure frequency, and breathing rate. These parameters will vary for different populations, such as residents, workers, active duty personnel, or visitors.

4.2.1 General Exposure Factors

The EPA risk assessment guidance (1989) discusses evaluating risk for the reasonable maximum exposure (RME) scenario, which is intended to represent a cumulative estimate of the maximum exposure that is reasonably expected to occur at a site. In some instances a second scenario, the central tendency exposure (CTE) may also be evaluated, to consider a more probable exposure estimate than the RME. The RME relies on upper bound estimates of chemical intake, while the CTE uses more representative (mean or median) estimates of intake.

An important component of the exposure assessment is calculation of the exposure point concentration (EPC), which is the concentration of a chemical to which a person is assumed to be exposed to for the duration of their exposure. EPCs are calculated for all chemicals of potential concern identified in the data evaluation step. The EPC should be a reasonable upper bound concentration of a chemical that a person could be exposed to. When there are sufficient samples, the EPC is often a statistically-derived upper bound value, typically the 95% UCL. When there are not enough samples to calculate a 95% UCL, the maximum detected concentration is typically used as the EPC. For most indoor air investigations there will not be a sufficient number of samples collected to calculate a 95%UCL. An alternate approach would be to evaluate risk for each sample collected, which would be more representative of potential exposure than relying solely on the maximum detected concentration.

This concentration will be used in the risk assessment to represent the long-term value to which a person is assumed to be exposed. It does not account for any attenuation or migration over time or changes in building or ventilation systems. As a result, it is considered to be a conservative concentration. The RPM should verify that the source can be considered to be either depleting (reducing in concentration over time as a result of either remediation or biodegradation) or nondepleting (often termed an infinite source, where the concentration of the contaminant source remains unchanging over time).

Exposure to volatile chemicals by the inhalation pathway can be evaluated using the following equation:

$$\text{Intake (mg/kg/day)} = \frac{\text{CA x IR x ET x EF x ED}}{\text{BW x AT}}$$

Where:

CA = Contaminant concentration in air (mg/m^3)

IR = Inhalation rate (m^3/hour)

ET = Exposure time (hours/day)

EF = Exposure frequency (days/year)

ED = Exposure duration (years)

BW = Body weight (kg)

AT = Averaging time (days)

4.2.2 Military-Specific Exposure Factors

As noted above, default exposure parameters may have reduced applicability for military personnel. Most military exposures will be shorter in duration than EPA's 30 years default exposure duration for residents and 25 years for commercial/industrial workers. The Air Force conducted a study of time spent on station for both officers and enlisted personnel (USAF, 2000) at Air Force installations within the continental United States. Nearly 2 million records were searched covering five distinct assignment dates to evaluate temporal variations in residence time of Air Force personnel. The timeframe evaluated covered from September 1987 through July 1999. This analysis indicated that mean residence time on station was 2.51 years for enlisted personnel and 1.90 years for officers. The 95th percentile residence time on station (based on 1998 data) was 7.86 years for enlisted personnel and 4.58 years for officers. The 95th percentile residence time is a factor of 3.82 lower for enlisted personnel and 6.55 lower for officers than EPA's default residential exposure duration of 30 years. Similar situations may exist at Army, Navy, and Marine Corps facilities. Reasonable exposure durations that reflect exposure of the target populations should be used in the risk assessment when available. In addition, it may be appropriate to adjust the generic screening values for soil gas and groundwater developed by EPA to account for the shorter exposure duration at active duty bases.

It may also be important to distinguish between exposures of active duty personnel and civilian personnel working on base. Civilian staff may work on a single base much longer than active duty personnel, who tend to get transferred with some regularity. Separate risk evaluations for civilians and active duty personnel may need to be conducted depending on the risk management decisions to be made.

4.3 Toxicity Assessment

The toxicity assessment identifies the potential hazards and dose-response information for the chemicals of potential concern. Toxicity values for carcinogens are often presented as cancer slope factors. A cancer slope factor identifies the relationship between the dose (or exposure level) of a chemical and the observed response (cancer). Toxicity values for chemicals that are carcinogenic by the inhalation pathway may also be presented as a unit risk factor. Unit risk factors represent the potential excess cancer risk a person could be subject to per unit of chemical exposure (usually $\mu g/m^3$ for inhalation carcinogens). For non-carcinogens, toxicity values are presented as a reference concentration (RfC) for the inhalation pathway and as a reference dose (RfD) for the oral pathway. Non-cancer toxicity endpoints can vary from chemical to chemical and can include such effects as dermal irritation or inflammation.

In September 2007, the Office of the Under Secretary of Defense released a memo that listed preferred sources for human health toxicity values for use in DoD CERCLA risk assessments (DoD, 2007). These sources were based on recommendations made by the Environmental Counsel of the States (ECOS)-DoD Sustainability Work Group, Emerging Contaminants Task Group contained in the 2007 DoD memo. The DoD recommendations were in part based on the OSWER Directive “Human Health Toxicity Values in Superfund Risk Assessments” (EPA, 2003).

The recommended hierarchy of toxicity values is as follows:

1. **EPA’s Integrated Risk Information Service (IRIS) Database:** These toxicity values normally represent the official EPA scientific position regarding toxicity of the chemicals based on data available at the time of review. The preferred EPA criteria can be found in the online IRIS database at: www.epa.gov/iris.
2. **EPA’s Provisional Peer Reviewed Toxicity Values (PPRTVs):** These are developed by EPA on a chemical-specific basis when requested by the Superfund program.
3. **Other Toxicity Values:** These values include additional EPA and non-EPA sources of toxicity information. Priority should be given to those sources of information that are most current, the basis for which is transparent and publicly available, and that have been peer-reviewed.

Toxicity values can be developed for both oral and inhalation exposure. Some chemicals of potential vapor intrusion interest may have an oral toxicity value but not an inhalation-derived toxicity value. In these instances it may be necessary to extrapolate from the oral toxicity value and estimate an inhalation value. This is termed “route to route extrapolation”. This technique introduces uncertainty into the risk assessment and is not commonly done. However, it may be useful for those instances where an important chemical of potential concern lacks an inhalation-derived toxicity value. Using this approach, the oral toxicity value is assumed to be the same as the inhalation toxicity value. This approach assumes that the route of exposure has no effect on the systemic toxicity seen once the chemical is absorbed into the body. This extrapolation method assumes that the health effects following exposure are not route specific, and that portal-of-entry effects (e.g., respiratory effects associated with inhalation exposure) are not the principal effects of concern. For example, the EPA recommends that the use of oral toxicity values is not appropriate for chemicals that are associated with respiratory tract irritation or sensitization.

If extrapolation from an oral toxicity value to an inhalation toxicity value is needed, careful review of the study used to derive the oral toxicity value should be performed to verify that the same assumptions are valid. If these assumptions are not valid for a specific chemical, then route-to-route extrapolation should not be performed.

In California, Cal-EPA has developed its own values for a number of chemicals which in several instances vary from EPA values. Information regarding California toxicity criteria can be found in *Guidance for the Evaluation and Mitigation of Subsurface Vapor Intrusion to Indoor Air* (DTSC 2005). These values are peer-reviewed and address both cancer and non-cancer effects. Validated Cal-EPA toxicity values are considered to meet the standards for Tier 3 toxicity values in the DoD hierarchy. RPMs should work with their toxicologists regarding their specific sites to select the most appropriate values for these sites.

One of the more important toxicology issues surrounding vapor intrusion risk assessments is selection of the toxicity criteria for TCE. The EPA withdrew its cancer toxicity value for TCE from the IRIS database in 1989 pending a reanalysis of the data. In 2001, EPA released a draft risk assessment for TCE that suggested that TCE was ten- to forty-fold more carcinogenic than previously thought. The draft risk assessment was submitted to the National Academy of Sciences (NAS) for review, and EPA is currently working to revise its 2001 draft risk assessment based on the 2006 NAS review comments. As a result, EPA does not currently have a validated toxicity value for TCE. Based on the DoD 2007 memo, it is DoD preference that the TCE toxicity value developed by Cal-EPA be used for TCE vapor intrusion risk assessments since it has been validated, peer-reviewed and meets the DoD and OSWER Tier 3 (“Other Toxicity Values”) criteria.

4.4 Risk Characterization

The risk characterization step combines analytical data, exposure information, and toxicity criteria in a series of calculations that results in numerical risk estimates for each chemical. Risks for carcinogens are presented as a probability estimate for cancer due to exposure to a chemical; this factor is often presented as “one in a million,” 1×10^{-6}, or 1E-06. These cancer risks estimates are called “excess lifetime cancer risks” and are solely associated with exposure to site-related chemicals. They are separate and distinct from “background” cancer incidence risks (essentially the lifetime risk of getting cancer from all causes), which are around 1 in 2 for males and 1 in 3 for females (American Cancer Society, 2006). Cancer risks for carcinogenic chemicals are typically added together for a cumulative risk estimate. Similarly, cancer risks for different pathways (e.g., vapor intrusion and soil ingestion) associated with the same chemical should be added together to yield the total cancer risk associated with site exposure.

Risks to carcinogenic chemicals can be evaluated using the following equation:

$$\text{Risk} = \text{Intake} \times \text{Toxicity factor}$$

Non-cancer hazards for individual chemicals are presented as a hazard quotient (HQ), which is essentially a ratio of the threshold level with the estimated exposure level (dose) to a particular chemical. HQs for different chemicals are typically added together, resulting in a cumulative hazard index (HI). Similarly, HIs for different pathways may also be summed for a total HI associated with exposure to site chemicals. An acceptable HQ or HI is typically 1- the site-related exposure should not exceed the level considered acceptable under the relevant statutory scheme under which the risk characterization is undertaken. If an HI exceeds 1, HQs for chemicals can be separated by target organ effects.

Risks for noncarcinogenic chemicals can be evaluated using the following equation:

$$HQ = \text{Intake}/\text{RfD}$$

An important component of the risk characterization step is identification of the primary uncertainties present in the risk assessment. Accounting for the uncertainties is important for the risk manager, to support defensible decision making. All four primary components of a vapor intrusion risk assessment have uncertainties associated with them, as discussed below.

The effectiveness of the data evaluation step is dependent primarily on the thoroughness of the sampling strategy at the site. Given that no site can be thoroughly sampled, it is always possible to miss an area or areas where chemicals are located, just as the area of maximum concentration may be missed. Similarly, it may not be possible to identify all subsurface preferential channels that can enhance vapor intrusion in a building. Selection of an EPC for the risk assessment should take into account these uncertainties. For most indoor air investigations there will not be a sufficient number of samples collected to calculate a 95 UCL. An alternate approach would be to evaluate risk for each sample collected, which would provide a more accurate evaluation of potential exposure than relying solely on the maximum detected concentration.

There are also a number of uncertainties in the exposure assessment. The standard default assumptions used by regulatory agencies are generally upper bound values (but not worst-case). These assumptions - particularly those related to exposure frequency and exposure duration - may not be appropriate or relevant to DoD personnel. For example, the standard default assumption that a resident will live for 30 years in the same house is likely to be an overestimate for most DoD personnel. Available information regarding military exposure profiles should be reviewed to determine the most appropriate assumptions.

The toxicity assessment has a number of inherent uncertainties associated with it. For many chemicals, toxicity values are derived from animal studies and extrapolated to humans. Testing protocols for animal studies may be very different than the exposure scenarios for humans. Extrapolation between exposure routes (oral to inhalation) may introduce uncertainties for those chemicals being evaluated. A number of uncertainty factors are also included in toxicity values for both carcinogens and noncarcinogens. In general, uncertainty factors (historically called “safety factors”) are not something that can be modified, as regulatory personnel will not allow this. As a result, the uncertainties associated with the toxicity assessment are fairly standard from one risk assessment to the next.

The risk characterization step provides the quantitative basis for risk management decision making. The NCP (40 CFR 300.430 (e)(2)(i)(A)(*2*)), states that ARARs will be used to establish remediation goals and, for known or suspected carcinogens, acceptable exposure levels are generally concentration levels that represent an excess upper bound lifetime cancer risk to an individual between 10^{-4} and 10^{-6} using information on the relationship between dose and response. The 10^{-6} risk level shall be used as the point of departure for determining remediation goals for alternatives when ARARs are not available or are not sufficiently protective because of the presence of multiple contaminants at a site or multiple pathways of exposure. The EPA 1991 memo “Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions” provides additional information for risk-based decision making at Superfund sites. Specifically, it clarifies that where the cumulative carcinogenic site risk to an individual based on RME for both current and future land use is less than 10^{-4}, and the non-carcinogenic HQ is less than 1, action generally is not warranted unless there are adverse environmental impacts.

4.5 Additional Risk-Related Issues

4.5.1 Petroleum Hydrocarbons

It is recommended that this Handbook not be used for evaluation of vapor intrusion associated with Subtitle 1 UST sites because petroleum hydrocarbons released from USTs are susceptible to natural attenuation and biodegradation. Since the J&E model does not account for degradation, modeling-based vapor intrusion risk assessments of petroleum hydrocarbon sites will often overestimate the long term exposure concentration, in turn overestimating the potential risk to receptors that may be present.

However, not all states concur with this position. The Cal-EPA requires that petroleum hydrocarbons at sites in California be evaluated for the possibility of vapor intrusion (DTSC, 2005). The Cal-EPA guidance acknowledges that while biodegradation may occur at many sites, there are locations where conditions will not support biodegradation. Its guidance recommends that two geochemical indicators of aerobic biodegradation—oxygen consumption and generation of carbon dioxide—be measured in soil gas to evaluate biodegradation. If biodegradation is occurring, oxygen levels would decrease and carbon dioxide levels would increase. Measurements made over time can be used to determine whether biodegradation of petroleum hydrocarbons is occurring. The appropriate regulators should be consulted prior to initiating a vapor intrusion study for petroleum hydrocarbons.

4.5.2 Regulation of Industrial Sites

Regulation and management of vapor intrusion and indoor air in an occupational setting has been identified as a concern by both EPA and OSHA. OSHA has authority under the Occupational Safety and Health Act, 29 U.S.C. 650, et seq., to regulate safety in the workplace for employees in many occupational settings. This includes exposure to chemicals in the workplace that may create indoor air health threats. OSHA and EPA have since 1990 conferred regarding the jurisdiction of each agency to protect persons exposed to indoor air contamination in the workplace. EPA’s authority arises under statutes such as CERCLA and RCRA that provide response oversight authority for environmental remediation and corrective action, which may include vapor intrusion into the indoor air of workplaces where OSHA has regulatory authority for worker health and safety. The two regulatory agencies have not established protocols or a clear separation of authority for workplaces where both workplace chemical exposure and vapor intrusion as a result of environmental releases from sources external to the work location have occurred. When situations arise at DoD response sites where this overlapping authority may affect project decisions, DoD or Component legal counsel or occupational safety and health offices should be consulted to determine the applicable requirements.

The acceptable OSHA Permissible Exposure Limits (PELs) are the maximum concentration of a chemical in air that a worker may be exposed to without respiratory protection. OSHA PELs are typically two to three orders of magnitude higher than EPA’s more restrictive risk-based screening values. At DoD facilities, OSHA standards will be considered in workplace settings where chemicals are used, in accordance with Service occupational safety regulations and policy. For workplace settings where vapor intrusion is being evaluated as part of a DoD response action as a result of releases to the environment, risk assessments that consider the indoor air exposure pathways should recognize any background concentrations for commercial or industrial settings as appropriate to the specific workplace and exclude them from the calculation of risk and use relevant non-residential exposure assumptions for the assessment of risk from the vapor intrusion sources of indoor air contamination.

5 Risk Management at Vapor Intrusion Sites

The risk management phase of a vapor intrusion study should be based on the results of the risk assessment and other relevant information needed to make informed site management decisions. The risk assessment establishes whether an unacceptable risk is present (or may be present in the future) and identifies chemicals and pathways associated with that risk. In risk management, the results of the risk assessment are integrated with other considerations, such as economic or legal concerns, to reach decisions regarding the need to conduct a remedial action at a site or to implement other risk reduction activities. Additional factors—such as regulatory requirements, technical implementability, and public acceptance—must also be considered when making risk management decisions.

Risk management is not necessarily a single option (agency personnel often use it to mean "remediation"), but rather it is a range of options that can be selectively applied to manage risk in response to the site-specific needs. For example, risks associated with workers in a hypothetical future building can be managed through land-use controls (do not build on the site without appropriate construction techniques); while risks associated with current and ongoing exposures may justify direct action (subsurface remediation, ventilation improvements). This section describes various risk management options, the pros and cons of each option, and the requirements to implement them.

An important distinction needs to be made between remediation and mitigation as used in this handbook. Although they are different concepts, many people use these terms interchangeably. Remediation herein refers to the treatment, removal, and reduction in the amount of contaminants present at a site. Examples of remediation include soil vapor extraction and groundwater pump and treat systems. Mitigation means the measures taken to minimize or reduce exposure. Mitigation, by itself, does not have any direct effect on the contaminant source area although it may be a component of a remedy. Examples of mitigation include sealing of a floor, sub-slab depressurization devices, or increased ventilation of a dwelling. This section discusses both mitigation and remediation measures that can be used at vapor intrusion sites.

5.1 Risk Management for Acute Risks

Acute risk scenarios may be identified in a variety of ways: by the obvious presence of a spill or release, the presence of odors, or high measured levels of chemicals that exceed either an acute exposure criteria or the lower explosive limit (LEL). These scenarios may pose an acute threat to human health; in some cases, actual effects may be observed — the most common symptoms include nausea, headaches, and dizziness. It may not be necessary (or possible) to fully quantify the magnitude of the acute risk, but often the situation is fairly noticeable. The RPM should contact health officials in his or her respective Service branch to determine the best course of action. Health-based acute risk exposure values are not available for all exposure scenarios; acute exposure levels for most chemicals are only available for occupational exposures.

Acute risk from vapor intrusion may require a rapid response to minimize exposure or risk to human health. Possible responses for acute risk include vacating the premises to eliminate exposure or providing additional ventilation. This action is especially important when potentially explosive gases are present, such as petroleum hydrocarbons or methane. For acute risk situations from vapor intrusion, the local fire department, health department, or other regulatory authorities should be alerted regarding the possibility of explosive hazards.

5.2 Risk Management for Chronic Risks

A risk management strategy should be developed if the risk assessment indicates that chronic risks are unacceptable. There are a number of options for reducing chronic exposure to vapors, ranging from groundwater and soil remediation to mitigating building parameters. This section outlines some standard remediation and mitigation options used to reduce long-term exposure. Appendix I describes a number of air-flow mitigation measures that can be implemented at buildings with high levels of risk.

The MassDEP indoor air guidance document (2002) listed several remediation and mitigation options for reducing risk from vapor intrusion. The mitigation options include:

- **Sealing cracks/annular spaces around utilities and where the floor meets the wall, and/or cracks in basement floor:** This is done using epoxy-based sealants that are impenetrable to vapors. Although this approach may help in reducing the flux rate at specific locations, it may not be adequate to eliminate intrusion over a large slab.
- **Sealing and venting groundwater sumps:** Many buildings with basements have sumps that are intended to capture any unexpected water release (flooding, burst hose, etc.). These sumps are dug into the ground below the level of the rest of the foundation and may serve as an easy access point for vapors. Sealing and venting them will allow them to maintain their function while preventing vapor intrusion.
- **Vapor barriers beneath the building:** Vapor barriers can be plastic or geotextile sheeting or can be a sealant that is applied directly to the foundation or basement wall. Barriers are more easily installed during construction of a building than during a retrofit. This technique is often used in conjunction with active mitigation systems at sites with known contamination. Damage to even a small portion of the barrier during installation can result in significant leakage across the barrier.
- **Reducing basement depressurization by ducting in outside air for furnace combustion:** By bringing outside air into the furnace, this approach decreases the pressure differential across the slab. Lowering the pressure in the basement lessens the pull on subsurface vapors.
- **Overpressurization of the building using air/air heat exchangers:** This technique creates a positive pressure within the building by supplying more outdoor air to the inside than the amount of air exhausted. To work effectively, buildings should be tightly sealed and have a ventilation system capable of producing the output needed to maintain the pressure differential.
- **Passive or active sub-slab depressurization systems:** This technique relies on formation of a vacuum that is created beneath the building foundation; this vacuum is greater in strength than the pressure differential that exists between the building and the soil. Low-pressure zones that are created beneath the slab reverse the flow direction, so air is drawn from inside the building and into the soil, thus preventing vapors from migrating into the structure. Passive and active systems are very similar in design; the only real difference is inclusion of a powered fan to create a low-pressure zone for the

active system. A passive depressurization system may not be particularly effective because it lacks any means of actively moving vapors and instead relies on natural thermal and wind effects to move the soil gas from the collection zone and to the external vent.

Some of the advantages and disadvantages associated with sub-slab depressurization systems are shown in Table 5-1.

Table 5-1 Advantages and Disadvantages of Sub-Slab Depressurization Systems

Advantages	Disadvantages
Successful track record of performance, 90%-99% reductions typical, 99.5% or greater reduction possible with well-designed system	Requires periodic maintenance; active systems require power hookups
Adaptable technology, applicable to a wide variety of site conditions and geology	Wet and low-permeability soils retard soil gas movement
Simple gauges or flowmeters show whether the system is working	Building-specific conditions may limit options for suction pit, riser pipe, and fan locations

From ITRC (2007a)

These mitigation techniques may be used individually or they may be used in combination to form a more comprehensive plan.

Remediation options include the following:

- **Groundwater treatment:** This can be active (pump-and-treat) or passive (permeable reactive barrier wall). Groundwater treatment is one of the most common remediation strategies at vapor intrusion sites because contaminated groundwater is often the source of soil gas and indoor air contamination. Active treatment pumps groundwater to the surface where it is treated by a variety of techniques (e.g., carbon, ozone) that remove or destroy the contaminant. Other treatments involve injection of material (such as permanganate) into the groundwater to destroy the contamination or the construction of subsurface barrier walls that the water passes through. Given the right design, the material in the barrier wall (e.g., iron filings) will chemically destroy the contaminant without having to remove the groundwater.
- **Soil excavation and removal:** This option can be very effective in reducing the mass of contaminant at a site with a surface or shallow subsurface release. The older or deeper the release, the further contamination will spread; as a result, soil removal will be less effective.
- **Soil vapor extraction:** For this option, a series of perforated pipes are installed underground adjacent to the contamination. A pump is connected to the pipes, and suction is established. Contaminants in the soil gas are then collected in carbon filters and disposed of. This technique can be effective in reducing the concentration of contamination in specific areas, but it will not address the typical source of contamination (groundwater).
- **Monitored natural attenuation:** This technique essentially consists of allowing contaminants to degrade on their own. Samples are taken periodically to monitor the rate

of degradation. Monitored natural attenuation does not involve the addition of any amendments or supplements as part of this remedy.

- **Enhanced bioremediation:** For this remedy, various amendments or supplements may be introduced into the groundwater as a nutrient source for naturally occurring microorganisms. These amendments allow the microorganisms to degrade the chemicals in the groundwater at a faster rate than they would without them.

Removing the source of vapors is often the preferred remediation strategy at vapor intrusion sites. These different approaches will have variable effects on the contaminant concentration in soil gas. Soil removal and soil vapor extraction may have the most substantial short-term effects either by eliminating the source of contamination (removal) or by intercepting the contaminated soil gas and partially or completely cutting off the pathway. Groundwater remediation is a long-term option that could take years or decades before cleanup goals are met.

It may be necessary to implement both a remediation and a mitigation strategy at a particular site. For example, the risks may be high enough at a building that is currently occupied that some kind of mitigation measure is needed immediately to reduce exposure. However, since mitigation does not affect the source concentration, a remediation strategy may also need to be implemented so that the source mass and long-term risks can be reduced.

Possible impacts of remedial alternatives on vapor intrusion should also be considered. Certain groundwater remedies may change the chemical conditions of the subsurface, which may in turn increase the possibility of vapor intrusion. For example, enhanced bioremediation remedies typically involve the injection of an organic carbon substrate which induces biodegradation of parent compounds such as PCE and TCE. This may in turn result in elevated concentrations of the metabolites dichloroethylene and vinyl chloride, which have more stringent risk screening levels than their parent compounds. These possibilities should be considered as part of risk management project planning.

There are alternate risk management strategies that rely on land-use and building-use controls more than remediation or mitigation. For example, DoD can choose to not use a particular building or direct use for activities that would reduce exposure time, or require the use of protective measure that would reduce actual human exposure, if vapor intrusion risks to the occupants are too high. Similarly, it can choose not to develop property that is located over a contaminant plume, thus avoiding indoor air problems from vapor intrusion. Land use controls are common tools for limiting access and/or development at a site. Land use controls may be applied at undeveloped sites or sites where land use may change in the future. Land use controls may be necessary to assure that the vapor intrusion pathway is effectively addressed in the future. Land use controls may include requirements to install engineering controls on buildings to mitigate potential pathways. Land use controls may also be used to limit certain kinds of land use (such as residential use) that might be associated with unacceptable health risks. For land that does not currently contain any enclosed structures and where new construction for occupancy could generate a potential unacceptable vapor intrusion risk, DoD Components should provide notice to new owners or operators providing information on the potential for unacceptable risk and outlining the owner/operator's options either for evaluating risk or undertaking mitigation measures in building construction. This is necessary to avoid model derived criteria becoming enforceable by being recorded in a decision document. The disadvantages of land use controls include potential issues concerning long-term reliability (particularly if property ownership changes) and determining or documenting the continued effectiveness of controls. For example, engineering controls that are implemented as a part of land use controls require operations and maintenance (O&M) to retain their effectiveness.

5.3 Planning an Exit Strategy

An important component of a vapor intrusion study is development of an exit strategy. In this context, an exit strategy is used to mean a plan for reducing risk from vapor intrusion to a level where no further mitigation or monitoring is needed. When this status is achieved, the site will no longer require active management. The exit strategy should clearly identify what criteria will be used to determine that the site no longer poses an unacceptable vapor intrusion risk. This strategy should be developed early in a vapor intrusion project, so as to provide a defined criteria for when risks at a site or building have been adequately mitigated or controlled and focus project efforts and expenditures on achieving this goal. Factors such as mitigation and/or remediation techniques, final cleanup goals, land use, and possibly future building construction, should be considered for the exit strategy.

RPMs and their consultants are encouraged to consider future improvements in modeling and assessment methods in the exit strategy and allow for refinement of goals as appropriate. For example, if remedial action objectives for groundwater are developed using a vapor intrusion model, care should be taken to define criteria in the remedial action objective that can later objectively be satisfied. This is necessary to avoid model derived criteria becoming enforceable by being recorded in a decision document. In such cases where the basis of remediation goals is highly uncertain, it is preferable to define them as concentrations that we seek to achieve and make clear that when appropriate, they should be revisited to reduce uncertainty as models and other technology improve. This exit strategy should be memorialized in a formal decision document with specific, reasonable and achievable outcomes defined in the response action decision document.

6 Risk Communication

An important yet often overlooked component of vapor intrusion projects is communicating potential risks with building occupants as well as with regulatory agencies. Vapor intrusion is an unfamiliar concept to most people and there is great potential for alarm, fear and/or outrage. Because of the unfamiliarity, lack of control over the potential risk, and lack of any benefit from the exposure, there is likely to be a high perception of risk no matter what the numbers say. Sampling for a vapor intrusion study and remedial response actions can be invasive to building occupants because they can involve drilling through floors, the presence of obtrusive equipment (e.g., noisy samplers), and excavation. These situations and activities have great potential to alarm building occupants who may be concerned about their health and/or property values. Additionally, because vapor intrusion issues occur indoors where people work and live, their input, understanding and cooperation can significantly impact assessment or mitigation activities.

The success of the project may well depend on early and effective communication with all interested parties. It is very important to be aware of the risk communication challenges and to apply risk communication practices and principles throughout a project. This section presents a brief discussion about what risk communication is, how it fits in with vapor intrusion investigations (or any environmental investigation) and some basic guidance on how to communicate risk.

Effective risk communication is based on building, maintaining, and repairing relationships with stakeholders that impact your mission. A stakeholder is any individual or group that has an interest in or could be impacted by a specific issue or activity. In the context of a DoD vapor intrusion study, the most common stakeholders include the service branch, EPA and local regulator authority, the building occupants and possibly offsite residents or workers, media, and environmental advocacy groups. The most common concerns of stakeholders at vapor intrusion sites relate to possible health impacts, real estate values, groundwater contamination issues, and the noise and impacts from remediation efforts.

Early stakeholder involvement is critical. Too often, risk communication is seen as something that takes place only at the end of a project after all the important decisions have been made. This approach often negatively impacts the mission because people are outraged that they haven’t been informed early on in the project and it can lead to rejection of the solution. An example of this could be telling residents during a meeting that TCE had been detected in the groundwater below their houses; DoD had investigated the situation and determined that vapor intrusion was not a concern and they were not going to do anything else. If the stakeholders were not involved, or at least informed, of the steps leading up to this conclusion, there is a high possibility that they will not only reject the study conclusions and that DoD officials will lose trust and credibility in the process. Such a scenario may lead to protracted arguments and discussion about what was done at the site, what the results mean, the path forward and finding someone the stakeholders will trust and believe. Involving stakeholders early and often is a much better way to execute a successful project.

While challenging, effective risk communication can be achieved through knowledge and use of risk communication principles and skills. Risk communication is not public speaking nor “spinning” or embellishing messages. It requires being open, honest, genuine, and sincere and applying good communication skills (verbal and nonverbal) in a variety of situations. It also requires an ongoing commitment for practice and preparation. There are multiple benefits that can be achieved by using risk communication principles:

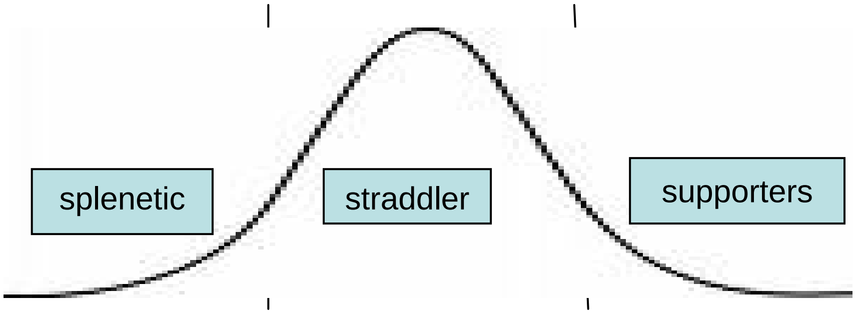
- Better project management and reduced expense
- Improved relationships with stakeholders, which can result in increased/maintained trust
- Better risk management decisions because of buy-in by various parties
- Improved public perception
- Fewer legal challenges when public involvement requirements have been satisfied
- Better experience with the media.

Getting stakeholder involvement and participation can be a challenging process. At most DoD bases or posts, the RPM often has to brief audiences on environmental projects. Given the nature of vapor intrusion and the potentially invasive nature of sampling, informing the public is critical. DoD RPMs should have training in effective risk communication.

Principles of Risk Communication

A. Identify stakeholders that impact your mission, favorably (supporters), neutrally (straddlers) or unfavorably (splenetics.) See curve below.

The *splenetics* are at the left end of the curve and immoveable – their minds are made up. They oppose you and will have no interest in finding common ground. Generally there are not a large number of individuals or groups at that left end of the curve. People/groups on the right end of the curve are your *supporters* – people who agree with your position. Most stakeholders are somewhere in the middle and are called *straddlers*. Their minds are not made up; they are open to more information and finding common ground.



There are different strategies for each stakeholder group:

- For supporters, the primary mission is to maintain the relationship. Keep them informed and keep up the two-way dialogue. Ask them for advice, ideas, other stakeholders to contact, etc.
- For straddlers, the mission is to recognize that this may be your most important stakeholder group and your goal is to move them towards a more supportive position on the bottom axis.

- For splenetics, recognize that they will NOT be supportive so your strategy is not to try to influence them to support you – this is very unlikely to happen. The goal for working with splenetics is to show good faith (provide information, listen to them, and invite them to your meetings) with the goal of influencing the straddlers. Good faith does not mean permitting splenetics to do what they want; let them disrupt your meetings, etc. It does mean demonstrating willingness for discussion.

B. Determine the underling motivation:

- Emotions (anger, disgust, irritation, fear)
- Agendas (personal, political, economic, social, historical or cultural)
- Risk Perception (people think it is riskier than it is or less risky than it is).

C. Utilize third party supporters:

A third party supporter is a stakeholder who is trusted and seen as knowledgeable by the straddlers. Third party supporters can help in many different ways, from formal or informal support, or providing you with background or suggestions on approaches.

For internal communication, third party supporters are frequently lower in the hierarchical chain of the organization. Regulators can also be effective third party supporters as can local health officials. In any case, it would be someone who is respected and ideally has extensive experience in the organization and with the community. Third party supporters often are good sources for identifying additional supporters. Because contractors are paid for their work, they are usually not perceived as good third party supporters.

D. Get in front of issues;

- Tell people what you do know
- Tell them what you don’t know
- Update them as you learn more
- Talk to your stakeholders early and often.

Getting in front of issues rapidly is critical for successful risk communication. The longer an organization takes to provide information, the more difficult it is to overcome erroneous information. Don’t wait to get all your facts. Instead, provide what you do know with the assurance that more information will be provided as it comes available. The longer the delay associated with “getting out” the story/facts, the more the perception of hiding and covering up grows.

E. Ensure all communicators are properly trained.

F. Learn the media communication process and build professional relationships with the media. The public affairs office should be able to provide extensive assistance with this.

G. Maintain flexibility in the communication planning process. Recognize that change is inevitable.

The Navy, Army and Air Force all have risk communication recourses available to assist with vapor intrusion investigations or other environmental issues.

Air Force School of Aerospace Medicine, Occupational and Environmental Health (OEHTH), Brooks City-Base, San Antonio, TX. http://www.brooks.af.mil/units/usafsam/index.asp Navy and Marine Corps Public Health Center, Environmental Programs Department, Portsmouth, VA. http://www-nehc.med.navy.mil

U.S. Army Center for Health Promotion and Preventive Medicine, Risk Communication Branch, Aberdeen, MD. http://chppm-www.apgea.army.mil/risk/

7 Summary and Recommendations

This Handbook provides a general framework for conducting vapor intrusion investigations under the DERP and discusses various technical approaches associated with evaluating the vapor intrusion pathway. It includes information and references to the most current knowledge that exists relative to vapor intrusion at the time it was prepared. Since the state of the science relative to vapor intrusion is rapidly evolving, readers are encouraged to balance the information contained herein with the most current technical information available

Overall the current “state of the science” approach is to collect and evaluate multiple lines of evidence to support decision making regarding the vapor intrusion pathway. As mentioned in this document, there are many possible lines of evidence that can be used to determine if a vapor intrusion pathway is complete and if so at a level that could result in unacceptable risks to receptors. It is unlikely that all of the possible lines of evidence will need to be evaluated in order to investigate the vapor intrusion pathway. More often than not, the lines of evidence considered will include existing information along with datasets identified by the project team to answer the project-specific DQOs.

A screening level assessment can provide an initial understanding of the level of possible risk posed by the vapor intrusion pathway in an efficient and cost-effective manner. Screening includes the initial development of a Conceptual Site Model, and Data Quality Objectives, and use of conservative screening concentrations. The collection and evaluation of indoor air data at this point should be conducted with caution. The results of this conservative evaluation should be considered to be indicative of potential site risk rather than an accurate predictor of risk. The screening level assessment is typically used to distinguish between sites or buildings that pose little or no vapor intrusion risk and those with potential risk that require further study.

The first step of a site-specific vapor intrusion study is to determine the regulations which govern the conduct of response actions at the site, as well as those that may be appropriate to consider. Generally DERP hazardous substance response actions are conducted under CERCLA or RCRA. It is recommended that site-specific investigation documents be prepared and include a work plan. The multiple lines of evidence approach is currently considered an appropriate strategy for investigating potential vapor intrusion. This may include groundwater, soil gas, near-slab, sub-slab soil gas, or indoor air samples. Predictive modeling or calculation of indoor air with predetermined attenuation factors may also be considered as lines of evidence. It is unlikely that all of the possible lines of evidence will need to be evaluated in order to investigate the vapor intrusion pathway. More often than not, the lines of evidence considered will include existing information along with datasets identified by the project team to answer the project-specific DQOs.

If the investigation concludes that the vapor intrusion pathway is complete, the data collected will often be used in a health risk assessment to evaluate if the exposure pathway could pose an unacceptable risk. This Handbook discusses toxicity information and specific DoD exposure parameters that are recommended for use in the assessment of risk from vapor intrusion. As with any human health risk assessment, an important component of the risk characterization step is identification of the primary uncertainties present in the risk assessment. Accounting for the uncertainties is important for the risk manager, to support defensible decision making.

Readers are encouraged to be aware of the regulatory jurisdiction of evaluating health effects from vapor intrusion pursuant to occupational (i.e. OSHA) vs. environmental (EPA authority). Mitigation and other risk management options need to be evaluated against the factors that affect the best decisions for the DoD and should include an exit strategy.

Risk communication is an important aspect of vapor intrusion projects, and should not be overlooked. The success of the project may well depend on early and effective communication with all stakeholders.

Overall, the following strategic considerations are recommended:

- Undertake appropriate planning to assess vapor intrusion including assistance and input from other disciplines.
- Work with legal counsel to identify the relevant regulations which govern the conduct of response actions at the site.
- Determine whether migration of volatile subsurface contaminants to indoor air is occurring as a result of a complete exposure pathway, not just whether contaminants of concern are present in indoor air.
- Assess as many lines of evidence as appropriate to evaluate potential vapor intrusion in light of the inherent variability and uncertainty with any one line of evidence.
- To the extent practical, collect and use site specific information and data to avoid the use of conservative default values when performing fate and transport modeling to assess risk.
- Be aware of the limitations and impact of collecting and using indoor air samples.
- Be prepared to respond to requests to reassess the vapor intrusion pathway at sites, including closed or previously determined no further action sites, etc.
- Carefully consider all mitigation and remedial options in light of DERP guidance.
- Prepare, plan for the use of, and use risk communication.

8 Additional Technical Resources

There are numerous additional resources that can be consulted to provide more detail on a specific topic related to vapor intrusion. This section lists a number of these resources, but the list is not exhaustive. Additional material on vapor intrusion is being published on a regular basis by EPA, state health agencies, and various experts in the field.

As previously noted in this document, both knowledge about vapor intrusion and guidance to assess the vapor intrusion pathway is evolving. The DoD project team should check for new Federal or state guidance as they work on these projects and evaluate whether the available guidance is technically reliable and useful to DoD. It is recommended that the reader check the web site for the state regulatory agency managing the site of interest to see what information might be available.

Several organizations have compiled lists of different websites that contain information on the assessment of the vapor intrusion pathway. (Note: the listing of a company does not constitute endorsement by the DoD.)

- Envirogroup, Ltd. maintains a list that is searchable both by state and by topic. This list can be viewed at http://www.envirogroup.com/links.php.
- H&P Mobile Geochemistry maintains a website that contains a number of reports on vapor intrusion and indoor air. These articles can be found at http://www.handpmg.com/.
- The American Petroleum Institute (API) funds and manages studies of petroleum products, and is active in developing sampling and analysis techniques for vapor intrusion projects. More information can be found at www.api.org.

The ITRC finalized its set of vapor intrusion documents in January 2007 using the collective input of a number of national experts from state and federal agencies, industry, and the consulting field. The guidance and its companion document can be found on the ITRC website at http://www.itrcweb.org/gd_VI.asp. In addition, ITRC offers training in the assessment of the vapor intrusion pathway. Details regarding this training may be obtained from their website.

The ITRC companion document (2007b) contains six example scenarios along with a logical, flexible framework, a variety of tools and remedial approaches, and the practical rationale for developing an investigative strategy for assessing vapor intrusion. This document and its associated scenarios are described here because several of them will have direct relevance to many DoD sites and bases. A review of the approaches and assumptions made by ITRC could streamline investigation and mitigation efforts at similar sites.

These six scenarios are:

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

Bibliography

***Note**: This bibliography contains writings cited in this document, as well as other reports and guidance that will be of use to DoD RPMs.*

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Appendix A: Chemicals that are Sufficiently Volatile and Toxic

Table A-1 lists chemicals that may be found at hazardous waste sites that are sufficiently volatile and toxic to be considered as presenting potential vapor intrusion risk. Sufficiently volatile is defined as having a Henry's Law Constant greater than 10^{-5} atm m^3/mol. A chemical is considered sufficiently toxic if its pure component vapor concentration results in an incremental lifetime cancer risk greater than 10^{-6} or a non-cancer hazard index greater than 1 (in some cases both). Meeting these two criteria is an initial indicator that a given chemical in the subsurface may present potentially unacceptable indoor air inhalation risks when complete exposure pathways exist. The approach used to develop Table A-1 is similar to the method used to develop the table documented in Appendix D of EPA's 2002 *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils*.

Appendix B of this Handbook provides all the information considered to compile the information summarized in Table A-1. The calculations should be revisited for a given chemical in the event of new or revised toxicity values.

Table A-1: Chemical-Specific Toxicity and Volatility Assessment

Analyte	CAS No.	Sufficiently Volatile?	Sufficiently Toxic?
Acetaldehyde	75-07-0	YES	YES
Acetone	67-64-1	YES	YES
Acetonitrile	75-05-8	YES	YES
Acetophenone	98-86-2	YES	NA
Acrolein	107-02-8	YES	YES
Acrylonitrile	107-13-1	YES	YES
Aldrin	309-00-2	YES	YES
Ammonium Perchlorate	7790-98-9	NA	NA
Aniline	62-53-3	YES	YES
Benzaldehyde	100-52-7	YES	NA
Benzene	71-43-2	YES	YES
Benzoic Acid	65-85-0	NO	NA
Benzyl Alcohol	100-51-6	YES	NA
Benzyl Chloride	100-44-7	YES	YES
Biphenyl, 1,1'-	92-52-4	YES	NA
Bis(2-chloroethyl)ether	111-44-4	YES	YES
Bis(2-chloro-1-methylethyl) ether	108-60-1	YES	YES
Bis(2-ethylhexyl)phthalate	117-81-7	YES	NA
Bis(chloromethyl)ether	542-88-1	YES	YES
Bromodichloromethane	75-27-4	YES	NA
Bromoform	75-25-2	YES	YES
Bromomethane	74-83-9	YES	YES
Butadiene, 1,3-	106-99-0	YES	YES
Butanol, N-	71-36-3	YES	NA
Butyl Benzyl Phthlate	85-68-7	YES	NA
Carbon Disulfide	75-15-0	YES	YES
Carbon Tetrachloride	56-23-5	YES	YES
Chlordane	12789-03-6	YES	YES
Chloro-1,3-butadiene, 2-	126-99-8	YES	YES

Chloroaniline, p-	106-47-8	YES	NA
Chlorobenzene	108-90-7	YES	YES
Chlorobutane, 1-	109-69-3	YES	NA
Chlorodifluoromethane	75-45-6	YES	YES
Chloroform	67-66-3	YES	YES
Chloromethane	74-87-3	YES	YES
Chloronaphthalene, Beta-	91-58-7	YES	NA
Chlorophenol, 2-	95-57-8	YES	NA
Cresol, m-	108-39-4	YES	NA
Cresol, o-	95-48-7	YES	NA
Cresol, p-	106-44-5	YES	NA
Crotonaldehyde, trans-	123-73-9	YES	NA
Cumene	98-82-8	YES	YES
Hydrogen Cyanide	74-90-8	YES	YES
DDD	72-54-8	YES	NA
DDE, p,p'-	72-55-9	YES	NA
DDT	50-29-3	YES	YES
Dibromo-3-chloropropane, 1,2-	96-12-8	YES	YES
Dibromoethane, 1,2-	106-93-4	YES	YES
Dibromomethane (Methylene Bromide)	74-95-3	YES	NA
Dibutyl Phthalate	84-74-2	YES	NA
Dichlorobenzene, 1,2-	95-50-1	YES	YES
Dichlorobenzene, 1,4-	106-46-7	YES	YES
Dichlorobenzidine, 3,3'-	91-94-1	NO	NA
Dichlorodifluoromethane	75-71-8	YES	YES
Dichloroethane, 1,1-	75-34-3	YES	YES
Dichloroethane, 1,2-	107-06-2	YES	YES
Dichloroethylene, 1,1-	75-35-4	YES	YES
Dichloroethylene, 1,2- (Mixed Isomers)	540-59-0	YES	NA
Dichloroethylene, 1,2-cis-	156-59-2	YES	NA
Dichloroethylene, 1,2-trans-	156-60-5	YES	YES
Dichlorophenol, 2,4-	120-83-2	YES	NA
Dichloropropane, 1,2-	78-87-5	YES	YES
Dichloropropene, 1,3-	542-75-6	YES	YES
Dieldrin	60-57-1	YES	YES
Diethyl Phthalate	84-66-2	YES	NA
Dimethylphenol, 2,4-	105-67-9	YES	NA
Dinitro-o-cresol, 4,6-	534-52-1	YES	NA
Dinitrophenol, 2,4-	51-28-5	NO	NA
Dinitrotoluene Mixture, 2,4/2,6-	25321-14-6	YES	NA
Dinitrotoluene, 2,4-	121-14-2	NO	NA
Dinitrotoluene, 2,6-	606-20-2	YES	NA
Dinitrotoluene, 2-Amino-4,6-	35572-78-2	NO	NA
Dinitrotoluene, 4-Amino-2,6-	19406-51-0	NO	NA
Endosulfan	115-29-7	YES	NA
Endrin	72-20-8	YES	NA
Epichlorohydrin	106-89-8	YES	YES
Ethyl Acetate	141-78-6	YES	NA
Ethyl Chloride	75-00-3	YES	YES
Ethyl Ether	60-29-7	YES	NA
Ethyl Methacrylate	97-63-2	YES	NA
Ethylbenzene	100-41-4	YES	YES
Ethylene Oxide	75-21-8	YES	YES

Formaldehyde	50-00-0	YES	YES
Furan	110-00-9	YES	NA
Heptachlor	76-44-8	YES	YES
Heptachlor Epoxide	1024-57-3	YES	YES
Hexachlorobenzene	118-74-1	YES	YES
Hexachlorobutadiene	87-68-3	YES	YES
Hexachlorocyclohexane, Alpha-	319-84-6	YES	YES
Hexachlorocyclohexane, Beta-	319-85-7	YES	YES
Hexachlorocyclohexane, Gamma- (Lindane)	58-89-9	YES	YES
Hexachlorocyclohexane, Technical	608-73-1	YES	YES
Hexachlorocyclopentadiene	77-47-4	YES	YES
Hexachloroethane	67-72-1	YES	YES
Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX)	121-82-4	NO	NA
Hexane, N-	110-54-3	YES	YES
Hydrazine	302-01-2	NA	NA
Isobutyl Alcohol	78-83-1	YES	NA
Isophorone	78-59-1	YES	YES
Lead Compounds		NA	NA
Lead and Compounds	7439-92-1	NA	NA
Tetraethyl Lead	78-00-2	YES	NA
Methacrylonitrile	126-98-7	YES	YES
Methoxychlor	72-43-5	NO	NA
Methyl Acetate	79-20-9	YES	NA
Methyl Acrylate	96-33-3	YES	NA
Methyl Ethyl Ketone (2-Butanone)	78-93-3	YES	YES
Methyl Isobutyl Ketone (4-methyl-2-pentanone)	108-10-1	YES	YES
Methyl Methacrylate	80-62-6	YES	YES
Methyl tert-Butyl Ether (MTBE)	1634-04-4	YES	YES
Methylene Chloride	75-09-2	YES	YES
Mercury Compounds		NA	NA
Mercuric Chloride	7487-94-7	NA	NA
Mercuric Sulfide	1344-48-5	NA	NA
Mercury (elemental)	7439-97-6	YES	YES
Mercury, Inorganic Salts	NA	NA	NA
Methyl Mercury	22967-92-6	NA	NA
Nitrobenzene	98-95-3	YES	YES
Nitroglycerin	55-63-0	NO	NA
Nitroguanidine	556-88-7	NO	NA
Nitropropane, 2-	79-46-9	YES	YES
Nitroso-di-N-butylamine, N-	924-16-3	YES	YES
Nitroso-di-N-propylamine, N-	621-64-7	YES	NA
Nitrosodiphenylamine, N-	86-30-6	YES	NA
Nitrotoluene, m-	99-08-1	YES	NA
Nitrotoluene, o-	88-72-2	YES	NA
Nitrotoluene, p-	99-99-0	YES	NA
Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetra (HMX)	2691-41-0	NO	NA
Pentachlorophenol	87-86-5	NO	NA
Pentaerythritol tetranitrate (PETN)	78-11-5	NO	NA
Perchlorate and Perchlorate Salts	14797-73-0	NA	NA
Phenol	108-95-2	YES	YES
Phosgene	75-44-5	YES	YES
Picramic Acid (2-Amino-4,6-dinitrophenol)	96-91-3	NO	NA
Pyridine	110-86-1	YES	NA

Acenaphthene	83-32-9	YES	NA
Anthracene	120-12-7	YES	NA
Benz[a]anthracene	56-55-3	YES	YES
Benzo[a]pyrene	50-32-8	YES	YES
Benzo[b]fluoranthene	205-99-2	YES	YES
Benzo[k]fluoranthene	207-08-9	YES	YES
Chrysene	218-01-9	YES	YES
Dibenz[a,h]anthracene	53-70-3	NO	YES
Fluoranthene	206-44-0	YES	NA
Fluorene	86-73-7	YES	NA
Indeno[1,2,3-cd]pyrene	193-39-5	YES	NO
Methylnaphthalene, 1-	90-12-0	YES	NA
Methylnaphthalene, 2-	91-57-6	YES	NA
Naphthalene	91-20-3	YES	YES
Pyrene	129-00-0	YES	NA
Styrene	100-42-5	YES	YES
Tetrachloroethane, 1,1,1,2-	630-20-6	YES	YES
Tetrachloroethane, 1,1,2,2-	79-34-5	YES	YES
Tetrachloroethylene	127-18-4	YES	YES
Tetryl (Trinitrophenylmethylnitramine)	479-45-8	NO	NA
Toluene	108-88-3	YES	YES
Toxaphene	8001-35-2	YES	YES
Trichloro-1,2,2-trifluoroethane, 1,1,2-	76-13-1	YES	YES
Trichlorobenzene, 1,2,4-	120-82-1	YES	YES
Trichloroethane, 1,1,1-	71-55-6	YES	YES
Trichloroethane, 1,1,2-	79-00-5	YES	YES
Trichloroethylene	79-01-6	YES	YES
Trichlorofluoromethane	75-69-4	YES	YES
Trichlorophenol, 2,4,5-	95-95-4	YES	NA
Trichlorophenol, 2,4,6-	88-06-2	YES	YES
Trichloropropane, 1,1,2-	598-77-6	YES	NA
Trichloropropane, 1,2,3-	96-18-4	YES	NA
Trichloropropene, 1,2,3-	96-19-5	YES	YES
Trimethylbenzene, 1,2,4-	95-63-6	YES	YES
Trimethylbenzene, 1,3,5-	108-67-8	YES	YES
Trinitrobenzene, 1,3,5-	99-35-4	NO	NA
Trinitrotoluene, 2,4,6-	118-96-7	YES	NA
Vinyl Acetate	108-05-4	YES	YES
Vinyl Chloride	75-01-4	YES	YES
Xylene, Mixture	1330-20-7	YES	YES
Xylene, P-	106-42-3	YES	YES
Xylene, m-	108-38-3	YES	YES
Xylene, o-	95-47-6	YES	YES

Appendix B: Identification of Chemicals that are Sufficiently Volatile and Toxic

Table B-1 shows the information considered to determine if chemicals that may be found at U.S. Department of Defense (DoD) and hazardous waste sites are sufficiently volatile and toxic and therefore may need to be considered for the vapor intrusion pathway. The table also includes data for a broad list of chemicals not listed in Appendix A, this information is provided to ensure transparency and that reevaluation could be conducted if and when new data becomes available.

Chemicals were considered sufficiently volatile if the United States Environmental Protection Agency (EPA's) **"Regional Screening Levels for Chemical Contaminants at Superfund Sites",** dated 12 SEP 2008 reported a Henry's Law Constant greater than 1×10^{-5} atm m^3/mol.

Chemicals were considered sufficiently toxic if the pure component vapor concentration was greater than the risk-based screening concentration for residential air provided in EPA's **"Regional Screening Levels for Chemical Contaminants at Superfund Sites"[1],** dated 12 SEP 2008. The risk-based screening levels are based on an incremental lifetime cancer risk greater than 1×10^{-6} or a non-cancer hazard index greater than 1.

Maximum pure component vapor concentrations were determined using the equation:

$$C_{\max,vp} = S \times H' \times \frac{1x10^3\,\mu g}{mg}\, x \,\frac{1x10^3\,L}{m^3}$$

Where:

$C_{max,vp}$ = concentration in air (µg/m^3)

S = pure component solubility at 25ºC (mg/L)

H' = unitless Henry's Law Constant at 25ºC

Chemical-specific parameters and risk-based concentrations for residential air were taken directly from the EPA's "Regional Screening Levels for Chemical Contaminants at Superfund Sites", dated 12 SEP 2008.

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[1] Users should note that when the EPA issues updates to this table, it will be necessary to use the method presented in this Appendix to re-evaluate site-specific chemicals based on the most current toxicity information available.

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC_i	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? [1]	S	$C_{max,vp}$	Sufficiently Toxic? [2]
		$(ug/m^3)^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
Acephate	30560-19-1								2.0E-11	NO	8.2E+05	1.6E+01	NA
Acetaldehyde	75-07-0	2.2E-06	I	9.0E-03	I		1.1E+00	c**	2.7E-03	YES	1.0E+06	2.7E+09	YES
Acetochlor	34256-82-1								9.1E-07	NO	2.2E+02	2.0E+02	NA
Acetone	67-64-1			3.1E+01	A		3.2E+04	n	1.6E-03	YES	1.0E+06	1.6E+09	YES
Acetone Cyanohydrin	75-86-5			6.0E-02	P		6.3E+01	n	5.3E-04	YES	1.0E+06	5.3E+08	YES
Acetonitrile	75-05-8			6.0E-02	I		6.3E+01	n	1.4E-03	YES	1.0E+06	1.4E+09	YES
Acetophenone	98-86-2								4.3E-04	YES	6.1E+03	2.6E+06	NA
Acrolein	107-02-8			2.0E-05	I		2.1E-02	n	5.0E-03	YES	2.1E+05	1.1E+09	YES
Acrylamide	79-06-1	1.3E-03	I				1.9E-03	c	4.1E-08	NO	6.4E+05	2.6E+04	YES
Acrylic Acid	79-10-7			1.0E-03	I		1.0E+00	n	1.5E-05	YES	1.0E+06	1.5E+07	YES
Acrylonitrile	107-13-1	6.8E-05	I	2.0E-03	I		3.6E-02	c*	5.6E-03	YES	7.5E+04	4.2E+08	YES
Adiponitrile	111-69-3			6.0E-03	P		6.3E+00	n	4.9E-08	NO	8.0E+04	3.9E+03	YES
Alachlor	15972-60-8								3.4E-07	NO	2.4E+02	8.2E+01	NA
ALAR	1596-84-5								1.7E-08	NO	1.0E+05	1.7E+03	NA
Aldicarb	116-06-3								5.9E-08	NO	6.0E+03	3.6E+02	NA
Aldicarb Sulfone	1646-88-4								1.4E-07	NO	1.0E+04	1.4E+03	NA
Aldrin	309-00-2	4.9E-03	I				5.0E-04	c	1.8E-03	YES	1.7E-02	3.1E+01	YES
Ally	74223-64-6								3.1E-12	NO	9.5E+03	2.9E-02	NA
Allyl Alcohol	107-18-6			3.0E-04	P		3.1E-01	n	2.0E-04	YES	1.0E+06	2.0E+08	YES
Allyl Chloride	107-05-1			1.0E-03	I		1.0E+00	n	4.5E-01	YES	3.4E+03	1.5E+09	YES
Aluminum	7429-90-5			5.0E-03	P		5.2E+00	n		NA	0.0E+00	NA	NA
Aluminum Phosphide	20859-73-8									NA	0.0E+00	NA	NA
Amdro	67485-29-4								9.0E-05	YES	6.0E-03	5.4E-01	NA
Ametryn	834-12-8								9.8E-08	NO	2.1E+02	2.0E+01	NA
Aminophenol, m-	591-27-5								1.1E-08	NO	2.7E+04	3.0E+02	NA
Aminophenol, p-	123-30-8								3.9E-08	NO	6.0E+03	2.3E+02	NA
Amitraz	33089-61-1								4.0E-04	YES	1.0E+00	4.0E+02	NA
Ammonia	7664-41-7			1.0E-01	I		1.0E+02	n	6.6E-04	YES	4.8E+05	3.2E+08	YES
Ammonium Perchlorate	7790-98-9									NA	2.5E+05	NA	NA
Ammonium Sulfamate	7773-06-0									NA		NA	NA
Aniline	62-53-3			1.0E-03	I		1.0E+00	n	8.3E-05	YES	3.6E+04	3.0E+06	YES
Antimony (metallic)	7440-36-0									NA	0.0E+00	NA	NA
Antimony Pentoxide	1314-60-9									NA	3.0E+03	NA	NA
Antimony Potassium Tartrate	11071-15-1									NA		NA	NA
Antimony Tetroxide	1332-81-6									NA		NA	NA
Antimony Trioxide	1309-64-4			2.0E-04	I		2.1E-01	n		NA		NA	NA
Apollo	74115-24-5								1.6E-08	NO	1.0E+00	1.6E-02	NA
Aramite	140-57-8	7.1E-06	I				3.4E-01	c	7.8E-06	NO	5.9E-01	4.6E+00	YES
Arsenic, Inorganic	7440-38-2	4.3E-03	I	3.0E-05	C		5.7E-04	c*		NA	0.0E+00	NA	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC$_i$	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? [1]	S	C$_{max,vp}$	Sufficiently Toxic? [2]
		(ug/m^3)$^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
Arsine	7784-42-1			5.0E-05	I		5.2E-02	n		NA	9.6E+02	NA	NA
Assure	76578-14-8								4.3E-07	NO	4.0E-01	1.7E-01	NA
Asulam	3337-71-1								7.0E-11	NO	5.0E+03	3.5E-01	NA
Atrazine	1912-24-9								9.6E-08	NO	3.5E+01	3.3E+00	NA
Avermectin B1	65195-55-3								5.4E-26	NO	3.5E-04	1.9E-23	NA
Azobenzene	103-33-3	3.1E-05	I				7.8E-02	c	5.5E-04	YES	6.4E+00	3.5E+03	YES
Barium	7440-39-3			5.0E-04	H		5.2E-01	n		NA	0.0E+00	NA	NA
Baygon	114-26-1								5.8E-08	NO	1.9E+03	1.1E+02	NA
Bayleton	43121-43-3								3.3E-09	NO	7.2E+01	2.4E-01	NA
Baythroid	68359-37-5								6.1E-09	NO	3.0E-03	1.8E-05	NA
Benefin	1861-40-1								1.2E-02	YES	1.0E-01	1.2E+03	NA
Benomyl	17804-35-2								2.0E-10	NO	3.8E+00	7.6E-04	NA
Bentazon	25057-89-0								8.9E-08	NO	5.0E+02	4.5E+01	NA
Benzaldehyde	100-52-7								1.1E-03	YES	6.6E+03	7.2E+06	NA
Benzene	71-43-2	7.8E-06	I	3.0E-02	I		3.1E-01	c	2.3E-01	YES	1.8E+03	4.1E+08	YES
Benzenethiol	108-98-5								1.4E-02	YES	8.4E+02	1.2E+07	NA
Benzidine	92-87-5	6.7E-02	I			M	1.4E-05	c	2.9E-09	NO	3.2E+02	9.3E-01	YES
Benzoic Acid	65-85-0								1.6E-06	NO	3.4E+03	5.4E+03	NA
Benzotrichloride	98-07-7								1.1E-02	YES	2.2E+01	2.4E+05	NA
Benzyl Alcohol	100-51-6								1.4E-05	YES	4.3E+04	6.0E+05	NA
Benzyl Chloride	100-44-7			1.0E-03	P		1.0E+00	n	1.7E-02	YES	2.0E+01	3.4E+05	YES
Beryllium and compounds	7440-41-7	2.4E-03	I	2.0E-05	I		1.0E-03	c*		NA	0.0E+00	NA	NA
Bidrin	141-66-2								2.1E-09	NO	1.0E+06	2.1E+03	NA
Bifenox	42576-02-3								4.4E-06	NO	4.0E-01	1.8E+00	NA
Biphenthrin	82657-04-3								4.1E-05	YES	1.0E-01	4.1E+00	NA
Biphenyl, 1,1'-	92-52-4								1.3E-02	YES	6.9E+00	9.0E+04	NA
Bis(2-chloroethoxy)methane	111-91-1								6.9E-06	NO	7.8E+03	5.4E+04	NA
Bis(2-chloroethyl)ether	111-44-4	3.3E-04	I				7.4E-03	c	7.0E-04	YES	1.7E+04	1.2E+07	YES
Bis(2-chloro-1-methylethyl) ether	108-60-1	1.0E-05	H				2.4E-01	c	4.6E-03	YES	1.7E+03	7.8E+06	YES
Bis(2-ethylhexyl)phthalate	117-81-7								1.1E-05	YES	2.7E-01	3.0E+00	NA
Bis(chloromethyl)ether	542-88-1	6.2E-02	I				3.9E-05	c	8.4E-03	YES	2.2E+04	1.8E+08	YES
Bisphenol A	80-05-7								3.7E-10	NO	1.2E+02	4.4E-02	NA
Boron And Borates Only	7440-42-8			2.0E-02	H		2.1E+01	n		NA	0.0E+00	NA	NA
Boron Trifluoride	7637-07-2			7.0E-04	H		7.3E-01	n		NA	3.3E+06	NA	NA
Bromate	15541-45-4									NA		NA	NA
Bromobenzene	108-86-1			1.0E-02	P		1.0E+01	n	1.0E-01	YES	4.5E+02	4.5E+07	YES
Bromodichloromethane	75-27-4								8.7E-02	YES	3.0E+03	2.6E+08	NA
Bromoform	75-25-2	1.1E-06	I				2.2E+00	c	2.2E-02	YES	3.1E+03	6.8E+07	YES
Bromomethane	74-83-9			5.0E-03	I		5.2E+00	n	2.6E-01	YES	1.5E+04	4.0E+09	YES

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR $(ug/m^3)^{-1}$	key	RfC_i mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? [1]	S mg/L	$C_{max,vp}$ ug/m^3	Sufficiently Toxic? [2]
Bromophos	2104-96-3								8.4E-03	YES	3.0E-01	2.5E+03	NA
Bromoxynil	1689-84-5								5.4E-09	NO	1.3E+02	7.0E-01	NA
Bromoxynil Octanoate	1689-99-2								1.3E-03	YES	8.0E-02	1.0E+02	NA
Butadiene, 1,3-	106-99-0	3.0E-05	I	2.0E-03	I		8.1E-02	c*	3.0E+00	YES	7.4E+02	2.2E+09	YES
Butanol, N-	71-36-3								3.6E-04	YES	6.3E+04	2.3E+07	NA
Butyl Benzyl Phthlate	85-68-7								5.2E-05	YES	2.7E+00	1.4E+02	NA
Butylate	2008-41-5								3.5E-03	YES	4.5E+01	1.6E+05	NA
Butylphthalyl Butylglycolate	85-70-1								1.3E-07	NO	2.1E+00	2.8E-01	NA
Cacodylic Acid	75-60-5									NA	2.0E+06	NA	NA
Cadmium (Diet)	7440-43-9	1.8E-03	I							NA	0.0E+00	NA	NA
Cadmium (Water)	7440-43-9	1.8E-03	I				1.4E-03	c		NA	0.0E+00	NA	NA
Caprolactam	105-60-2								1.0E-06	NO	7.7E+05	7.7E+05	NA
Captafol	2425-06-1	4.3E-05	C				5.7E-02	c	8.8E-08	NO	1.4E+00	1.2E-01	YES
Captan	133-06-2	6.6E-07	C				3.7E+00	c	2.9E-07	NO	5.1E+00	1.5E+00	NO
Carbaryl	63-25-2								1.8E-07	NO	1.1E+02	2.0E+01	NA
Carbofuran	1563-66-2								1.3E-07	NO	3.2E+02	4.2E+01	NA
Carbon Disulfide	75-15-0			7.0E-01	I		7.3E+02	n	5.9E-01	YES	1.2E+03	7.0E+08	YES
Carbon Tetrachloride	56-23-5	1.5E-05	I	1.9E-01	A		1.6E-01	c	1.1E+00	YES	7.9E+02	8.7E+08	YES
Carbosulfan	55285-14-8								2.1E-05	YES	3.0E-01	6.3E+00	NA
Carboxin	5234-68-4								1.1E-08	NO	2.0E+02	2.2E+00	NA
Chloral Hydrate	302-17-0								4.5E-09	NO	3.8E+06	1.7E+04	NA
Chloramben	133-90-4								1.6E-09	NO	7.0E+02	1.1E+00	NA
Chloranil	118-75-2								1.3E-08	NO	2.5E+02	3.3E+00	NA
Chlordane	12789-03-6	1.0E-04	I	7.0E-04	I		2.4E-02	c*	2.0E-03	YES	5.6E-02	1.1E+02	YES
Chlordecone (Kepone)	143-50-0	4.6E-03	C				5.3E-04	c	2.2E-06	NO	2.7E+00	5.9E+00	YES
Chlorimuron, Ethyl-	90982-32-4								7.4E-14	NO	1.2E+03	8.9E-05	NA
Chlorine	7782-50-5			1.5E-04	A		1.5E-01	n	4.8E-01	YES	6.3E+03	3.0E+09	YES
Chlorine Dioxide	10049-04-4			2.0E-04	I		2.1E-01	n		NA	1.1E+05	NA	NA
Chlorite (Sodium Salt)	7758-19-2									NA	6.4E+05	NA	NA
Chloro-1,1-difluoroethane, 1-	75-68-3			5.0E+01	I		5.2E+04	n	2.4E+00	YES	1.4E+03	3.4E+09	YES
Chloro-1,3-butadiene, 2-	126-99-8			7.0E-03	H		7.3E+00	n	2.3E+00	YES	8.7E+02	2.0E+09	YES
Chloro-2-methylaniline HCl, 4-	3165-93-3								8.1E-05	YES	9.5E+02	7.7E+04	NA
Chloro-2-methylaniline, 4-	95-69-2	7.7E-05	C				3.2E-02	c	8.1E-05	YES	9.5E+02	7.7E+04	YES
Chloroacetic Acid	79-11-8								3.9E-07	NO	8.6E+05	3.3E+05	NA
Chloroacetophenone, 2-	532-27-4			3.0E-05	I		3.1E-02	n	1.3E-04	YES	1.6E+03	2.1E+05	YES
Chloroaniline, p-	106-47-8								4.7E-05	YES	3.9E+03	1.8E+05	NA
Chlorobenzene	108-90-7			5.0E-02	P		5.2E+01	n	1.3E-01	YES	5.0E+02	6.5E+07	YES
Chlorobenzilate	510-15-6	3.1E-05	C				7.8E-02	c	3.0E-06	NO	1.3E+01	3.9E+01	YES
Chlorobenzotrifluoride, 4-	98-56-6			3.0E-01	P		3.1E+02	n	1.4E+00	YES	4.6E+01	6.4E+07	YES

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC$_i$	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? [1]	S	C$_{max,vp}$	Sufficiently Toxic? [2]
		(ug/m^3)$^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
Chlorobutane, 1-	109-69-3								6.8E-01	YES	1.1E+03	7.5E+08	NA
Chlorodifluoromethane	75-45-6			5.0E+01	I		5.2E+04	n	1.7E+00	YES	2.8E+03	4.7E+09	YES
Chloroform	67-66-3	2.3E-05	I	9.8E-02	A		1.1E-01	c	1.5E-01	YES	8.0E+03	1.2E+09	YES
Chloromethane	74-87-3	1.8E-06	H	9.0E-02	I		1.4E+00	c*	3.6E-01	YES	5.3E+03	1.9E+09	YES
Chloronaphthalene, Beta-	91-58-7								1.3E-02	YES	1.2E+01	1.5E+05	NA
Chloronitrobenzene, o-	88-73-3			7.0E-05	P		7.3E-02	n	3.8E-04	YES	4.4E+02	1.7E+05	YES
Chloronitrobenzene, p-	100-00-5			6.0E-04	P		6.3E-01	n	2.0E-04	YES	2.3E+02	4.5E+04	YES
Chlorophenol, 2-	95-57-8								4.6E-04	YES	2.9E+04	1.3E+07	NA
Chlorothalonil	1897-45-6	8.9E-07	C				2.7E+00	c	8.2E-05	YES	6.0E-01	4.9E+01	YES
Chlorotoluene, o-	95-49-8								1.5E-01	YES	3.7E+02	5.6E+07	NA
Chlorotoluene, p-	106-43-4								1.8E-01	YES	1.1E+02	1.9E+07	NA
Chlorpropham	101-21-3								9.8E-07	NO	8.9E+01	8.7E+01	NA
Chlorpyrifos	2921-88-2								1.2E-04	YES	1.1E+00	1.3E+02	NA
Chlorpyrifos Methyl	5598-13-0								1.5E-04	YES	4.8E+00	7.1E+02	NA
Chlorsulfuron	64902-72-3								1.6E-13	NO	2.8E+04	4.5E-03	NA
Chlorthiophos	60238-56-4								4.9E-05	YES	5.9E-02	2.9E+00	NA
Chromium (III) (Insoluble Salts)	16065-83-1									NA	0.0E+00	NA	NA
Chromium VI (chromic acid mists)	18540-29-9	8.4E-02	I	8.0E-06	I		2.9E-05	c		NA	1.7E+06	NA	NA
Chromium VI (particulates)	18540-29-9	8.4E-02	I	1.0E-04	I		2.9E-05	c		NA	1.7E+06	NA	NA
Chromium, Total (1:6 ratio Cr VI : Cr III)	7440-47-3	1.2E-02	I			M	2.0E-04	c		NA	0.0E+00	NA	NA
Cobalt	7440-48-4	9.0E-03	P	6.0E-06	P		2.7E-04	c*		NA	0.0E+00	NA	NA
Coke Oven Emissions	8007-45-2	6.2E-04	I			M	1.5E-03	c	2.3E-01	YES	1.8E+03	4.1E+08	YES
Copper	7440-50-8									NA	0.0E+00	NA	NA
Cresol, m-	108-39-4								3.5E-05	YES	2.3E+04	7.9E+05	NA
Cresol, o-	95-48-7								4.9E-05	YES	2.6E+04	1.3E+06	NA
Cresol, p-	106-44-5								4.1E-05	YES	2.2E+04	8.8E+05	NA
Crotonaldehyde, trans-	123-73-9								7.9E-04	YES	1.8E+05	1.4E+08	NA
Cumene	98-82-8			4.0E-01	I		4.2E+02	n	4.7E-01	YES	6.1E+01	2.9E+07	YES
Cyanazine	21725-46-2								1.2E-10	NO	1.7E+02	2.0E-02	NA
Cyclohexane	110-82-7			6.0E+00	I		6.3E+03	n	6.1E+00	YES	5.5E+01	3.4E+08	YES
Cyclohexane, 1,2,3,4,5-pentabromo-6-chloro	87-84-3								4.4E-10	NO	5.5E-02	2.4E-05	NA
Cyclohexanone	108-94-1								3.7E-04	YES	2.5E+04	9.3E+06	NA
Cyclohexylamine	108-91-8								1.7E-04	YES	1.0E+06	1.7E+08	NA
Cyhalothrin/karate	68085-85-8								6.1E-05	YES	5.0E-03	3.1E-01	NA
Cypermethrin	52315-07-8								1.7E-05	YES	4.0E-03	6.8E-02	NA
Cyromazine	66215-27-8								2.3E-12	NO	1.3E+04	3.0E-02	NA
Cyanides									NA	NA	NA	NA	NA
Calcium Cyanide	592-01-8									NA		NA	NA
Copper Cyanide	544-92-3									NA	0.0E+00	NA	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC$_i$	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? [1]	S	$C_{max,vp}$	Sufficiently Toxic? [2]
		(ug/m^3)$^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
Cyanide (CN-)	57-12-5									NA		NA	NA
Cyanogen	460-19-5								2.2E-01	YES	1.1E+04	2.3E+09	NA
Cyanogen Bromide	506-68-3									NA		NA	NA
Cyanogen Chloride	506-77-4								7.9E-02	YES	6.0E+04	4.7E+09	NA
Hydrogen Cyanide	74-90-8			3.0E-03	I		3.1E+00	n	5.4E-03	YES	1.0E+06	5.4E+09	YES
Potassium Cyanide	151-50-8									NA	7.0E+05	NA	NA
Potassium Silver Cyanide	506-61-6									NA	2.5E+05	NA	NA
Silver Cyanide	506-64-9									NA	1.1E-02	NA	NA
Sodium Cyanide	143-33-9									NA	5.8E+05	NA	NA
Thiocyanate	463-56-9								6.0E-03	YES	4.4E+04	2.6E+08	NA
Zinc Cyanide	557-21-1									NA	5.8E+02	NA	NA
Dacthal	1861-32-1								8.9E-05	YES	5.0E-01	4.5E+01	NA
Dalapon	75-99-0								3.7E-06	NO	5.0E+05	1.9E+06	NA
DDD	72-54-8								2.7E-04	YES	9.0E-02	2.4E+01	NA
DDE, p,p'-	72-55-9								1.7E-03	YES	4.0E-02	6.8E+01	NA
DDT	50-29-3	9.7E-05	I				2.5E-02	c	3.4E-04	YES	5.5E-03	1.9E+00	YES
Decabromodiphenyl ether, 2,2',3,3',4,4',5,5',6	1163-19-5								1.8E-06	NO	2.5E-02	4.5E-02	NA
Demeton	8065-48-3									NA		NA	NA
Di(2-ethylhexyl)adipate	103-23-1								1.8E-05	YES	7.8E-01	1.4E+01	NA
Diallate	2303-16-4								1.6E-04	YES	1.4E+01	2.2E+03	NA
Diazinon	333-41-5								4.6E-06	NO	4.0E+01	1.8E+02	NA
Dibromo-3-chloropropane, 1,2-	96-12-8	6.0E-03	P	2.0E-04	I	M	1.6E-04	c	6.0E-03	YES	1.2E+03	7.4E+06	YES
Dibromobenzene, 1,4-	106-37-6								3.7E-02	YES	2.6E+01	9.8E+05	NA
Dibromochloromethane	124-48-1								3.2E-02	YES	2.7E+03	8.6E+07	NA
Dibromoethane, 1,2-	106-93-4	6.0E-04	I	9.0E-03	I		4.1E-03	c	2.7E-02	YES	3.9E+03	1.1E+08	YES
Dibromomethane (Methylene Bromide)	74-95-3								3.4E-02	YES	1.2E+04	4.0E+08	NA
Dibutyl Phthalate	84-74-2								7.4E-05	YES	1.1E+01	8.3E+02	NA
Dibutyltin Compounds	NA									NA		NA	NA
Dicamba	1918-00-9								8.9E-08	NO	8.3E+03	7.4E+02	NA
Dichloro-2-butene, 1,4-	764-41-0	2.6E-03	H				9.4E-04	c	3.5E-01	YES	5.8E+02	2.0E+08	YES
Dichloroacetic Acid	79-43-6								1.4E-05	YES	1.0E+06	1.4E+07	NA
Dichlorobenzene, 1,2-	95-50-1			2.0E-01	H		2.1E+02	n	7.8E-02	YES	8.0E+01	6.2E+06	YES
Dichlorobenzene, 1,4-	106-46-7	1.1E-05	C	8.0E-01	I		2.2E-01	c	9.9E-02	YES	8.1E+01	8.0E+06	YES
Dichlorobenzidine, 3,3'-	91-94-1								2.1E-09	NO	3.1E+00	6.5E-03	NA
Dichlorodifluoromethane	75-71-8			2.0E-01	H		2.1E+02	n	1.4E+01	YES	2.8E+02	3.9E+09	YES
Dichloroethane, 1,1-	75-34-3	1.6E-06	C				1.5E+00	c	2.3E-01	YES	5.0E+03	1.2E+09	YES
Dichloroethane, 1,2-	107-06-2	2.6E-05	I	2.4E+00	A		9.4E-02	c	4.8E-02	YES	5.1E+03	2.4E+08	YES
Dichloroethylene, 1,1-	75-35-4			2.0E-01	I		2.1E+02	n	1.1E+00	YES	2.4E+03	2.7E+09	YES
Dichloroethylene, 1,2- (Mixed Isomers)	540-59-0								1.7E-01	YES	3.5E+03	6.0E+08	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR $(ug/m^3)^{-1}$	key	RfC_i mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? [1]	S mg/L	$C_{max,vp}$ ug/m^3	Sufficiently Toxic? [2]
Dichloroethylene, 1,2-cis-	156-59-2								1.7E-01	YES	3.5E+03	6.0E+08	NA
Dichloroethylene, 1,2-trans-	156-60-5			6.0E-02	P		6.3E+01	n	3.8E-01	YES	3.5E+03	1.3E+09	YES
Dichlorophenol, 2,4-	120-83-2								9.0E-05	YES	4.5E+03	4.1E+05	NA
Dichlorophenoxy Acetic Acid, 2,4-	94-75-7								1.4E-06	NO	6.8E+02	9.5E+02	NA
Dichlorophenoxy)butyric Acid, 4-(2,4-	94-82-6								2.4E-07	NO	4.6E+01	1.1E+01	NA
Dichloropropane, 1,2-	78-87-5	1.0E-05	C	4.0E-03	I		2.4E-01	c*	1.2E-01	YES	2.8E+03	3.4E+08	YES
Dichloropropane, 1,3-	142-28-9								4.0E-02	YES	2.8E+03	1.1E+08	NA
Dichloropropanol, 2,3-	616-23-9								1.5E-07	NO	6.4E+04	9.6E+03	NA
Dichloropropene, 1,3-	542-75-6	4.0E-06	I	2.0E-02	I		6.1E-01	c*	1.5E-01	YES	2.8E+03	4.2E+08	YES
Dichlorvos	62-73-7			5.0E-04	I		5.2E-01	n	2.3E-05	YES	8.0E+03	1.8E+05	YES
Dicyclopentadiene	77-73-6			7.0E-03	P		7.3E+00	n	2.6E+00	YES	5.2E+01	1.3E+08	YES
Dieldrin	60-57-1	4.6E-03	I				5.3E-04	c	4.1E-04	YES	2.5E-01	1.0E+02	YES
Diesel Engine Exhaust	NA			5.0E-03	I		5.2E+00	n		NA		NA	NA
Diethyl Phthalate	84-66-2								2.5E-05	YES	1.1E+03	2.7E+04	NA
Diethylene Glycol Monobutyl Ether	112-34-5			2.0E-02	P		2.1E+01	n	1.8E-09	NO	1.0E+06	1.8E+03	YES
Diethylene Glycol Monoethyl Ether	111-90-0			3.0E-03	P		3.1E+00	n	9.1E-10	NO	1.0E+06	9.1E+02	YES
Diethylformamide	617-84-5								5.3E-06	NO	1.0E+06	5.3E+06	NA
Diethylstilbestrol	56-53-1	1.0E-01	C				2.4E-05	c	2.4E-10	NO	1.2E+01	2.9E-03	YES
Difenzoquat	43222-48-6									NA	1.5E+03	NA	NA
Diflubenzuron	35367-38-5								1.9E-07	NO	8.0E-02	1.5E-02	NA
Difluoroethane, 1,1-	75-37-6			4.0E+01	I		4.2E+04	n	8.3E-01	YES	3.2E+03	2.7E+09	YES
Diisopropyl Ether	108-20-3			4.0E-01	P		4.2E+02	n	9.3E-02	YES	8.8E+03	8.2E+08	YES
Diisopropyl Methylphosphonate	1445-75-6								1.8E-03	YES	1.5E+03	2.7E+06	NA
Dimethipin	55290-64-7								9.4E-10	NO	4.6E+03	4.3E+00	NA
Dimethoate	60-51-5								4.3E-09	NO	2.5E+04	1.1E+02	NA
Dimethoxybenzidine, 3,3'-	119-90-4								1.9E-09	NO	6.0E+01	1.1E-01	NA
Dimethyl methylphosphonate	756-79-6								5.1E-05	YES	1.0E+06	5.1E+07	NA
Dimethylaniline HCl, 2,4-	21436-96-4								1.0E-04	YES	3.7E+03	3.7E+05	NA
Dimethylaniline, 2,4-	95-68-1								1.0E-04	YES	3.7E+03	3.7E+05	NA
Dimethylaniline, N,N-	121-69-7								2.3E-03	YES	1.5E+03	3.3E+06	NA
Dimethylbenzidine, 3,3'-	119-93-7								3.3E-09	NO	1.3E+03	4.3E+00	NA
Dimethylformamide	68-12-2			3.0E-02	I		3.1E+01	n	3.0E-06	NO	1.0E+06	3.0E+06	YES
Dimethylphenol, 2,4-	105-67-9								3.9E-05	YES	7.9E+03	3.1E+05	NA
Dimethylphenol, 2,6-	576-26-1								2.7E-04	YES	6.1E+03	1.6E+06	NA
Dimethylphenol, 3,4-	95-65-8								1.7E-05	YES	4.8E+03	8.1E+04	NA
Dimethylterephthalate	120-61-6								5.5E-03	YES	1.9E+01	1.0E+05	NA
Dinitro-o-cresol, 4,6-	534-52-1								5.7E-05	YES	2.0E+02	1.1E+04	NA
Dinitro-o-cyclohexyl Phenol, 4,6-	131-89-5								1.4E-09	NO	1.5E+01	2.1E-02	NA
Dinitrobenzene, 1,2-	528-29-0								1.5E-05	YES	5.0E+02	7.5E+03	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR $(ug/m^3)^{-1}$	key	RfC_i mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? [1]	S mg/L	$C_{max,vp}$ ug/m^3	Sufficiently Toxic? [2]
Dinitrobenzene, 1,3-	99-65-0								2.0E-06	NO	5.3E+02	1.1E+03	NA
Dinitrobenzene, 1,4-	100-25-4								1.5E-05	YES	6.9E+01	1.0E+03	NA
Dinitrophenol, 2,4-	51-28-5								3.5E-06	NO	2.8E+03	9.8E+03	NA
Dinitrotoluene Mixture, 2,4/2,6-	25321-14-6								1.6E-05	YES	2.7E+02	4.3E+03	NA
Dinitrotoluene, 2,4-	121-14-2								2.2E-06	NO	2.7E+02	5.9E+02	NA
Dinitrotoluene, 2,6-	606-20-2								3.1E-05	YES	3.5E+02	1.1E+04	NA
Dinitrotoluene, 2-Amino-4,6-	35572-78-2								6.6E-09	NO	1.2E+03	8.1E+00	NA
Dinitrotoluene, 4-Amino-2,6-	19406-51-0								6.6E-09	NO	1.2E+03	8.1E+00	NA
Dinoseb	88-85-7								1.9E-05	YES	5.2E+01	9.9E+02	NA
Dioxane, 1,4-	123-91-1			3.6E+00	A		3.8E+03	n	2.0E-04	YES	1.0E+06	2.0E+08	YES
Diphenamid	957-51-7								1.5E-09	NO	2.6E+02	3.9E-01	NA
Diphenyl Sulfone	127-63-9								1.0E-05	NO	3.1E+02	3.1E+03	NA
Diphenylamine	122-39-4								1.4E-04	YES	5.3E+01	7.4E+03	NA
Diphenylhydrazine, 1,2-	122-66-7	2.2E-04	I				1.1E-02	c	1.8E-07	NO	2.2E+02	4.0E+01	YES
Diquat	85-00-7								5.8E-12	NO	7.1E+05	4.1E+00	NA
Direct Black 38	1937-37-7	2.1E-03	C				1.2E-03	c	3.4E-38	NO	1.8E-05	6.1E-37	NO
Direct Blue 6	2602-46-2	2.1E-03	C				1.2E-03	c	6.7E-42	NO	3.1E+01	2.1E-34	NO
Direct Brown 95	16071-86-6	1.9E-03	C				1.3E-03	c		NA	1.0E+06	NA	NA
Disulfoton	298-04-4								8.8E-05	YES	1.6E+01	1.4E+03	NA
Dithiane, 1,4-	505-29-3								2.4E-05	YES	6.6E+03	1.6E+05	NA
Diuron	330-54-1								2.1E-08	NO	4.2E+01	8.8E-01	NA
Dodine	2439-10-3								2.5E-17	NO	6.3E+02	1.6E-08	NA
Dioxins									NA	NA	NA	NA	NA
Hexachlorodibenzo-p-dioxin	34465-46-8	3.8E+00	W				6.4E-07	c	2.3E-04	YES	4.0E-06	9.2E-04	YES
Hexachlorodibenzo-p-dioxin, Mixture	NA	1.3E+00	I				1.9E-06	c		NA		NA	NA
HpCDD, 2,3,7,8-	37871-00-4	3.8E-01	W				6.4E-06	c	7.2E-03	YES	1.4E-06	1.0E-02	YES
OCDD	3268-87-9	1.1E-02	W				2.1E-04	c	2.8E-04	YES	4.0E-07	1.1E-04	NO
PeCDD, 2,3,7,8-	36088-22-9	3.8E+01	W				6.4E-08	c	9.0E-05	YES	1.2E-04	1.1E-02	YES
TCDD, 2,3,7,8-	1746-01-6	3.8E+01	C				6.4E-08	c	2.0E-03	YES	2.0E-04	4.0E-01	YES
Endosulfan	115-29-7								2.7E-03	YES	4.5E-01	1.2E+03	NA
Endothall	145-73-3								1.6E-14	NO	1.0E+05	1.6E-03	NA
Endrin	72-20-8								2.6E-04	YES	2.5E-01	6.5E+01	NA
Epichlorohydrin	106-89-8	1.2E-06	I	1.0E-03	I		1.0E+00	n	1.2E-03	YES	6.6E+04	7.9E+07	YES
Epoxybutane, 1,2-	106-88-7			2.0E-02	I		2.1E+01	n	7.4E-03	YES	9.5E+04	7.0E+08	YES
EPTC	759-94-4								6.5E-04	YES	3.8E+02	2.4E+05	NA
Ethephon	16672-87-0								2.3E-10	NO	1.0E+06	2.3E+02	NA
Ethion	563-12-2								3.9E-05	YES	2.0E+00	7.8E+01	NA
Ethoxyethanol Acetate, 2-	111-15-9								1.3E-04	YES	2.5E+05	3.2E+07	NA
Ethoxyethanol, 2-	110-80-5			2.0E-01	I		2.1E+02	n	1.9E-05	YES	1.0E+06	1.9E+07	YES

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC$_i$	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? ^{1}	S	C$_{max,vp}$	Sufficiently Toxic? ^{2}
		(ug/m^3)$^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
Ethyl Acetate	141-78-6								5.5E-03	YES	8.0E+04	4.4E+08	NA
Ethyl Acrylate	140-88-5								1.4E-02	YES	1.5E+04	2.1E+08	NA
Ethyl Chloride	75-00-3			1.0E+01	I		1.0E+04	n	4.5E-01	YES	6.7E+03	3.0E+09	YES
Ethyl Ether	60-29-7								5.0E-02	YES	6.0E+04	3.0E+09	NA
Ethyl Methacrylate	97-63-2								2.3E-02	YES	5.4E+03	1.2E+08	NA
Ethyl-p-nitrophenyl Phosphonate	2104-64-5								1.8E-05	YES	3.1E+00	5.6E+01	NA
Ethylbenzene	100-41-4	2.5E-06	C	1.0E+00	I		9.7E-01	c	3.2E-01	YES	1.7E+02	5.4E+07	YES
Ethylene Cyanohydrin	109-78-4								1.8E-08	NO	1.0E+06	1.8E+04	NA
Ethylene Diamine	107-15-3								7.1E-08	NO	1.0E+06	7.1E+04	NA
Ethylene Glycol	107-21-1			4.0E-01	C		4.2E+02	n	2.5E-06	NO	1.0E+06	2.5E+06	YES
Ethylene Glycol Monobutyl Ether	111-76-2			1.3E+01	I		1.4E+04	n	6.5E-05	YES	1.0E+06	6.5E+07	YES
Ethylene Oxide	75-21-8	8.8E-05	C				2.8E-02	c	6.1E-03	YES	1.0E+06	6.1E+09	YES
Ethylene Thiourea	96-45-7	1.3E-05	C				1.9E-01	c	1.4E-05	YES	2.0E+04	2.8E+05	YES
Ethylphthalyl Ethyl Glycolate	84-72-0								3.2E-08	NO	2.2E+02	6.9E+00	NA
Express	101200-48-0								4.2E-12	NO	5.0E+01	2.1E-04	NA
Fenamiphos	22224-92-6								4.9E-08	NO	3.3E+02	1.6E+01	NA
Fenpropathrin	39515-41-8								2.2E-04	YES	1.4E-02	3.1E+00	NA
Fluometuron	2164-17-2								7.4E-08	NO	1.1E+02	8.1E+00	NA
Fluorine (Soluble Fluoride)	7782-41-4									NA	0.0E+00	NA	NA
Fluridone	59756-60-4								3.3E-07	NO	1.2E+01	4.0E+00	NA
Flurprimidol	56425-91-3								5.4E-08	NO	1.1E+02	6.2E+00	NA
Flutolanil	66332-96-5								1.3E-07	NO	6.5E+00	8.5E-01	NA
Fluvalinate	69409-94-5								5.9E-07	NO	5.0E-03	3.0E-03	NA
Folpet	133-07-3								3.1E-06	NO	1.0E+00	3.1E+00	NA
Fomesafen	72178-02-0								3.1E-11	NO	5.0E+01	1.6E-03	NA
Fonofos	944-22-9								2.9E-04	YES	1.6E+01	4.6E+03	NA
Formaldehyde	50-00-0	1.3E-05	I	9.8E-03	A		1.9E-01	c*	1.4E-05	YES	4.0E+05	5.6E+06	YES
Formic Acid	64-18-6			3.0E-03	P		3.1E+00	n	6.8E-06	NO	1.0E+06	6.8E+06	YES
Fosetyl-AL	39148-24-8									NA	1.2E+05	NA	NA
Furazolidone	67-45-8								1.3E-09	NO	4.0E+01	5.2E-02	NA
Furfural	98-01-1			5.0E-02	H		5.2E+01	n	1.4E-04	YES	7.7E+04	1.1E+07	YES
Furium	531-82-8	4.3E-04	C				5.7E-03	c	5.4E-14	NO	2.7E+02	1.4E-05	NO
Furmecyclox	60568-05-0								2.8E-07	NO	3.0E-01	8.4E-02	NA
Furans									NA	NA	NA	NA	NA
Furan	110-00-9								2.2E-01	YES	1.0E+04	2.2E+09	NA
HpCDF, 2,3,7,8-	38998-75-3	3.8E-01	W				6.4E-06	c	2.6E-04	YES	1.4E-06	3.5E-04	YES
HxCDF, 2,3,7,8-	55684-94-1	3.8E+00	W				6.4E-07	c	3.5E-04	YES	1.1E-04	4.0E-02	YES
OCDF	39001-02-0	1.1E-02	W				2.1E-04	c	7.7E-05	YES	1.2E-06	8.9E-05	NO
PeCDF, 1,2,3,7,8-	57117-41-6	1.1E+00	W				2.1E-06	c	4.7E-04	YES	2.4E-04	1.1E-01	YES

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC$_i$	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? [1]	S	$C_{max,vp}$	Sufficiently Toxic? [2]
		$(ug/m^3)^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
PeCDF, 2,3,4,7,8-	57117-31-4	1.1E+01	W				2.1E-07	c	4.7E-04	YES	2.4E-04	1.1E-01	YES
TCDF, 2,3,7,8-	51207-31-9	3.8E+00	W				6.4E-07	c	6.3E-04	YES	6.9E-04	4.4E-01	YES
Glufosinate, Ammonium	77182-82-2								1.0E-22	NO	1.4E+06	1.4E-10	NA
Glycidyl	765-34-4			1.0E-03	H		1.0E+00	n	3.2E-05	YES	1.0E+06	3.2E+07	YES
Glyphosate	1071-83-6								1.7E-17	NO	1.2E+04	2.0E-07	NA
Goal	42874-03-3								3.4E-05	YES	1.2E-01	3.9E+00	NA
Haloxyfop, Methyl	69806-40-2								1.3E-05	YES	9.3E+00	1.2E+02	NA
Harmony	79277-27-3								1.7E-12	NO	2.3E+02	3.9E-04	NA
Heptachlor	76-44-8	1.3E-03	I				1.9E-03	c	1.2E-02	YES	1.8E-01	2.2E+03	YES
Heptachlor Epoxide	1024-57-3	2.6E-03	I				9.4E-04	c	8.6E-04	YES	2.0E-01	1.7E+02	YES
Hexabromobenzene	87-82-1								1.1E-03	YES	1.6E-04	1.8E-01	NA
Hexachlorobenzene	118-74-1	4.6E-04	I				5.3E-03	c	7.0E-02	YES	6.2E-03	4.3E+02	YES
Hexachlorobutadiene	87-68-3	2.2E-05	I				1.1E-01	c	4.2E-01	YES	3.2E+00	1.3E+06	YES
Hexachlorocyclohexane, Alpha-	319-84-6	1.8E-03	I				1.4E-03	c	5.0E-04	YES	8.0E+00	4.0E+03	YES
Hexachlorocyclohexane, Beta-	319-85-7	5.3E-04	I				4.6E-03	c	1.8E-05	YES	8.0E+00	1.4E+02	YES
Hexachlorocyclohexane, Gamma- (Lindane)	58-89-9	3.1E-04	C				7.8E-03	c	2.1E-04	YES	8.0E+00	1.7E+03	YES
Hexachlorocyclohexane, Technical	608-73-1	5.1E-04	I				4.8E-03	c	1.8E-05	YES	8.0E+00	1.4E+02	YES
Hexachlorocyclopentadiene	77-47-4			2.0E-04	I		2.1E-01	n	1.1E+00	YES	1.8E+00	2.0E+06	YES
Hexachloroethane	67-72-1	4.0E-06	I				6.1E-01	c	1.6E-01	YES	5.0E+01	8.0E+06	YES
Hexachlorophene	70-30-4								2.2E-11	NO	1.4E+02	3.1E-03	NA
Hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX)	121-82-4								2.6E-06	NO	6.0E+01	1.6E+02	NA
Hexamethylene Diisocyanate, 1,6-	822-06-0			1.0E-05	I		1.0E-02	n	2.0E-03	YES	1.2E+02	2.3E+05	YES
Hexane, N-	110-54-3			7.0E-01	I		7.3E+02	n	7.4E+01	YES	9.5E+00	7.0E+08	YES
Hexanedioic Acid	124-04-9								1.9E-10	NO	3.1E+04	5.9E+00	NA
Hexazinone	51235-04-2								9.2E-11	NO	3.3E+04	3.0E+00	NA
Hydrazine	302-01-2	4.9E-03	I	2.0E-04	C		5.0E-04	c		NA	1.0E+06	NA	NA
Hydrazine Sulfate	10034-93-2	4.9E-03	I				5.0E-04	c		NA	3.1E+04	NA	NA
Hydrogen Chloride	7647-01-0			2.0E-02	I		2.1E+01	n		NA	7.2E+05	NA	NA
Hydrogen Sulfide	7783-06-4			2.0E-03	I		2.1E+00	n		NA	5.1E+03	NA	NA
Hydroquinone	123-31-9								1.9E-09	NO	7.2E+04	1.4E+02	NA
Hexabromodiphenyl ether, 2,2',4,4',5,5'- (BDE	68631-49-2									NA		NA	NA
Imazalil	35554-44-0								1.1E-07	NO	1.8E+02	2.0E+01	NA
Imazaquin	81335-37-7								2.8E-16	NO	9.0E+01	2.5E-08	NA
Iprodione	36734-19-7								5.1E-09	NO	1.4E+01	7.1E-02	NA
Iron	7439-89-6									NA	0.0E+00	NA	NA
Isobutyl Alcohol	78-83-1								4.0E-04	YES	8.5E+04	3.4E+07	NA
Isophorone	78-59-1			2.0E+00	C		2.1E+03	n	2.7E-04	YES	1.2E+04	3.2E+06	YES
Isopropalin	33820-53-0								4.5E-03	YES	1.1E-01	5.0E+02	NA
Isopropyl Methyl Phosphonic Acid	1832-54-8								2.8E-07	NO	5.0E+04	1.4E+04	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR $(ug/m^3)^{-1}$	key	RfC_i mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? [1]	S mg/L	$C_{max,vp}$ ug/m^3	Sufficiently Toxic? [2]
Isoxaben	82558-50-7								5.2E-08	NO	1.4E+00	7.4E-02	NA
Kerb	23950-58-5								4.0E-07	NO	1.5E+01	6.0E+00	NA
Lactofen	77501-63-4								2.3E-08	NO	1.0E-01	2.3E-03	NA
Linuron	330-55-2								2.6E-07	NO	7.5E+01	2.0E+01	NA
Lithium	7439-93-2									NA	0.0E+00	NA	NA
Lithium Perchlorate	7791-03-9									NA	5.9E+05	NA	NA
Londax	83055-99-6								1.5E-13	NO	1.2E+02	1.8E-05	NA
Lead Compounds									NA	NA	NA	NA	NA
Lead and Compounds	7439-92-1									NA	0.0E+00	NA	NA
Tetraethyl Lead	78-00-2								2.3E+01	YES	2.9E-01	6.7E+06	NA
Malathion	121-75-5								2.0E-07	NO	1.4E+02	2.9E+01	NA
Maleic Anhydride	108-31-6			7.0E-04	C		7.3E-01	n	1.6E-04	YES	4.9E+03	7.9E+05	YES
Maleic Hydrazide	123-33-1								1.1E-09	NO	4.5E+03	5.0E+00	NA
Malononitrile	109-77-3								5.2E-07	NO	1.3E+05	6.9E+04	NA
Mancozeb	8018-01-7								2.3E-05	YES	6.2E+00	1.4E+02	NA
Maneb	12427-38-2								2.3E-05	YES	6.2E+00	1.4E+02	NA
Manganese (Diet)	7439-96-5			5.0E-05	I					NA	0.0E+00	NA	NA
Manganese (Water)	7439-96-5			5.0E-05	I		5.2E-02	n		NA	0.0E+00	NA	NA
MCPA	94-74-6								5.4E-08	NO	6.3E+02	3.4E+01	NA
MCPB	94-81-5								1.1E-07	NO	4.8E+01	5.3E+00	NA
MCPP	93-65-2								4.0E-08	NO	8.6E+02	3.4E+01	NA
Mephosfolan	950-10-7								4.9E-09	NO	5.7E+01	2.8E-01	NA
Mepiquat Chloride	24307-26-4								1.8E-10	NO	5.0E+05	9.0E+01	NA
Merphos	150-50-5								9.3E-04	YES	3.5E-03	3.3E+00	NA
Merphos Oxide	78-48-8								1.2E-05	YES	2.3E+00	2.8E+01	NA
Metalaxyl	57837-19-1								1.2E-07	NO	2.6E+04	3.1E+03	NA
Methacrylonitrile	126-98-7			7.0E-04	H		7.3E-01	n	1.0E-02	YES	2.5E+04	2.5E+08	YES
Methamidophos	10265-92-6								3.5E-08	NO	1.0E+06	3.5E+04	NA
Methanol	67-56-1			4.0E+00	C		4.2E+03	n	1.9E-04	YES	1.0E+06	1.9E+08	YES
Methidathion	950-37-8								2.9E-07	NO	1.9E+02	5.4E+01	NA
Methomyl	16752-77-5								8.1E-10	NO	5.8E+04	4.7E+01	NA
Methoxy-5-nitroaniline, 2-	99-59-2	1.4E-05	C				1.7E-01	c	6.0E-07	NO	1.2E+02	6.9E+01	YES
Methoxychlor	72-43-5								8.3E-06	NO	1.0E-01	8.3E-01	NA
Methoxyethanol Acetate, 2-	110-49-6								1.0E-05	NO	1.0E+06	1.0E+07	NA
Methoxyethanol, 2-	109-86-4			2.0E-02	I		2.1E+01	n	1.3E-05	YES	1.0E+06	1.3E+07	YES
Methyl Acetate	79-20-9								4.7E-03	YES	2.4E+05	1.1E+09	NA
Methyl Acrylate	96-33-3								8.1E-03	YES	4.9E+04	4.0E+08	NA
Methyl Ethyl Ketone (2-Butanone)	78-93-3			5.0E+00	I		5.2E+03	n	2.3E-03	YES	2.2E+05	5.1E+08	YES
Methyl Isobutyl Ketone (4-methyl-2-pentano	108-10-1			3.0E+00	I		3.1E+03	n	5.6E-03	YES	1.9E+04	1.1E+08	YES

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR (ug/m^3)$^{-1}$	key	RfC$_i$ mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile?[1]	S mg/L	C$_{max,vp}$ ug/m^3	Sufficiently Toxic?[2]
Methyl Methacrylate	80-62-6			7.0E-01	I		7.3E+02	n	1.4E-02	YES	1.5E+04	2.1E+08	YES
Methyl Parathion	298-00-0								4.1E-06	NO	3.8E+01	1.5E+02	NA
Methyl Styrene (Mixed Isomers)	25013-15-4			4.0E-02	H		4.2E+01	n	3.2E-01	YES	8.9E+01	2.8E+07	YES
Methyl tert-Butyl Ether (MTBE)	1634-04-4	2.6E-07	C	3.0E+00	I		9.4E+00	c	2.4E-02	YES	5.1E+04	1.2E+09	YES
Methyl-5-Nitroaniline, 2-	99-55-8								7.9E-07	NO	1.9E+03	1.5E+03	NA
Methylaniline Hydrochloride, 2-	636-21-5	3.7E-05	C				6.6E-02	c	8.1E-05	YES	1.7E+04	1.3E+06	YES
Methylarsonic acid	124-58-3				A					NA	2.6E+05	NA	NA
Methylene Chloride	75-09-2	4.7E-07	I	1.1E+00	A		5.2E+00	c	1.3E-01	YES	1.3E+04	1.7E+09	YES
Methylene-bis(2-chloroaniline), 4,4'-	101-14-4	4.3E-04	C			M	2.2E-03	c	4.7E-10	NO	1.4E+01	6.5E-03	YES
Methylene-bis(N,N-dimethyl) Aniline, 4,4'-	101-61-1								4.9E-06	NO	4.1E+00	2.0E+01	NA
Methylenebisbenzenamine, 4,4'-	101-77-9	4.6E-04	C				5.3E-03	c	6.5E-10	NO	1.0E+03	6.5E-01	YES
Methylenediphenyl Diisocyanate	101-68-8			6.0E-04	I		6.3E-01	n	3.7E-05	YES	8.3E-01	3.1E+01	YES
Methylstyrene, Alpha-	98-83-9								1.0E-01	YES	8.9E+01	8.9E+06	NA
Metolachlor	51218-45-2								3.7E-07	NO	5.3E+02	2.0E+02	NA
Metribuzin	21087-64-9								4.8E-09	NO	1.1E+03	5.0E+00	NA
Mirex	2385-85-5	5.1E-03	C				4.8E-04	c	3.3E-02	YES	8.5E-02	2.8E+03	YES
Molinate	2212-67-1								1.7E-04	YES	9.7E+02	1.6E+05	NA
Molybdenum	7439-98-7									NA	0.0E+00	NA	NA
Monochloramine	10599-90-3									NA		NA	NA
Monomethylaniline	100-61-8								3.6E-04	YES	5.6E+03	2.0E+06	NA
Mercury Compounds									NA	NA	NA	NA	NA
Mercuric Chloride	7487-94-7									NA	7.3E+04	NA	NA
Mercuric Sulfide	1344-48-5									NA	0.0E+00	NA	NA
Mercury (elemental)	7439-97-6			3.0E-04	I		3.1E-01	n	4.7E-01	YES	6.0E-02	2.8E+04	YES
Mercury, Inorganic Salts	NA									NA		NA	NA
Methyl Mercury	22967-92-6									NA		NA	NA
Phenylmercuric Acetate	62-38-4								2.3E-08	NO	4.4E+03	1.0E+02	NA
N,N'-Diphenyl-1,4-benzenediamine	74-31-7								8.4E-09	NO	7.4E+00	6.2E-02	NA
Naled	300-76-5								2.7E-03	YES	1.5E+00	4.1E+03	NA
Napropamide	15299-99-7								3.4E-08	NO	7.3E+01	2.5E+00	NA
Nickel Refinery Dust	NA	2.4E-04	I				1.0E-02	c		NA		NA	NA
Nickel Soluble Salts	7440-02-0									NA	0.0E+00	NA	NA
Nickel Subsulfide	12035-72-2	4.8E-04	I				5.1E-03	c		NA	0.0E+00	NA	NA
Nitrate	14797-55-8									NA		NA	NA
Nitrite	14797-65-0									NA		NA	NA
Nitroaniline, 3-	99-09-2			1.0E-03	P		1.0E+00	n	3.2E-07	NO	1.2E+03	3.8E+02	YES
Nitroaniline, 4-	100-01-6			4.0E-03	P		4.2E+00	n	5.2E-08	NO	7.3E+02	3.8E+01	YES
Nitrobenzene	98-95-3			2.0E-03	H		2.1E+00	n	9.8E-04	YES	2.1E+03	2.0E+06	YES
Nitrofurantoin	67-20-9								5.4E-11	NO	8.0E+01	4.3E-03	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR $(ug/m^3)^{-1}$	key	RfC_i mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? [1]	S mg/L	$C_{max,vp}$ ug/m^3	Sufficiently Toxic? [2]
Nitrofurazone	59-87-0	3.7E-04	C				6.6E-03	c	1.3E-11	NO	2.1E+02	2.7E-03	NO
Nitroglycerin	55-63-0								4.0E-06	NO	1.4E+03	5.5E+03	NA
Nitroguanidine	556-88-7								1.8E-10	NO	4.4E+03	7.9E-01	NA
Nitromethane	75-52-5	9.0E-06	P	2.0E-02	P		2.7E-01	c*	1.2E-03	YES	1.1E+05	1.3E+08	YES
Nitropropane, 2-	79-46-9	2.7E-03	H	2.0E-02	I		9.0E-04	c	4.9E-03	YES	1.7E+04	8.3E+07	YES
Nitroso-di-N-butylamine, N-	924-16-3	1.6E-03	I				1.5E-03	c	5.4E-04	YES	1.3E+03	6.9E+05	YES
Nitroso-di-N-propylamine, N-	621-64-7								2.2E-04	YES	1.3E+04	2.9E+06	NA
Nitroso-N-ethylurea, N-	759-73-9	7.7E-03	C			M	1.2E-04	c	5.4E-09	NO	1.3E+04	7.0E+01	YES
Nitrosodiethanolamine, N-	1116-54-7								9.3E-15	NO	1.0E+06	9.3E-03	NA
Nitrosodiethylamine, N-	55-18-5	4.3E-02	I			M	2.2E-05	c	1.5E-04	YES	1.1E+05	1.6E+07	YES
Nitrosodimethylamine, N-	62-75-9	1.4E-02	I			M	6.9E-05	c	7.4E-05	YES	1.0E+06	7.4E+07	YES
Nitrosodiphenylamine, N-	86-30-6								4.9E-05	YES	3.5E+01	1.7E+03	NA
Nitrosomethylethylamine, N-	10595-95-6								1.7E-05	YES	3.0E+05	5.1E+06	NA
Nitrosopyrrolidine, N-	930-55-2	6.1E-04	I				4.0E-03	c	2.0E-06	NO	1.0E+06	2.0E+06	YES
Nitrotoluene, m-	99-08-1								3.8E-04	YES	5.0E+02	1.9E+05	NA
Nitrotoluene, o-	88-72-2								5.1E-04	YES	6.5E+02	3.3E+05	NA
Nitrotoluene, p-	99-99-0								2.3E-04	YES	4.4E+02	1.0E+05	NA
Norflurazon	27314-13-2								1.4E-08	NO	3.4E+01	4.7E-01	NA
Nustar	85509-19-9								2.1E-05	YES	5.4E+01	1.1E+03	NA
Octabromodiphenyl Ether	32536-52-0								1.0E-05	NO	1.1E-08	1.1E-07	NA
Octahydro-1,3,5,7-tetranitro-1,3,5,7-tetra (H	2691-41-0								3.5E-08	NO	9.4E+03	3.3E+02	NA
Octamethylpyrophosphoramide	152-16-9								2.6E-15	NO	1.0E+06	2.6E-03	NA
Oryzalin	19044-88-3								7.8E-08	NO	2.5E+00	2.0E-01	NA
Oxadiazon	19666-30-9								3.0E-06	NO	7.0E-01	2.1E+00	NA
Oxamyl	23135-22-0								9.7E-09	NO	2.8E+05	2.7E+03	NA
Paclobutrazol	76738-62-0								3.4E-09	NO	2.6E+01	8.8E-02	NA
Paraquat Dichloride	1910-42-5								1.3E-11	NO	6.2E+05	8.1E+00	NA
Parathion	56-38-2								1.2E-05	YES	1.1E+01	1.3E+02	NA
Pebulate	1114-71-2								9.7E-03	YES	1.0E+02	9.7E+05	NA
Pendimethalin	40487-42-1								3.5E-05	YES	2.8E-01	9.6E+00	NA
Pentabromodiphenyl Ether	32534-81-9								1.4E-04	YES	3.9E-04	5.5E-02	NA
Pentabromodiphenyl ether, 2,2',4,4',5- (BDE-	60348-60-9									NA		NA	NA
Pentachlorobenzene	608-93-5								2.9E-02	YES	8.3E-01	2.4E+04	NA
Pentachloroethane	76-01-7								7.9E-02	YES	4.8E+02	3.8E+07	NA
Pentachloronitrobenzene	82-68-8								1.8E-03	YES	4.4E-01	7.9E+02	NA
Pentachlorophenol	87-86-5								1.0E-06	NO	1.4E+01	1.4E+01	NA
Perchlorate and Perchlorate Salts	14797-73-0									NA	2.5E+05	NA	NA
Permethrin	52645-53-1								7.6E-05	YES	6.0E-03	4.6E-01	NA
Phenmedipham	13684-63-4								3.4E-11	NO	4.7E+00	1.6E-04	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR $(ug/m^3)^{-1}$	key	RfC_i mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? [1]	S mg/L	$C_{max,vp}$ ug/m^3	Sufficiently Toxic? [2]
Phenol	108-95-2			2.0E-01	C		2.1E+02	n	1.4E-05	YES	8.3E+04	1.2E+06	YES
Phenylenediamine, m-	108-45-2								3.9E-09	NO	2.4E+05	9.3E+02	NA
Phenylenediamine, o-	95-54-5								2.9E-07	NO	4.0E+04	1.2E+04	NA
Phenylenediamine, p-	106-50-3								3.6E-08	NO	3.7E+04	1.3E+03	NA
Phenylphenol, 2-	90-43-7								4.3E-05	YES	7.0E+02	3.0E+04	NA
Phorate	298-02-2								1.8E-04	YES	5.0E+01	9.0E+03	NA
Phosgene	75-44-5			3.0E-04	I		3.1E-01	n	3.6E-01	YES	4.8E+05	1.7E+11	YES
Phosmet	732-11-6								3.4E-07	NO	2.4E+01	8.3E+00	NA
Phosphine	7803-51-2			3.0E-04	I		3.1E-01	n		NA	4.0E+02	NA	NA
Phosphoric Acid	7664-38-2			1.0E-02	I		1.0E+01	n		NA	5.5E+06	NA	NA
Phosphorus, White	7723-14-0									NA	0.0E+00	NA	NA
Phthalic Acid, P-	100-21-0								1.6E-11	NO	1.5E+01	2.4E-04	NA
Phthalic Anhydride	85-44-9			2.0E-02	C		2.1E+01	n	6.7E-07	NO	6.2E+03	4.2E+03	YES
Picloram	1918-02-1								2.2E-12	NO	4.3E+02	9.5E-04	NA
Picramic Acid (2-Amino-4,6-dinitrophenol)	96-91-3								7.6E-13	NO	1.4E+03	1.1E-03	NA
Pirimiphos, Methyl	29232-93-7								2.9E-05	YES	8.6E+00	2.5E+02	NA
Polybrominated Biphenyls	59536-65-1	8.6E-03	C				2.8E-04	c		NA		NA	NA
Polymeric Methylene Diphenyl Diisocyanate (	9016-87-9			6.0E-04	I		6.3E-01	n	5.4E-10	NO	6.9E-07	3.7E-10	NO
Potassium Perchlorate	7778-74-7									NA	2.1E+04	NA	NA
Prochloraz	67747-09-5								6.7E-07	NO	3.4E+01	2.3E+01	NA
Profluralin	26399-36-0								1.3E-02	YES	1.0E-01	1.3E+03	NA
Prometon	1610-18-0								1.3E-07	NO	7.5E+02	9.8E+01	NA
Prometryn	7287-19-6								5.4E-07	NO	3.3E+01	1.8E+01	NA
Propachlor	1918-16-7								3.7E-06	NO	7.0E+02	2.6E+03	NA
Propanil	709-98-8								7.0E-07	NO	1.5E+02	1.1E+02	NA
Propargite	2312-35-8								1.7E-06	NO	5.0E-01	8.5E-01	NA
Propargyl Alcohol	107-19-7								4.7E-05	YES	1.0E+06	4.7E+07	NA
Propazine	139-40-2								1.9E-07	NO	8.6E+00	1.6E+00	NA
Propham	122-42-9								1.6E-06	NO	1.8E+02	2.9E+02	NA
Propiconazole	60207-90-1								1.7E-07	NO	1.1E+02	1.9E+01	NA
Propylene Glycol	57-55-6								5.4E-09	NO	1.0E+06	5.4E+03	NA
Propylene Glycol Dinitrate	6423-43-4			2.7E-04	A		2.8E-01	n	3.9E-05	YES	2.8E+03	1.1E+05	YES
Propylene Glycol Monoethyl Ether	1569-02-4								1.0E-06	NO	3.7E+05	3.7E+05	NA
Propylene Glycol Monomethyl Ether	107-98-2			2.0E+00	I		2.1E+03	n	3.8E-05	YES	1.0E+06	3.8E+07	YES
Propylene Oxide	75-56-9	3.7E-06	I	3.0E-02	I		6.6E-01	c*	2.8E-03	YES	5.9E+05	1.7E+09	YES
Pursuit	81335-77-5								4.3E-15	NO	1.4E+03	6.0E-06	NA
Pydrin	51630-58-1								1.4E-06	NO	2.0E-03	2.8E-03	NA
Pyridine	110-86-1								4.5E-04	YES	1.0E+06	4.5E+08	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR (ug/m^3)$^{-1}$	key	RfC$_i$ mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? ^{1}	S mg/L	C$_{max,vp}$ ug/m^3	Sufficiently Toxic? ^{2}
Polychlorinated Biphenyls (PCBs)									NA	NA	NA	NA	NA
Aroclor 1016	12674-11-2	2.0E-05	I				1.2E-01	c	8.2E-03	YES	2.7E-01	2.2E+03	YES
Aroclor 1221	11104-28-2	5.7E-04	I				4.3E-03	c	9.3E-03	YES	4.8E+00	4.5E+04	YES
Aroclor 1232	11141-16-5	5.7E-04	I				4.3E-03	c	9.3E-03	YES	4.8E+00	4.5E+04	YES
Aroclor 1242	53469-21-9	5.7E-04	I				4.3E-03	c	1.4E-02	YES	2.8E-01	3.9E+03	YES
Aroclor 1248	12672-29-6	5.7E-04	I				4.3E-03	c	1.8E-02	YES	5.3E-02	9.6E+02	YES
Aroclor 1254	11097-69-1	5.7E-04	I				4.3E-03	c	1.2E-02	YES	3.4E-03	4.1E+01	YES
Aroclor 1260	11096-82-5	5.7E-04	I				4.3E-03	c	1.4E-02	YES	2.8E-04	4.0E+00	YES
Heptachlorobiphenyl, 2,2',3,3',4,4',5- (PCB 17	35065-30-6	1.1E-04	(3)				2.2E-02	c	3.7E-04	YES	3.5E-03	1.3E+00	YES
Heptachlorobiphenyl, 2,2',3,4,4',5,5'- (PCB 1	35065-29-3	1.1E-04	(3)				2.2E-02	c	4.1E-04	YES	3.9E-03	1.6E+00	YES
Heptachlorobiphenyl, 2,3,3',4,4',5,5'- (PCB 1	39635-31-9	1.1E-03	W				2.1E-03	c	5.6E-03	YES	7.5E-04	4.2E+00	YES
Hexachlorobiphenyl, 2,3',4,4',5,5'- (PCB 167)	52663-72-6	1.1E-03	W				2.1E-03	c	6.6E-03	YES	2.2E-03	1.5E+01	YES
Hexachlorobiphenyl, 2,3,3',4,4',5'- (PCB 157)	69782-90-7	1.1E-03	W				2.1E-03	c	6.6E-03	YES	1.6E-03	1.1E+01	YES
Hexachlorobiphenyl, 2,3,3',4,4',5- (PCB 156)	38380-08-4	1.1E-03	W				2.1E-03	c	6.6E-03	YES	5.3E-03	3.5E+01	YES
Hexachlorobiphenyl, 3,3',4,4',5,5'- (PCB 169)	32774-16-6	1.1E+00	W				2.1E-06	c	6.6E-03	YES	5.1E-04	3.4E+00	YES
Pentachlorobiphenyl, 2',3,4,4',5- (PCB 123)	65510-44-3	1.1E-03	W				2.1E-03	c	7.8E-03	YES	1.6E-02	1.2E+02	YES
Pentachlorobiphenyl, 2,3',4,4',5- (PCB 118)	31508-00-6	1.1E-03	W				2.1E-03	c	1.2E-02	YES	1.3E-02	1.6E+02	YES
Pentachlorobiphenyl, 2,3,3',4,4'- (PCB 105)	32598-14-4	1.1E-03	W				2.1E-03	c	3.4E-02	YES	3.4E-03	1.2E+02	YES
Pentachlorobiphenyl, 2,3,4,4',5- (PCB 114)	74472-37-0	1.1E-03	W				2.1E-03	c	7.8E-03	YES	1.6E-02	1.2E+02	YES
Pentachlorobiphenyl, 3,3',4,4',5- (PCB 126)	57465-28-8	3.8E+00	W				6.4E-07	c	7.8E-03	YES	9.4E-03	7.3E+01	YES
Polychlorinated Biphenyls (high risk)	1336-36-3	5.7E-04	C				4.3E-03	c	1.4E-02	YES	2.8E-01	3.9E+03	YES
Polychlorinated Biphenyls (low risk)	1336-36-3	1.0E-04	I				2.4E-02	c	1.4E-02	YES	2.8E-01	3.9E+03	YES
Polychlorinated Biphenyls (lowest risk)	1336-36-3								1.4E-02	YES	2.8E-01	3.9E+03	NA
Tetrachlorobiphenyl, 3,3',4,4'- (PCB 77)	32598-13-3	3.8E-03	W				6.4E-04	c	3.8E-04	YES	5.7E-04	2.2E-01	YES
Tetrachlorobiphenyl, 3,4,4',5- (PCB 81)	70362-50-4	1.1E-02	W				2.1E-04	c	9.1E-03	YES	5.3E-02	4.8E+02	YES
Polynuclear Aromatic Hydrocarbons (PAHs)									NA	NA	NA	NA	NA
Acenaphthene	83-32-9								7.4E-03	YES	3.9E+00	2.9E+04	NA
Anthracene	120-12-7								2.3E-03	YES	4.3E-02	1.0E+02	NA
Benz[a]anthracene	56-55-3	1.1E-04	C			M	8.7E-03	c	4.9E-04	YES	9.4E-03	4.6E+00	YES
Benzo[a]pyrene	50-32-8	1.1E-03	C			M	8.7E-04	c	1.9E-05	YES	1.6E-03	3.1E-02	YES
Benzo[b]fluoranthene	205-99-2	1.1E-04	C			M	8.7E-03	c	2.7E-05	YES	1.5E-03	4.1E-02	YES
Benzo[k]fluoranthene	207-08-9	1.1E-04	C			M	8.7E-03	c	2.4E-05	YES	8.0E-04	1.9E-02	YES
Chrysene	218-01-9	1.1E-05	C			M	8.7E-02	c	2.1E-04	YES	2.0E-03	4.2E-01	YES
Dibenz[a,h]anthracene	53-70-3	1.2E-03	C			M	8.0E-04	c	5.0E-06	NO	1.0E-03	5.2E-03	YES
Fluoranthene	206-44-0								3.6E-04	YES	2.6E-01	9.4E+01	NA
Fluorene	86-73-7								3.9E-03	YES	1.9E+00	7.4E+03	NA
Indeno[1,2,3-cd]pyrene	193-39-5	1.1E-04	C			M	8.7E-03	c	1.4E-05	YES	1.9E-04	2.7E-03	NO
Methylnaphthalene, 1-	90-12-0								2.1E-02	YES	2.5E+01	5.3E+05	NA
Methylnaphthalene, 2-	91-57-6								2.1E-02	YES	2.5E+01	5.2E+05	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC$_i$	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? [1]	S	C$_{max,vp}$	Sufficiently Toxic? [2]
		(ug/m^3)$^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
Naphthalene	91-20-3	3.4E-05	C	3.0E-03	I		7.2E-02	c*	1.8E-02	YES	3.1E+01	5.6E+05	YES
Pyrene	129-00-0								4.9E-04	YES	1.4E-01	6.6E+01	NA
Quinalphos	13593-03-8								2.3E-06	NO	2.2E+01	5.1E+01	NA
Quinoline	91-22-5								6.8E-05	YES	6.1E+03	4.2E+05	NA
Refractory Ceramic Fibers	NA			3.0E-02	A		3.1E+01	n		NA		NA	NA
Resmethrin	10453-86-8								5.4E-06	NO	3.0E-01	1.6E+00	NA
Ronnel	299-84-3								1.3E-03	YES	1.0E+00	1.3E+03	NA
Rotenone	83-79-4								4.6E-12	NO	2.0E-01	9.2E-07	NA
Savey	78587-05-0								9.7E-07	NO	5.0E-01	4.9E-01	NA
Selenious Acid	7783-00-8									NA	9.0E+05	NA	NA
Selenium	7782-49-2									NA	0.0E+00	NA	NA
Selenourea	630-10-4									NA	1.0E+06	NA	NA
Sethoxydim	74051-80-2								8.8E-10	NO	2.5E+01	2.2E-02	NA
Silver	7440-22-4									NA	0.0E+00	NA	NA
Simazine	122-34-9								3.9E-08	NO	6.2E+00	2.4E-01	NA
Sodium Acifluorfen	62476-59-9								2.5E-09	NO	2.5E+05	6.3E+02	NA
Sodium Azide	26628-22-8									NA	4.1E+05	NA	NA
Sodium Diethyldithiocarbamate	148-18-5									NA	1.0E+06	NA	NA
Sodium Fluoroacetate	62-74-8								4.5E-05	YES	1.1E+06	5.0E+07	NA
Sodium Metavanadate	13718-26-8									NA	2.1E+05	NA	NA
Sodium Perchlorate	7601-89-0									NA	2.1E+06	NA	NA
Stirofos (Tetrachlorovinphos)	961-11-5								7.5E-08	NO	1.1E+01	8.3E-01	NA
Strontium, Stable	7440-24-6									NA	0.0E+00	NA	NA
Strychnine	57-24-9								2.4E-12	NO	1.6E+02	3.8E-04	NA
Styrene	100-42-5			1.0E+00	I		1.0E+03	n	1.1E-01	YES	3.1E+02	3.4E+07	YES
Sulfonylbis(4-chlorobenzene), 1,1'-	80-07-9								5.6E-06	NO	6.9E+00	3.8E+01	NA
Systhane	88671-89-0								1.7E-07	NO	1.4E+02	2.4E+01	NA
TCMTB	21564-17-0								2.7E-10	NO	1.3E+02	3.4E-02	NA
Tebuthiuron	34014-18-1								4.9E-09	NO	2.5E+03	1.2E+01	NA
Temephos	3383-96-8								8.0E-08	NO	2.7E-01	2.2E-02	NA
Terbacil	5902-51-2								4.9E-09	NO	7.1E+02	3.5E+00	NA
Terbufos	13071-79-9								9.8E-04	YES	5.1E+00	5.0E+03	NA
Terbutryn	886-50-0								4.7E-07	NO	2.5E+01	1.2E+01	NA
Tetrachlorobenzene, 1,2,4,5-	95-94-3								4.1E-02	YES	6.0E-01	2.4E+04	NA
Tetrachloroethane, 1,1,1,2-	630-20-6	7.4E-06	I				3.3E-01	c	9.9E-02	YES	1.1E+03	1.1E+08	YES
Tetrachloroethane, 1,1,2,2-	79-34-5	5.8E-05	I				4.2E-02	c	1.5E-02	YES	2.9E+03	4.3E+07	YES
Tetrachloroethylene	127-18-4	5.9E-06	C	2.7E-01	A		4.1E-01	c	7.2E-01	YES	2.1E+02	1.5E+08	YES
Tetrachlorophenol, 2,3,4,6-	58-90-2								3.6E-04	YES	2.3E+01	8.3E+03	NA
Tetrachlorotoluene, p- alpha, alpha, alpha-	5216-25-1								7.9E-03	YES	4.0E+00	3.2E+04	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR	key	RfC_i	key	mutagen	Residential Air	key	H'	Sufficiently Volatile? [1]	S	$C_{max,vp}$	Sufficiently Toxic? [2]
		$(ug/m^3)^{-1}$		mg/m^3			ug/m^3		unitless		mg/L	ug/m^3	
Tetraethyl Dithiopyrophosphate	3689-24-5								9.8E-05	YES	3.0E+01	2.9E+03	NA
Tetrafluoroethane, 1,1,1,2-	811-97-2			8.0E+01	I		8.3E+04	n	2.0E+00	YES	7.7E+02	1.5E+09	YES
Tetryl (Trinitrophenylmethylnitramine)	479-45-8								1.1E-07	NO	7.4E+01	8.1E+00	NA
Thallium (I) Nitrate	10102-45-1									NA	9.6E+04	NA	NA
Thallium (Soluble Salts)	7440-28-0									NA	0.0E+00	NA	NA
Thallium Acetate	563-68-8									NA		NA	NA
Thallium Carbonate	6533-73-9									NA	4.7E+04	NA	NA
Thallium Chloride	7791-12-0									NA	3.3E+03	NA	NA
Thallium Sulfate	7446-18-6									NA	5.5E+04	NA	NA
Thiobencarb	28249-77-6								1.1E-05	YES	2.8E+01	3.1E+02	NA
Thiofanox	39196-18-4								3.8E-07	NO	5.2E+03	2.0E+03	NA
Thiophanate, Methyl	23564-05-8								1.2E-11	NO	4.4E+02	5.3E-03	NA
Thiram	137-26-8								1.2E-05	YES	3.0E+01	3.6E+02	NA
Tin	7440-31-5									NA	0.0E+00	NA	NA
Toluene	108-88-3			5.0E+00	I		5.2E+03	n	2.7E-01	YES	5.3E+02	1.4E+08	YES
Toluene diisocyanate mixture (TDI)	26471-62-5			7.0E-05	I		7.3E-02	n	4.5E-04	YES	3.8E+01	1.7E+04	YES
Toluene-2,4-diamine	95-80-7	1.1E-03	C				2.2E-03	c	3.9E-08	NO	7.5E+04	2.9E+03	YES
Toluene-2,5-diamine	95-70-5								3.9E-08	NO	7.2E+04	2.8E+03	NA
Toluene-2,6-diamine	823-40-5								3.9E-08	NO	7.2E+04	2.8E+03	NA
Toluidine, o- (Methylaniline, 2-)	95-53-4	5.1E-05	C				4.8E-02	c	8.1E-05	YES	1.7E+04	1.3E+06	YES
Toluidine, p-	106-49-0								8.3E-05	YES	6.5E+03	5.4E+05	NA
Toxaphene	8001-35-2	3.2E-04	I				7.6E-03	c	2.5E-04	YES	5.5E-01	1.4E+02	YES
Tralomethrin	66841-25-6								1.6E-08	NO	8.0E-02	1.3E-03	NA
Triallate	2303-17-5								7.9E-04	YES	4.0E+00	3.2E+03	NA
Triasulfuron	82097-50-5								1.3E-11	NO	3.2E+01	4.2E-04	NA
Tribromobenzene, 1,2,4-	615-54-3								1.6E-02	YES	4.9E+00	7.8E+04	NA
Tributyl Phosphate	126-73-8								6.1E-06	NO	2.8E+02	1.7E+03	NA
Tributyltin Compounds	NA									NA		NA	NA
Tributyltin Oxide	56-35-9								3.9E+03	YES	1.0E+02	3.9E+11	NA
Trichloro-1,2,2-trifluoroethane, 1,1,2-	76-13-1			3.0E+01	H		3.1E+04	n	2.2E+01	YES	1.7E+02	3.7E+09	YES
Trichloroaniline HCl, 2,4,6-	33663-50-2								2.9E-12	NO	1.1E+05	3.2E-01	NA
Trichloroaniline, 2,4,6-	634-93-5								5.5E-05	YES	4.0E+01	2.2E+03	NA
Trichlorobenzene, 1,2,4-	120-82-1			4.0E-03	P		4.2E+00	n	5.8E-02	YES	4.9E+01	2.8E+06	YES
Trichloroethane, 1,1,1-	71-55-6			5.0E+00	I		5.2E+03	n	7.0E-01	YES	1.3E+03	9.0E+08	YES
Trichloroethane, 1,1,2-	79-00-5	1.6E-05	I				1.5E-01	c	3.4E-02	YES	1.1E+03	3.7E+07	YES
Trichloroethylene	79-01-6	2.0E-06	C				1.2E+00	c	4.0E-01	YES	1.3E+03	5.1E+08	YES
Trichlorofluoromethane	75-69-4			7.0E-01	H		7.3E+02	n	4.0E+00	YES	1.1E+03	4.4E+09	YES
Trichlorophenol, 2,4,5-	95-95-4								6.6E-05	YES	1.2E+03	7.9E+04	NA
Trichlorophenol, 2,4,6-	88-06-2	3.1E-06	I				7.8E-01	c	1.1E-04	YES	8.0E+02	8.8E+04	YES

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	CAS No.	IUR $(ug/m^3)^{-1}$	key	RfC_i mg/m^3	key	mutagen	Residential Air ug/m^3	key	H' unitless	Sufficiently Volatile? ^{1}	S mg/L	$C_{max,vp}$ ug/m^3	Sufficiently Toxic? ^{2}
Trichlorophenoxy) Propionic Acid, 2(2,4,5-	93-72-1								3.7E-07	NO	2.0E+02	7.4E+01	NA
Trichlorophenoxyacetic Acid, 2,4,5-	93-76-5								1.9E-06	NO	2.8E+02	5.3E+02	NA
Trichloropropane, 1,1,2-	598-77-6								1.3E-02	YES	1.9E+03	2.5E+07	NA
Trichloropropane, 1,2,3-	96-18-4								1.4E-02	YES	1.8E+03	2.5E+07	NA
Trichloropropene, 1,2,3-	96-19-5			1.0E-03	P		1.0E+00	n	7.2E-01	YES	3.3E+02	2.4E+08	YES
Tridiphane	58138-08-2								0.0E+00	NO	3.5E-01	0.0E+00	NA
Triethylamine	121-44-8			7.0E-03	I		7.3E+00	n	6.1E-03	YES	7.4E+04	4.5E+08	YES
Trifluralin	1582-09-8								4.2E-03	YES	1.8E-01	7.7E+02	NA
Trimethyl Phosphate	512-56-1								2.9E-07	NO	5.0E+05	1.5E+05	NA
Trimethylbenzene, 1,2,4-	95-63-6			7.0E-03	P		7.3E+00	n	2.5E-01	YES	5.7E+01	1.4E+07	YES
Trimethylbenzene, 1,3,5-	108-67-8			6.0E-03	P		6.3E+00	n	3.6E-01	YES	4.8E+01	1.7E+07	YES
Trinitrobenzene, 1,3,5-	99-35-4								1.3E-07	NO	2.8E+02	3.6E+01	NA
Trinitrotoluene, 2,4,6-	118-96-7								1.9E-05	YES	1.3E+02	2.5E+03	NA
Triphenylphosphine Oxide	791-28-6								2.2E-08	NO	6.3E+01	1.4E+00	NA
Tris(2-chloroethyl)phosphate	115-96-8								1.0E-06	NO	7.0E+03	7.0E+03	NA
Tris(2-ethylhexyl)phosphate	78-42-2								3.2E-06	NO	6.0E-01	1.9E+00	NA
Tetrabromodiphenyl ether, 2,2',4,4'- (BDE-47	5436-43-1									NA		NA	NA
Tri-n-butyltin	688-73-3								6.2E+01	YES	7.3E-03	4.5E+05	NA
Uranium (Soluble Salts)	NA									NA		NA	NA
Vanadium Pentoxide	1314-62-1	8.3E-03	P	7.0E-06	P		2.9E-04	c*		NA	7.0E+02	NA	NA
Vanadium Sulfate	36907-42-3									NA		NA	NA
Vanadium and Compounds	NA									NA		NA	NA
Vanadium, Metallic	7440-62-2									NA	0.0E+00	NA	NA
Vernolate	1929-77-7								1.3E-03	YES	9.0E+01	1.2E+05	NA
Vinclozolin	50471-44-8								5.4E-07	NO	2.6E+00	1.4E+00	NA
Vinyl Acetate	108-05-4			2.0E-01	I		2.1E+02	n	2.1E-02	YES	2.0E+04	4.2E+08	YES
Vinyl Bromide	593-60-2	3.2E-05	H	3.0E-03	I		7.6E-02	c*	5.0E-01	YES	5.1E+03	2.5E+09	YES
Vinyl Chloride	75-01-4	4.4E-06	I	1.0E-01	I	M	1.6E-01	c	1.1E+00	YES	8.8E+03	9.7E+09	YES
Warfarin	81-81-2								1.1E-07	NO	1.7E+01	1.9E+00	NA
Xylene, Mixture	1330-20-7			1.0E-01	I		1.0E+02	n	2.7E-01	YES	1.1E+02	2.9E+07	YES
Xylene, P-	106-42-3			7.0E-01	C		7.3E+02	n	2.8E-01	YES	1.6E+02	4.5E+07	YES
Xylene, m-	108-38-3			7.0E-01	C		7.3E+02	n	2.9E-01	YES	1.6E+02	4.7E+07	YES
Xylene, o-	95-47-6			7.0E-01	C		7.3E+02	n	2.1E-01	YES	1.1E+02	2.2E+07	YES
Zinc (Metallic)	7440-66-6									NA	0.0E+00	NA	NA
Zinc Phosphide	1314-84-7									NA	0.0E+00	NA	NA
Zineb	12122-67-7								6.5E-09	NO	1.0E+01	6.5E-02	NA

Table B-1: Sufficiently Toxic and Volatile Chemicals

Key: I = IRIS; P = PPRTV; A = ATSDR; C = Cal EPA; H = HEAST; W = WHO; M = mutagen; c = cancer; * = where: n SL < 100X c SL; ** = where n SL < 10X c SL; n = noncancer.

Contaminant		Toxicity and Chemical-specific Information					Risk-Based		Determination of		Determination of Sufficiently		
Analyte	**CAS No.**	**IUR**	**key**	**RfC$_i$**	**key**	**mutagen**	**Residential Air**	**key**	**H'**	**Sufficiently Volatile?** [1]	**S**	**C$_{max,vp}$**	**Sufficiently Toxic?** [2]
		(ug/m^3)$^{-1}$		**mg/m^3**			**ug/m^3**		**unitless**		**mg/L**	**ug/m^3**	

Notes:

1. Chemicals are considered sufficiently volatile if H' is greater than $1x10^{-5}$.

2. Chemicals are considered sufficiently toxic if $C_{max,vp}$ >is greater than the risk-based screening level for residential air.

3. The IUR values shown in the 12 SEPT 2008 version of the EPA's Regional Screening Table (i.e., 3.8E-03 per ug/m3) were not used based on understanding that the value on the 12 SEP 2008 version of the table was incorrect. The values used in this table are the upper bound estimate for PCBs with low risk and persistence, consistent with recommendations in the IRIS profile for PCBs (online at: http://www.epa.gov/ncea/iris/subst/0294.htm).

Source table and all chemical-specific parameters are taken directly from the United States Environmental Protection Agency's "Regional Screening Levels for Chemical Contaminants at Superfund Sites", dated 12 SEP 2008.

$C_{max, vp}$ = Maximum Pure Component Vapor Concentration
H' = Dimensionless Henry’s Law Constant
IUR = Inhalation unit risk
ug/m^3 = Micrograms per cubic meter
mg/L = Milligrams per liter
mg/m^3 = Milligrams per cubic meter
NA = Not applicable since one of the required parameters is not available; do not evaluate.
RfC$_i$ = Inhalation reference concentration
S = Pure component solubility

Appendix C: State Regulations, Guidance, and Other Publications on Vapor Intrusion

This appendix provides a list of state guidance or policies related to evaluation of the VI pathway. The references associated with each state include a hyperlink to the Web site where this guidance and more information may be found on the subject. Other links that have lists of state guidance are also included. It should be noted that these links are subject to change or deletion over time; they were current at the time this appendix was prepared.

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Appendix D: Sampling and Analytical Methods Available for Evaluating the Vapor Intrusion Pathway

This appendix presents an overview of the sampling and analytical methods available for evaluating the vapor intrusion (VI) pathway. Methods are included for groundwater, air, sub-slab soil gas, soil gas (both near-slab and farther away), and soil. Sampling should be considered only after initial data collection and development of the conceptual site model (CSM) indicates that the pathway is potentially complete. If sampling is required at a site:

1. Consider a phased approach to evaluate the potential for subsurface vapors to intrude into indoor air and pose an inhalation risk.
2. If groundwater is the source of the potential VI contamination at a site that is proceeding to Tier III and if the groundwater data used in Tier I and II evaluations were collected at relatively distant locations from the building, consider collecting groundwater and soil gas (either sub-slab or near-slab) samples close to the building prior to collecting indoor air samples to better focus the Tier III evaluation on those contaminants detected in groundwater near the building.
3. Limit analysis to constituents of concern for the indoor air pathway at the site. Only analyze for constituents that are of concern for the VI pathway that have been detected in soil, soil gas, or groundwater (depending on data availability).
4. Consider sub-slab or near-slab soil gas sampling prior to other soil gas sampling. Sub-slab soil gas is collected directly below the building slab. Near-slab soil gas is collected as close to the building as possible, generally within 10 feet from the building. Near-slab or sub-slab data will be more representative of vapor infiltrating a building than soil gas samples taken farther away.
5. If indoor air sampling is required, include co-located and co-collected sub-slab soil gas, near-slab soil gas or groundwater, and outdoor air samples in the sampling and analysis plan.
6. Establish how the results will be used and how background data will be applied to the indoor air evaluation.
7. Include the approach for obtaining representative subsurface data in the sampling plan. Site-specific modeling is only as good as the subsurface data supporting your input parameters.

Collection Methods for Groundwater Sampling

Groundwater can be sampled either by installing permanent monitoring wells or through the use of temporary wells. Procedures for each are described below. Advantages, disadvantages, and recommendations to support data quality objectives (DQOs) for each method are presented in Table D-1. Guidance on the EPA's DQO process can be found in *Guidance on Systematic Planning Using the Data Quality Objectives (DQO) Process* (EPA, 2006).

Monitoring Wells

Groundwater samples should be collected from wells screened at or across the top of the water table. The user should establish that light, nonaqueous-phase liquid is not floating on the groundwater as the indoor air concentrations are predicted assuming equilibrium partitioning between the aqueous and vapor phases.

Presented below are suitable groundwater sampling methods for assessing the VI pathway. Low-flow purging and sampling generally results in the most reliable data for the VI pathway because mixing is minimized and a fairly depth-discrete sample can be collected across the water table.

- **Low Flow Purging and Sampling:** Low-flow purging is performed using a low pumping rate (typically less than 1 liter per minute [0.25 gallons per minute]) to reduce stress on the well and surrounding formation and to control sample turbidity. Depending on the geology, the method can consist of a mixed sample that mixes concentrations over varying intervals like a purge sample, or can approximate a point sample similar to a Passive Diffusion Bag (PDB) sample.
- **Passive Diffusion Bag Samplers:** A PDB sampler consists of a semi-permeable membrane tube made from low-density polyethylene (LDPE) that is filled with laboratory-grade deionized water and placed at a specific location within the screened interval of a monitoring well. The PDB sampler is left in place for at least two weeks while constituents in the groundwater diffuse into the water in the bag. Eventually, the concentration within the bag is the same as in the surrounding groundwater and the sampler is retrieved. Once retrieved, the sample is transferred to a standard volatile organic analysis (VOA) vial for analysis. PDB samplers generally constitute a point sample that represents outdoor conditions better than conventional methods because there is no mixing.
- **High Volume Purge Samples:** (at least three casing volumes) – This method provides a flow-weighted sample, meaning more permeable zones provide proportionally more water than less permeable zones. Sampling integrates water over a relatively large area and alters concentrations by mixing. Sometimes this induces flow from horizons not in the vicinity of the well screen. A substantial quantity of water is removed from the well. This method is generally not recommended for evaluating the VI pathway.

Temporary Wells – Direct Push Technology

Push-driven technology refers to tools used to investigate sites by driving, pushing and/or vibrating small-diameter hollow-stem rods into the ground. Sampling tools can be attached to the end of the steel rods to collect soil, soil gas, and groundwater samples. This approach allows the collection of more samples in a shorter period of time, and easier mobilization and access. However, under some conditions, push-driven technology may be limited by the subsurface material (e.g., compacted clean sand). One-time groundwater samples can be collected through a screen point sampler using direct push methods.

Analytical Methods for Groundwater

The EPA SW-846 methods should be used to analyze groundwater samples for use in assessing the VI pathway. However, the key factor in selecting the appropriate method is to review the method detection limits to determine if they are sensitive enough to support risk-based criteria for evaluating the VI pathway, which can be in the part-per-billion to part-per-trillion range. EPA Method SW-846 8260B, volatile organic compounds (VOCs) by gas chromatography/mass spectrometry (GC/MS), is an example of a method that can achieve detection limits for VOCs sensitive enough to support the VI pathway. Even lower detection limits can be achieved for specific constituents by applying the method in the select ion monitoring (SIM) mode.

Air Sampling

Air sampling can be performed to quantify the actual level of vapors to which building occupants are exposed. To determine the level of contamination attributable to VI, air sampling should be conducted concurrently in indoor and outdoor air. Co-located and concurrent near-slab or sub-slab soil gas and groundwater samples are also recommended along with the indoor air samples. One source of information on indoor air sampling methods is the Massachusetts Department of Environmental Protection (MassDEP) Indoor Air Sampling and Evaluation Guide (2002). This document provides a comprehensive overview of the considerations for planning and implementing an air sampling program to evaluate the VI pathway. MassDEP recommends that an outdoor (upwind) sample be collected during every indoor air sampling event.

For outdoor air, constituent concentrations can be highly variable over time and space. Therefore, a site-specific sampling strategy should be developed for each site to ensure that representative background outdoor air samples are collected.

Both indoor air/outdoor air and sub-slab soil gas sampling methodologies are presented below. Advantages, disadvantages, and recommendations to support DQOs for each method are presented in Table D-2.

Also, whenever direct sampling at a potentially affected building is done, a site visit and building evaluation should be performed prior to sampling. In addition, it may be appropriate to use tracer smoke tests or other methods to confirm pressure relationships and air flow patterns, especially between floor levels and between suspected contaminant sources and other areas.

Indoor/Outdoor Air Sampling

Monitoring indoor or outdoor air for the VI pathway generally involves active sampling techniques. Active sampling involves using a pump to actively pass air through a sorbent cartridge or collecting air in a flow-controlled evacuated canister. Passive sampling of VOCs, used primarily for industrial hygiene purposes, relies on the kinetic energy of gas molecules and diffusion of the gases onto a sorbent medium.

Active Air (Time-Weighted) Sampling

An active air time-weighted average sample represents a sample taken at a known sample rate over a fixed period of time (usually less than or equal to a 24-hour period). These methods give average concentrations (e.g., $\mu g/m^3$) over the sampling period, which can be compared directly to target risk concentrations. The most common issue raised with active air sampling is whether the concentrations measured at any given time and day are representative of normal or reasonable maximum exposure (RME) conditions. For indoor sampling, transient artificial conditions (e.g., heating and ventilation systems) or natural conditions (e.g., seasonal or atmospheric changes) can impact vapor flux and mixing within the building over time. In locations with large seasonal variations, more conservative indoor air samples may be collected during the winter months when building conditions (heater, ventilation systems, limited infiltration) increase the pressure differential and subsequent advective vapor flux into the building.

Active indoor air sampling for VI purposes can be performed by using pre-evacuated canisters or by sampling with adsorbent-filled traps. Air samples also can be collected in Tedlar™ bags, although this practice is not considered as reliable unless analysis can be accomplished within a few hours (MassDEP, 2002). Six-liter (L) stainless steel or silica-lined evacuated canisters are most commonly recommended by state and federal agencies. The canister and adsorbent trap methods are described below.

- **Evacuated Canisters:** This method involves collection of air into passivated stainless steel containers or silica-lined canisters that have been prepared under negative pressure and are lab-certified clean for the constituents of interest for the site. The canisters should be equipped with dedicated flow regulators and are typically set up to collect air over a 24-hour period for residential settings (often 8 hours for occupational settings). Results of analysis (e.g., EPA Method TO-14 and/or TO-15) are airborne concentrations of volatiles, typically measured down into the low ppbv levels. For indoor air sampling, 6-L canisters are recommended to collect sufficient sample and achieve required detection limits.
- **VOC Sampling with Adsorbent-Filled Traps:** Both VOCs and semivolatiles can be collected on adsorbent media by drawing air (at a calibrated flowrate) through a hollow tube (glass or metal) containing adsorbent media. Analysis is performed by thermal or constituent desorption and subsequent gas chromatography (GC) analysis (e.g., TO-1 or TO-17). Although sampling duration and flowrate can be optimized based on the adsorbent used and target constituent, the most common problem associated with this method is "breakthrough", in which the sorbent media becomes saturated and any additional VOCs passing through the sampling media are not collected resulting in erroneous concentration calculations. Background contamination of the sorbent material is also a potential problem, particularly for some of the petroleum vapors such as benzene, ethylbenzene and xylenes. Finally, only one sample run is possible for thermal desorption samples, in contrast to the canister method.

Passive Air Sampling

Passive air sampling may be appropriate for longer-term duration sampling (up to three weeks), but is not widely accepted for sampling indoor air in support of the VI pathway. The passive air sampling methodology is more often employed for soil gas monitoring. The most common use of passive indoor air sampling is for industrial hygiene sampling in occupational settings and this method is introduced below.

- **Diffusion badges**: This method involves the use of badges, which collect VOCs in air as they diffuse across the face of the badge. Once vapors cross the face of the badge, they are collected into a sorbent located in the back of the monitor. This sorbent is analyzed for VOCs by a laboratory. This method is not typically used to evaluate the VI pathway at residential locations because the detection limits are not low enough to assess potential residential VI pathway exposures.

Sub-Slab Soil Gas Sampling

Sub-slab soil gas sampling is included with air sampling because it is an approach for measuring vapors directly beneath the foundation/slab of a building. Sub-slab soil gas sampling entails drilling (using a hand drill or limited access drill) a series of small (3/8-inch diameter) holes through the concrete floor of the building foundation. New Teflon®-lined tubing is placed down each hole to a depth just below the foundation floor of a building. Plumber's putty, or a similar VOC-free substance, is applied to the hole around the tubing to seal the hole, and to minimize disturbance of the sub-slab soil gas concentrations and surface air intrusion. The tubing is attached to a purging pump outside of the hole and three to five tubing volumes are purged into a Tedlar™ bag (to avoid purging into indoor air) to ensure the sample represents subsurface conditions. A pre-evacuated stainless steel canister (1-L or 6-L) is attached to the sampling train, and sampled, as discussed above.

Interference from background (outdoor air and atmospheric dilution) is typically less for sub-slab samples than for indoor air samples. Sub-slab sampling may not be appropriate if the building has an existing vapor barrier, or a tension slab. Several considerations in support of DQOs during sub-slab soil gas sampling include the following:

- Sample from the central portion of the foundation to minimize dilution
- Minimize pressure changes by controlling appliances (e.g., exhaust fans), infiltration, etc. to achieve steady state conditions
- Confirm that analytical results meet the required detection thresholds
- Take precautions to minimize disturbance of sub-slab soil gas concentrations – plug holes immediately after drilling
- Consider temporal and spatial variability and sample accordingly
- Collect at least one duplicate sample per building, using dedicated stainless steel or Teflon® tubing.

Analytical Methods

The EPA has developed a series of analytical methods for measuring VOCs in air, known as the EPA Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air (also commonly referred to as the TO-methods). The EPA TO-methods for analysis are specific to the sampling method and are frequently recommended for air sampling associated with the VI pathway. Selection of the appropriate method is also dependent on the method detection limits needed to support risk-based criteria for evaluating the VI pathway. The canister method and the adsorbent method require different TO-methods, as discussed below.

- The EPA methods typically used for air sampling with the pre-evacuated canisters are methods TO-14A and TO-15. The advantage of the specially prepared canister and GC/mass spectrometry (MS) detection through TO-14A or TO-15 is the ability for multiple analyses, which cannot be achieved with the sorbent-based TO-1 or TO-17 method. Method TO-14A measures non-polar VOCs; Method TO-15 measures both polar and non-polar VOCs. Whole air samples are collected in an evacuated canister and VOCs are concentrated in the laboratory prior to being revolatilized and analyzed by GC/MS. Detection limits for constituents range from 0.2 to 25 ppbv. It is often necessary to apply GC/MS in SIM mode to achieve the required detection limits.
- EPA Methods TO-1 or TO-17 are used for analysis of collection sorbents. The use of hydrophobic sorbents in high moisture environments can be an advantage over the whole air TO-14/TO-15 method. Method TO-1 is used for TENAX-GC adsorption and Method TO-17 is used with a multi-bed adsorbent. In these methods, constituents are thermally desorbed from the adsorbent cartridge in the laboratory and analyzed by GC/MS and other methods. Detection limits for constituents using TO-1 range from 0.01 to 100 ppbv and for TO-17 range from 0.2 to 25 ppbv. Although TO-1 has a good database and low detection limits, highly volatile constituents and certain polar constituents are not collected with this method. Method TO-2 is used for more highly volatile constituents but has higher detection limits.

***Note:** Air concentrations of VOCs may be expressed as mass per unit volume (e.g., mg/m^3) or as volume of gas per volume of air (e.g., parts per million by volume [ppmv]). Assuming standard temperature and pressure, ppmv can be converted to mg/m^3 or vice versa by knowing the molecular weight (MW) of the constituent and using one of the following equations:*

$$ppmv \equiv \frac{mg/m^3 \times 24.45}{MW} \quad \text{or} \quad mg/m^3 \equiv \frac{ppmv \times MW}{24.45}$$

Near-Slab Soil Gas Sampling

With the appropriate methodology, soil gas sampling can provide measured values that account for processes that are hard to quantify through modeling (e.g., volatilization from groundwater, transport across the capillary fringe, bioattenuation, and soil-vapor partitioning). Measured values also reflect the presence of vapors in the vadose zone from sources other than the groundwater (e.g., contaminated soil or other unsaturated zone sources). Soil gas sampling is most applicable and reliable at sites with high constituent concentrations and permeable, low moisture soils. Considering the following can optimize reliability and application to the VI pathway.

- **Sample Location and Timing:** Samples should be collected as close to the building as possible, preferably near the location of the highest vadose zone contamination. It may be appropriate to collect soil gas samples concurrently with groundwater and indoor air samples.
- **Sample Depth:** Samples should be collected at a depth of greater than 5 ft below the foundation or below ground surface (bgs). Vertical profiling (e.g., sampling above the groundwater source and in discrete stratigraphic intervals) can be used to determine if measured concentrations decrease with increasing distance from the source. Measured soil gas concentrations above the water table should correlate with groundwater concentrations based on the Henry's Law relationship (e.g., vapor concentrations measured immediately above groundwater should not exceed the value calculated using Henry's Law unless there is a NAPL source nearby). Shallow soil gas sampling (usually less than 5 ft bgs) is considered less reliable than deeper soil gas samples due to potential infiltration of atmospheric air into the samples. For shallow sources, near-slab soil gas samples should be taken just above the source. Other factors to consider in selecting the appropriate depth for soil gas sampling include geologic conditions at the site (e.g., the presence of confining layers), source depth, foundation depth, and building area (Abreu et al., 2006), as these will influence the sub-slab and near-slab soil gas concentrations. For example, collecting near-slab soil gas samples below a confining layer would likely overestimate the concentrations present below the slab. Therefore, it is important to understand the specific conditions at the site.

When evaluating soil gas data and comparing to target concentrations, it is important to understand the subsurface lithology, preferential migration routes (conduits), and the potential for multiple sources. The sampler should identify whether the source of vapors in the area occurs in the unsaturated zone or whether contaminated groundwater is the only source of the contaminant.

Sampling Methodology

Both active and passive sampling methodologies, as well as flux chamber methods, are available for sampling soil gas and each method is introduced below. Active soil gas sampling methodology is most widely accepted for evaluating the VI pathway. Advantages, disadvantages, and recommendations to support DQOs for each method are presented in Table D-3.

Active Soil Gas Sampling

Active soil gas sampling consists of withdrawing soil vapor from the subsurface by driving a heavy-gauge steel probe with inert tubing running down the center of the drive rod or by burying a small-diameter inert tube to a given depth. Samples are collected at discrete depth intervals using vacuum methods (e.g., evacuated canisters) or by pulling the soil gas through adsorbent-filled traps. Active methods are appropriate for the VI pathway because results are reported as a mass of constituent detected per liter of air ($\mu g/m^3$), which is required for calculating the contaminant flux using the EPA VI Model. However, active methods represent a “snapshot” in time and may not reflect transient conditions.

A good overview of the active soil gas methodology is provided in Bulletin 42 (Hartman, 2002). Specific sampling methodologies and protocols are provided in Advisory – Active Soil Gas Investigations (DTSC and Regional Water Quality Control Board [RWQCB], 2003). Several considerations for sampling to evaluate the VI pathway are presented below.

- Large extraction volumes (e.g., 6-L canisters) increase the potential that samples may be drawn from a different depth or location and may create vacuum conditions that cause contaminant partitioning from the sorbed and dissolved phase into the soil gas. However, large volumes may be required to achieve the necessary detection limits for some constituents with very low risk-based screening criteria (e.g., trichloroethylene and vinyl chloride) and excessive vacuums can be prevented by controlling the fill rate. In some cases (at sites with high soil gas constituent concentrations), smaller canisters (e.g., 350 cubic centimeter (cc) “mini-cans”) may be adequate to achieve site-specific DQOs and be more representative of in situ soil gas.
- Purge a minimum of one and a maximum of five system volumes before collecting the sample and use a consistent purge volume throughout the sampling event.
- Seal probes at the surface to prevent breakthrough by packing the upper contact of the probe at the surface with grout or by using an inflatable seal. The possibility of breakthrough increases the closer to the surface the samples are collected (i.e., less than 5 ft bgs).
- Samples from collection systems that employ vacuum pumps should be collected on the intake side of the pump to prevent potential contamination from the pump and with gas-tight syringes and valves to ensure that the samples are not diluted from outside air.
- VOCs typically have very short holding times; therefore, it is important to coordinate with the laboratory to ensure that holding times are met. Tedlar™ bags are not advised unless analysis can be performed onsite.
- Consider transient effects. Temperature, barometric pressure and precipitation can influence vapor flux and measured concentrations. These effects are most pronounced at shallow depths (less than 5 ft bgs). In areas with large seasonal temperature variations, the most conservative samples (i.e., the samples with the highest concentrations of VOCs) will be collected during the summer months.

Passive Soil Gas Sampling

Passive sampling techniques (e.g., EMFLUX® or GORE-SORBER®) rely on diffusion and adsorption and are generally used for longer-duration sampling periods. Collectors housing adsorbent materials are placed in the subsurface and left for a period of time. Organic vapors migrating through the subsurface encounter the collector and are "passively" collected onto the adsorbent material. Passive samplers use hydrophobic adsorbent material or house the adsorbent in a waterproof membrane to prevent the uptake of water vapor, which can limit VOC adsorption. Passive samplers can be used for both VOCs and semivolatile organic compounds (SVOCs). Data are reported in units of mass of constituent adsorbed onto the sample cartridge, which is converted to mass per unit volume of air in the laboratory based on a "cartridge collection constant." This constant requires knowledge of the volume of vapor that passed by the buried adsorbent during the burial time period and there is no established protocol for estimating this volume. This uncertainty makes it difficult to use the passive methodology for quantitative evaluation of the VI pathway. However, passive soil gas sampling can be used as a screening method to identify areas with the highest relative VOC concentrations. These areas can then be targeted for active soil gas sampling.

Surface Flux Chambers

Surface flux chambers are not widely accepted by the regulatory community for evaluating the VI pathway. This method involves use of a flux chamber to sample gaseous emissions from a defined surface area for a period of time (generally a few hours to a few days). The flux is calculated by dividing the measured concentration in the chamber by the incubation time. The flux chamber, if properly applied, provides a direct measurement of the subsurface contaminant flux, which reflects the fate and transport processes (phase-partitioning, bioattenuation, preferential pathways, and advective flow) that are difficult to estimate when applying the EPA VI Model. There is currently no published EPA protocol for the surface flux chamber method. The advantages and limitations of this method are discussed below and presented in Table D-3.

Hartman (2003) describes two basic types of flux chambers: a) the Static (Closed) Chamber method and b) the Dynamic Chamber Method. Each method is summarized below.

- Static (Closed) Chamber Method – A static chamber consists of an inert, non-adsorbing material with sampling ports. No gas is introduced into the chamber during the incubation period in this method. Contaminants flux into the trapped and stagnant chamber volume and VOC concentration builds up over time. Discrete samples are withdrawn during regular intervals during the incubation period. This method is considered simpler and more sensitive (can detect lower time-integrated fluxes) than the dynamic chamber method, and is less prone to disturbances and interferences resulting from the flowing inlet and outlet gases. The primary disadvantage reported for this method is the potential for the chamber concentration to build up (when emission rates are high) and subsequently impede the vapor flux.
- Dynamic Chamber Method – Clean, dry sweep air is continuously added to the chamber at a fixed controlled rate (sweep gas) and an equivalent amount of the chamber gas is allowed to escape. After the system reaches steady state (assumed after four to five chamber residence times), the volumetric flowrate of sweep air through the chamber is recorded and the concentration of the vapor(s) of interest is measured at the exit of the chamber. This method is not limited by chamber concentration build up, as noted for the Static Chamber Method, but is more complex and less sensitive due to the high dilution of the chamber volume resulting from

the sweep gas. The Dynamic Chamber Method was documented by Radian under EPA contract (Kienbusch, 1986).

A flux chamber survey should include four to five chambers employed around the perimeter and central foundation area. For both dynamic and static methods, a typical sample collection includes real-time monitoring or grab sample collection using a syringe or evacuated canister. The result of this measurement is an emission rate for the vapor(s) of interest; actual concentration information is calculated by entering this emission rate data into a dispersion model.

Flux chambers can be employed inside or outside a building. However, several concerns have been raised with respect to their use for evaluating the VI pathway. It is difficult to place the chambers in the most permeable zones (often perimeter cracks in older buildings). For flux calculations, a chamber placed on the floor of a basement may not adequately represent flux from the sidewalls. Chambers placed outside of a building (or in the footprint of a proposed building) will not represent the potential impacts of the slab (resulting in overestimates) or advective flow associated with the building (resulting in underestimates).

Field Methodology

Recommended active soil gas sampling procedures generally include driving a heavy-gauge stainless steel screen with a drive point or drill rod or pipe into the ground by a hammer or vibratory hammer. Installation can be either temporary or semi-permanent. Soil gas is drawn through the port or screen through plastic (primarily polyethylene or Teflon™) or metal tubing and into a collection vessel using a vacuum device, such as an evacuated stainless steel canister or mini-can. Similar direct push methods can be used to install passive samplers. The passive sampling module is inserted into the hole at the prescribed depth.

Note: *The EPA Draft VI Guidance (EPA, 2002) notes that using slam bar methods results in highly variable results and, because the technique is frequently used for relatively shallow sampling, it is prone to errors from dilution by surface air. Particular problems are noted when the hole is punched or drilled with one instrument that is then replaced by a measurement probe (sometimes of smaller diameter).*

Analysis

Active soil gas samples collected for VOCs are generally analyzed using EPA Method TO-14A and/or TO-15, or equivalent. In some cases, based on state requirements and target criteria, it may be sufficient (and more cost-effective) to use EPA Method 8260B with SIM mode. However, Method 8260B is performed using a liquid standard versus a gas standard (used for the TO method). There is some concern that gas samples analyzed using the 8260 method may be biased low. Passive samplers are analyzed using EPA Method 8260 or 8270.

Soil Sampling

Soil sampling for constituent concentrations is not recommended for use in modeling indoor air calculations due to the uncertainties associated with soil partitioning calculations, soil sampling, and soil constituent analysis. Accordingly, no soil constituent criteria are derived in the EPA Draft VI Guidance. However, soil sampling for geotechnical parameters is crucial for obtaining information to use in groundwater vapor migration models such as the EPA VI Model.

Advantages, disadvantages, and recommendations to support DQOs for each method are presented in Table D-4.

Analytical methods for geotechnical soil samples should include: grain-size by American Society for Testing Materials (ASTM) D422, moisture content by ASTM D2216, wet and dry bulk density by ASTM D2937, and total porosity by ASTM D854. Geotechnical samples should be collected from vertical borings. It is recommended that the soil be logged to the top of the water table to determine the lithology. At a minimum, geotechnical samples should be collected from each lithologically different soil horizon. Samples should be collected in 2.5-inch-diameter sleeves or greater using stainless steel or brass containers to minimize disruption of the sample.

Quality Assurance/Quality Control

Quality assurance/quality control (QA/QC) is important for all sample collection and analysis activities associated with assessment of the VI pathway; however, detailed descriptions of QA/QC procedures are beyond the scope of this document. A comprehensive review of QA/QC requirements for VI sampling can be found in Appendix I of the New Jersey Department of Environmental Protection's VI Guidance (NJDEP, 2005).

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Table D-1. Groundwater Sampling Methods

Method	Advantages	Disadvantages	Recommendations
Groundwater Sampling DQO To determine groundwater concentrations at or across top of water table that most reflects aqueous phase concentrations at the source beneath building.			
Monitoring Wells	Permanent – can monitor time-dependent conditions (concentration and depth to groundwater).	More cost and time. Not as accessible to building. Long-term commitment.	Sample discrete interval across water table. Sample at least two events (seasonal). Collect depth to groundwater to show water table fluctuations. Sample as close to buildings as possible.
Monitoring Wells − Low- Flow Purge and Sample	Minimizes drawdown and total purge volume required. Less purge time and wastewater. Low turbidity samples, reduced field filtering costs and time. Minimizes aeration during sample collection. Reduces stress on well and surrounding formation. Increased accuracy due to improved well stabilization techniques.	Requires more purging than PDB sampling.	Use only positive-displacement pumps for VOC sampling. Pipe intake must be at the proper depth to ensure that constituent is intercepted correctly.
Monitoring Wells − Passive Diffusion Sampling[1]	Reflects groundwater concentration at sample location, not drawn in from another area. Inexpensive and relatively easy to deploy, minimal labor and field equipment. Samplers are disposable.	Requires more sample time than low flow. Time to equilibrate may exceed VOC changes in concentration.	Best used for well-characterized sites where target chemicals are known. Conduct side-by-side comparison with low flow or purge groundwater techniques before use.

Table D-1. Groundwater Sampling Methods (Continued)

Method	Advantages	Disadvantages	Recommendations
Monitoring Wells – Passive Diffusion Sampling[1] (Continued)	Multiple samplers can delineate constituent stratification. Pore size prevents sediment passing through membrane. Allows collection of VOCs in non-alkaline matrix, eliminating VOC loss through foaming during sample preservation.	Relies on free movement through well screen. May not represent concentrations if well screen is occluded or sand packed more transmissive than the well screen. Represents concentration at elevation of sampler-single PDB sampler may not adequately target most concentrated zone.	Samplers should equilibrate for at least 2 weeks in monitoring wells constructed in sandy soils. Demonstrate that equilibration period is sufficient in less permeable soils. Multiple samples should be used until constituent stratification or other complicating factors are determined to be not present.
Monitoring Wells – High Volume Purge	None	Large purge volume, increased wastewater. Induces mixing, aeration, and turbidity. May induce flow from other horizons.	Not recommended.
Temporary Wells – Direct Push Methodology	Relatively inexpensive. Less time to install – can be used for screening purposes. Equipment relatively compact, mobile, can be used indoors or around buildings. Allows for discrete sampling at top of water table.	One time only – No seasonal variation. May be limited by hard/compacted material.	Collect as close to building as possible. Sample at or across water table.

1. Obtained from USGS, 2001: *User's Guide for Polyethylene-Based Passive Diffusion Bag Samplers to Obtain VOC Concentration in Wells.*

Table D-2. Air Sampling Methods

Air Sampling Method	Advantages	Disadvantages	Recommendations
Air Sampling – Indoor Air/Outdoor Air DQO To determine the air concentrations of volatiles that building occupants are exposed to subsurface source.			
Active Air Sampling Using Evacuated Stainless Steel Canisters	Portable and easy to operate. Directly measures air concentrations. Can obtain detection limits that meet regulatory levels of interest. Not limited by breakthrough. Treated interior prevents sample decomposition and sample loss. Sufficient volume can be collected for multiple analysis.	Results can be difficult to interpret based on potential background contamination from other sources[1]. Higher analytical and certification costs.	Co-sample with outdoor air, sub-slab soil gas, soil gas and groundwater. Chose sampling and analytical methods to meet regulatory levels of concern. Collect time-integrated sample in 6-L flow meter for 24-hour period. Monitor flow during period to ensure consistent flowrate. Analyze samples with method TO14A and/or TO15. Collect at least one duplicate per building. Collect at least one outdoor air sample per indoor air event.
Active Air Sampling Using Adsorbent Tubes	May be validated for more constituents than canister methods. Can collect VOCs and SVOCs. Can be less costly than canister methods.	Results can be difficult to interpret based on potential background contamination from other sources.[1] More complex and difficult to use than canister methods. Each cartridge can be analyzed only once. Breakthrough may result in underestimating concentrations. Potential issues with blank contamination[2] and extraction efficiency.	Apply same indoor air field sampling protocol as above. Optimize sample duration and flowrate to minimize breakthrough.

Table D-2. Air Sampling Methods (Continued)

Air Sampling Method	Advantages	Disadvantages	Recommendations
Passive Sampling – Diffusion Badges/Sorbents	Can use for longer time period. Simple, cost-effective.	Higher detection limits than active sampling. Affected by humidity. Back diffusion off the sampling medium. Interferences between constituents. High blank values for some constituents[2]. Limited by the break through capacity of the sorbent.	Most appropriate for industrial hygiene purposes in industrial settings. Not recommended or VI pathway evaluations.
Air Sampling – Sub-Slab Soil Gas DQO – To characterize vapor concentrations directly under footprint of structure.			
Sub-Slab Soil Gas	Conservative estimate of vapor concentration inside building. Less influenced by outdoor air than indoor air. Reflects fate and transport processes in subsurface. Reflects subsurface conditions beneath building. In conjunction with indoor and outdoor air, can be used to assist in determining the source of contaminant.	Re-aeration under small slabs (houses) likely. Indoor samples logistically more difficult to collect than outdoor soil gas samples.	Collect during same period with indoor and outdoor air. Groundwater and/or soil gas may also be necessary. Use construction and sealing materials that are VOC-free. Install at least three sub-slab vapor probes in each residence to establish spatial variability (more for large buildings). Collect one duplicate per residence. Purge vapor probe by filling at least 2 Tedlar™ bags. Monitor O_2, CO_2, and CH_4 during purging. Place hydrated bentonite seal or equivalent above the screen near ground surface to minimize surface air intrusion.

1. Indoor air samples can be contaminated from the use of everyday cleaning products, beauty products, and home maintenance materials such as paints. Similarly, outdoor air samples can become contaminated from outdoor sources of contamination that are unrelated to site sources.
2. Blanks are more frequently contaminated by the solvents used by the laboratory to run the analysis.

Table D-3. Soil Gas Sampling Methods

Soil Gas Sampling Method	Advantages	Disadvantages	Recommendations
Soil Gas Sampling DQO To determine vapor concentrations in soil gas directly adjacent to or beneath a building of potential concern associated with the VI pathway.			
Active Soil Gas Sampling – Evacuated canisters	Real time and direct measurement of air concentrations. Provide concentration data (e.g., µg/m^3) Can show vertical gradients. Can obtain detection limits that meet regulatory levels of interest. Samplers are easy to use. Not limited by break through. Sufficient volume can be collected to allow for assessment of precision or analysis by several analyses.	Equipment, certification, and analysis can be costly. May be less sensitive in low permeability or high moisture environments. Large extraction volumes may pull artificially high concentrations from different depth or location. Excessive vacuums may cause contaminant partitioning from sorbed or dissolved phase. Regulatory community may be reluctant to use the information quantitatively.	Collect within same time period and location as indoor air, sub-slab soil gas, and groundwater samples. Evaluate permeability and moisture content, identify low permeability zones and collect from most permeable zones. Use minimum volume that can achieve necessary detection limits. Use minimum purge volume necessary to flush system. Seal probe at surface. Check for subsurface short-circuiting with aboveground atmosphere. Sample at depths greater than 5 ft bgs. Confirm laboratory holding times. Collect duplicate samples. Avoid sampling after significant precipitation or barometric pressure fluctuation.

Table D-3. Soil Gas Sampling Methods (Continued)

Soil Gas Sampling Method	Advantages	Disadvantages	Recommendations
Passive Soil Gas Sampling – Adsorbents (Emflux®, Goresorber®)	More sensitive to detecting the presence of VOCs, especially in less permeable (silt/clay) or high moisture units. Time-weighted average over longer period may capture transient conditions. May be sampled at shallower depths because of the sensitivity. Hydrophobic adsorbent materials minimize moisture issues.	Results are mass data - weight per sorbent. No practical way (or accepted protocol) to measure flowrate through material. May become saturated at higher levels, resulting in inaccurate concentrations. Regulatory community may be reluctant to use the information quantitatively.	More appropriate for screening level or determining if low levels of contaminants exist. Less certain for determining air volume concentrations. Collect method and trip blanks. Leave samplers in ground for sufficient period of time. Collect duplicate samples.
Flux Chamber Methods DQO To characterize the emission rates of volatile constituents and use this information to predict exposure point concentrations for building occupants.			
Flux Chamber Methods Static Chamber – Non-continuous (batch) sample taken after period of time. No sweep gas required. Dynamic Chamber – Sample taken over incubation period. Sweep gas required.	Can be used to define the emission rates across an entire surface area.	Regulatory community not familiar with approach and may be reluctant to use the information quantitatively. Location of chamber may not represent maximum influx or RME conditions. Sampling results in a measure of emission rate, not of air concentration. Multiple chambers (minimum of 3) required to obtain emission rate measurement. Multiple samples over incubation period required for representativeness. More expensive to conduct than active air sampling. Not appropriate for basements. Flux through sidewalls must be estimated.	Sampling, analytical, and modeling methods must be chosen to meet regulatory levels of concern. Use 8021B and 8260B analytics over TO-Methods because require smaller sample volume.

Table D-4. Soil Geotechnical Sampling Methods

Soil Sampling Method	Advantages	Disadvantages	Recommendations
Soil Geotechnical Samples To collect representative subsurface geological information in order to develop a site-specific EPA VI Model.			
Geotechnical Sampling and Analysis Grain Size (ASTM D422) Moisture Content (ASTM D2216) Wet and dry bulk density (ASTM D2937) Total porosity (ASTM D854)	Critical information for application of EPA VI Model	May be difficult to adequately represent horizontal and vertical heterogeneity at some sites.	Log soil to top of water table to determine if there are variations in soil lithology. Collect samples from different soil horizons. Use 2.5-inch ID brass or stainless steel sleeves to minimize sample disturbance.

Appendix E: EPA's Occupied Dwelling Questionnaire

Appendix E contains the "Occupied Dwelling Questionnaire" that was originally presented in the EPA's *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance;* EPA 2002). This information is presented here to provide an example list of questions to ask and issues to be aware of when conducting indoor air samples. Several state health departments also provide indoor air sampling checklists, including Massachusetts (MassDEP, 2002) and California (DTSC 2005). It is recommended that a similar questionnaire be used when collecting indoor air samples at DoD sites.

OCCUPIED DWELLING QUESTIONNAIRE
Indoor Air Assessment Survey

Date: _______________

1. Name:____

   Address:____

   ____

   Home Phone:_______________________ Work Phone:_________________________

2. What is the best time to call to speak with you?________ At: Work or Home?

3. Are you the Owner, Renter, Other (please specify)_________________________

   of this Home/Structure?

4. Total number of occupants/persons at this location?___________

   Number of children? _______ Ages?_________

5. How long have you lived at this location? ___________

General Home Description

6. Type of Home/Structure (check only one): Single Family Home, Duplex,

   Condominium, Townhouse, Other.______________________

7. Home/Structure Description: number of floors ________

   Basement? Yes. No.

   Crawl Space? Yes. No.

   If Yes, under how much of the house's area? ____%

8. Age of Home/Structure: ________ years, Not sure/Unknown.

9. General Above-Ground Home/Structure construction (check all that apply):

   Wood, Brick, Concrete, Cement block, Other ._____________

10. Foundation Construction (check all that apply):

Concrete slab.

Fieldstone.

Concrete block.

Elevated above ground/grade.

Other_____________________________

11. What is the source of your drinking water (check all that apply)?

Public water supply.

Private well.

Bottled water.

Other, please specify ________________________________

12. Do you have a private well for purposes other than drinking?

Yes. No.

If yes, please describe what you use the well for:___________________________

____

13. Do you have a septic system? Yes. No. Not used. Unknown.

14. Do you have standing water outside your home (pond, ditch, swale)? Yes. No.

Basement Description, please check appropriate boxes.

If you do not have a basement go to question 23.

15. Is the basement finished or unfinished?

16. If finished, how many rooms are in the basement?__________

How many are used for more than 2 hours/day?__________

17. Is the basement floor (check all that apply) concrete, tile, carpeted, dirt, Other (describe)_________________________?

18. Are the basement walls poured concrete, cement block, stone, wood, brick, other.____?

19. Does the basement have a moisture problem (check one only)?

Yes, frequently (3 or more times/yr).

Yes, occasionally (1-2 times/yr).

Yes, rarely (less than 1 time/yr).

No.

20. Does the basement ever flood (check one only)?

Yes, frequently (3 or more times/yr).

Yes, occasionally (1-2 times/yr).

Yes, rarely (less than 1 time/yr).

No .

21. Does the basement have any of the following? (check all that apply) Floor cracks, Wall cracks, Sump, Floor drain, Other hole/opening in floor.
(describe)_______

22. Are any of the following used or stored in the basement (check all that apply)
Paint. Paint stripper/remover. Paint thinner.
Metal degreaser/cleaner. Gasoline. Diesel fuel. Solvents. Glue.
Laundry spot removers. Drain cleaners. Pesticides.

23. Have you recently (within the last six months) done any painting or remodeling in your home? Yes. No.
If yes, please specify what was done, where in the home, and what month:
____
____

24. Have you installed new carpeting in your home within the last year? Yes. No.
If yes, when and where?____

25. Do you regularly use or work in a dry cleaning service (check only one box)?
Yes, use dry-cleaning regularly (at least weekly).
Yes, use dry-cleaning infrequently (monthly or less).
Yes, work at a dry cleaning service.
No.

26. Does anyone in your home use solvents at work?
Yes. If yes, how many persons__________
No. If no, go to question 28

27. If yes for question 26 above, are the work clothes washed at home? Yes. No.

28. Where is the washer/dryer located?
Basement.
Upstairs utility room.
Kitchen.

Garage.

Use a Laundromat.

Other, please specify.____________________________________

29. If you have a dryer, is it vented to the outdoors? Yes. No.

30. What type(s) of home heating do you have (check all that apply)

Fuel type: Gas, Oil, Electric, Wood, Coal, Other______________________

Heat conveyance system: Forced hot air.

Forced hot water.

Steam.

Radiant floor heat.

Wood stove.

Coal furnace.

Fireplace.

Other_________________________

31. Do you have air conditioning? Yes. No. If yes, please check the appropriate type(s)

Central air conditioning.

Window air conditioning unit(s).

Other., please specify_____________________________________

32. Do you use any of the following? Room fans, Ceiling fans, Attic fan.

Do you ventilate using the fan-only mode of your central air conditioning or forced air heating system? Yes. No.

33. Has your home had termite or other pesticide treatment: Yes. No. Unknown.

If yes, please specify type of pest controlled, ___________________________________

and approximate date of service ____

34. Water Heater Type: Gas., Electric., By furnace., Other._____________________

Water heater location: Basement, Upstairs utility room, Garage, Other. (please describe) ____

35. What type of cooking appliance do you have? Electric, Gas, Other.____________

36. Is there a stove exhaust hood present? Yes. No.

Does it vent to the outdoors? Yes. No.

37. Smoking in Home:

None., Rare (only guests)., Moderate (residents light smokers).,
Heavy (at least one heavy smoker in household).

38. If yes to above, what do they smoke?
Cigarettes. Cigars. Pipe. Other.

39. Do you regularly use air fresheners? Yes. No.

40. Does anyone in the home have indoor home hobbies of crafts involving: None .
Heating, soldering, welding, model glues, paint, spray paint,
wood finishing, Other. Please specify what type of hobby: ________________________
____

41. General family/home use of consumer products (please circle appropriate): Assume that **Never** = never used, **Hardly ever** = less than once/month, **Occasionally** = about once/month, **Regularly** = about once/week, and **Often** = more than once/week.

Product	**Frequency of Use**
Spray-on deodorant	
Aerosol deodorizers	
Insecticides	
Disinfectants	
Window cleaners	
Spray-on oven cleaners	
Nail polish remover	
Hair sprays	

42. Please check weekly household cleaning practices:
Dusting.
Dry sweeping.
Vacuuming.
Polishing (furniture, etc).
Washing/waxing floors.
Other.________________________

43. Other comments: ____

____

____

____

____

____

____

____

____

Appendix F: Sampling and Analysis Costs for Evaluating the Vapor Intrusion Pathway

This appendix provides Remedial Project Managers (RPMs) with general costs for selected sampling and analytical methodology considered appropriate for evaluating the vapor intrusion (VI) pathway. It should be noted that this is not a complete list of methods available for evaluating the VI pathway, and that other methods may be appropriate based on the characteristics (size and complexity) of the site. Sampling media, installation platforms, collection methods, and analytical requirements are site-specific. Several factors to consider when planning a sampling and analytical program for evaluating VI sites include the following:

- Agency (state/federal) specific sampling protocols may drive the appropriate sampling technique.
- Agency (state/federal) screening criteria will drive the necessary detection limits, and subsequent analytical choices, for each site.
- The sampling and data evaluation methodologies used to assess the VI pathway can vary from state to state and Environmental Protection Agency (EPA) Region to EPA Region. It is important to clearly understand the regulatory setting for a given site and develop the sampling and analysis program for evaluating the VI pathway accordingly.

Table F-1 provides cost estimates for various sampling methodologies (organized by media) used in evaluating the VI pathway. Table F-2 provides cost estimates for the most commonly applied analyses for evaluating the VI pathway. Table F-2 also estimates costs for characterizing physical/geotechnical parameters used in application of the EPA VI Model. These estimates do not reflect the labor costs associated with sample collection, data management, and data evaluation. In addition, mobilization costs typically are not included and there may be significant cost savings if a significant number of samples are being collected. The costs generally reflect the costs that may be incurred per sample for locations where approximately one to five samples are being collected.

Note: These costs were accurate at the time this appendix was prepared but are subject to change over time.

Table F-1. Cost Estimates for Typical Sample Collection Methodologies Used to Assess the VI Pathway

Sampling Activity	Cost Basis	Cost Estimate[1]
Groundwater		
Installation and Sampling Methods		
Monitoring well	Install, develop, 2-inch inside diameter (ID) well to 10-15 ft bgs + local mob and demob[2]. Assume $65 per ft. Excludes sampling costs. Note: per well costs will decrease slightly as the number of wells to be installed increases.	$1,300 per well + sampling cost
Direct-push methodology	Per sample cost using direct push technology to depth of 10-15 ft bgs. Includes local mob and demob.	$200 – $250 per direct push sample
Air		
Indoor/Outdoor Air Sampling Methods		
Active – evacuated stainless steel canister	Per sample: 6-L canister + flow controller + fittings/tubing (certification varies from $65 [batch] to $125[individual]).	$150 – $250
Passive – adsorbent badges	Cost per constituent-specific badge	$40 – $60 per badge
Sub-slab sampling	Install sampler at 5-10 ft below foundation. Cut concrete and use direct push or manual (jack hammer).	$300 – 500 per installation (excludes sampler and analysis)
Soil Gas		
Installation Methods (excludes sampler and analysis)		
Temporary or semi-permanent probe with sample train	Install 1-2 sample ports, with air rotary or hammer drill to max depth of 20 ft bgs.	$500 – $700 per probe
Install inert tubing with hand auger	Install 10-12 tubes with 2-ft and 4-ft sampling intervals	$1000 – $1,200 per day with contractor or about $100/tube location
Static flux chamber	Install 3-5 flux chambers around building or footprint with periodic sampling.	$1,500 – $2,500 per chamber
Sampling Methods		
Active – Evacuated stainless steel canister	6-L stainless steel canister + flow controller + fittings/tubing (certification varies $65-$125)	$150 – $250 per canister
Active – Evacuated stainless steel canister	Per sample with mini-can (350cc) canister + flow controller, fittings/tubing (certification varies $20 [batch] - $120 [individual])	$60 – $200 per canister
Active - Adsorbent-filled traps	Cost per sample for polymeric absorbent (e.g., Tenax™) to include sample cartridges/tubes and pump rental	$20 – $50 per sample $70-$100 per week for pump rental
Active - Tedlar bags	Per sample: 1-L Tedlar bag + pump	$10 – $15 per bag + pump and sample fitting cost
Passive – Buried adsorbent (EMFLUX® or GORE-SORBER®)	Per sample includes analysis (depends on constituents)	$200 – $350
Soil		
Soil borings for geotechnical	Two samples from 2.5-inch brass/steel sleeve to depth of 20 ft bgs. About $45 per ft, including local mob and demob.	$800 – $1,000 per boring
Soil borings for environmental sampling	Continuous sampling of 2-inch ID. About $45 per ft, including local mob and demob.	$800 – $1,000 per boring

1. Labor and analytical costs not included. See Table F-2 for analytical costs.
2. Mobilization costs vary based on size of site. In some cases, local mobilization costs are estimated.

Table F-2. Cost Estimates for Typical Analytical Methodologies Used to Assess the VI Pathway

Sample Type	General Detection Limitations[1]	Estimated Cost[2]
Groundwater		
VOC - SW-846 Method 8260B	1 – 10 µg/L	\$130 – \$160
VOC - SW-846 Method 8260B-SIM	0.02 – 1 µg/L	\$170 – \$250
Air (Indoor, Outdoor, Sub-Slab, Soil Gas)		
TO-1	0.01 – 100 ppbv	\$150 – \$200
TO-14a and/or TO-15 – Standard	1 µg/m^3	\$200 – \$300
TO-14a and/or TO-15 – SIM	<1 µg/m^3	\$250 – \$350
TO-17	0.2 – 25 ppbv	\$200 - \$300
8260/8260B	100 µg/m^3	\$100 – \$150
8260B – SIM	10 µg/m^3	\$125 – \$200
Soil		
Geotechnical Analysis	Description	
Total Porosity	Includes wet/dry density/ moisture, specific gravity and calculations for porosity	\$40 – \$60
ASTM D422 Grain Size	Sieve or hydrometer	\$70 – \$80
ASTM D2974 - Total Organic Matter		\$30 – \$40
Hydraulic Conductivity	Rigid wall test for clays	\$150 – \$170
	Flex wall test for silts and clays	\$250 – \$270

1. Detection limits vary by contaminant, sample size, and other interferences. Limits presented in this table are for general comparison purposes only.
2. Costs vary by number of constituents and number of samples being analyzed.

Appendix G: Assessment of Background at Vapor Intrusion Sites

Introduction

This appendix highlights issues associated with assessing the contribution of background sources to indoor air at vapor intrusion (VI) sites and presents a suggested approach for assessing this background contribution. The purpose of the background assessment is to focus the VI pathway evaluation on volatile organic compounds (VOCs) that are related to impacted groundwater, soil, or soil gas and, to the extent possible, quantify the contribution of chemicals that are present due to background sources (e.g., building materials, human activity patterns, and outdoor air). Background assessment is important when investigating the VI pathway because the purpose of the VI evaluation is to estimate the incremental risks attributable to releases from a site, without contribution from background sources.

Evaluation of the VI pathway is accomplished using a three-tiered approach. The first two tiers use data from groundwater, soil gas, or soil and involve comparison to conservative risk-based concentrations (RBCs) and modeling. Tier III relies primarily on direct measurements of near-slab or sub-slab soil gas and/or indoor air to examine vapor migration and potential exposures in more detail. Because of the difficulties in assessing background air contamination, indoor air sampling is typically the last step of a remedial investigation of the VI pathway. By the time a site proceeds to Tier III, the decision of whether to install a VI mitigation system may be driven by a time-critical schedule, and this requires a practical approach that transparently and relatively quickly assesses the risk associated with VI. A list of common household sources of background indoor air contaminants is presented in Exhibit G-1.

Measured concentrations of VOCs in indoor air consist of three components:

1. VOCs from subsurface VI
2. VOCs from indoor air background sources
3. VOCs from outdoor air background sources

When determining whether VI is impacting the building at levels of concern, it is important to evaluate the contributions from each of these sources. Therefore, for all direct indoor air measurements, it is recommended that co-located and concurrent groundwater, near-slab or sub-slab soil gas, and outdoor air sampling be performed so that the potential confounding factors (e.g., background concentrations) can be evaluated. Co-located background samples should focus only on target VOCs (i.e., VOCs that have been detected in soil, soil gas, and/or groundwater at the site) to help focus further assessment and potential mitigation on those VOCs known to be associated with the groundwater, soil, or soil gas. Also, it may be appropriate at some sites to collect outdoor air samples when collecting soil gas adjacent to (near-slab) and beneath buildings (sub-slab). The influence of background sources of VOCs on soil gas may be particularly important when sampling near landfills and geological sources of VOCs such as naturally-occurring petroleum.

Purpose

The purpose of this appendix is to present an approach that can be used by Remedial Project Managers (RPMs) to assess the contribution of background sources to indoor air at VI sites.

This approach uses literature values in conjunction with site-specific outdoor air measurements to determine whether the contaminants detected in indoor air are attributable to VI from the site and, if so, what concentrations may be attributable to background sources.

The approaches for collecting and analyzing samples, determining background concentrations, and determining how to assess indoor air concentrations for contributions from background in order to determine whether action is warranted should be considered during the data quality objective (DQO) process and discussed with the appropriate regulatory agencies prior to the collection of data.

Background Sources of VOCs in Indoor Air

Background concentrations of VOCs in indoor air are caused by use and storage of many common consumer products and building materials (e.g., paints, household cleaners, glues, fingernail polish remover, aerosol sprays, tobacco products, recently dry-cleaned clothes, carpeting, sheet-rock, plywood, and sheet vinyl flooring)[1]. Analytical methods, which are often required to meet sub-part per billion (ppb) risk-based method detection limits (MDLs), can detect VOCs in indoor air that are emitted from these common household products and building materials. Background contamination in outdoor air also will influence indoor air concentrations. Typical urban contaminant sources to outdoor air include nearby gasoline stations, automobile exhaust, dry cleaners, fuel storage tanks, diesel motors and generators, industrial facilities, and landfills. Outdoor air typically enters a building through infiltration, natural ventilation, and mechanical ventilation. Studies have shown that VOC background concentrations are consistently higher inside a building than in outdoor air (Zhu et al., 2005; Girman et al., 1999).

Approach for Assessing Background at VI Sites

Assessing the contribution of background sources to measured indoor air concentrations often requires a multi-faceted, "weight-of-evidence" approach and should be factored into the overall assessment of VI throughout the remedial investigation. In addition, once it is determined that measurement of indoor air is needed, a direct approach for evaluating the contribution of background sources in indoor air and outdoor air should be established. Within a building structure, both indoor and outdoor background sources may interfere with, mask, or enhance site-related concentrations migrating from groundwater, soil, or soil gas. The contribution from outdoor air can be measured through site-specific sampling.

Background Indoor Air Concentrations

Indoor air background concentrations can be determined either by use of literature values representing background or by collection of site-specific indoor air background samples from nearby control sites. However, there are numerous difficulties with the collection of site-specific indoor air background samples. As stated in the New Jersey Department of Health (NJDEP) VI Guidance (NJDEP, 2005a):

"Building interiors do not generally provide for 'upgradient' or 'non-impacted' sampling locations in order to establish background indoor air concentrations. Thus, an alternative

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[1] Ingredients in typical household products are shown in Exhibit G-1, which is taken from Appendix H of the NJDEP VI Guidance (http://householdproducts.nlm.nih.gov/index.htm).

approach is necessary for indoor air assessments to distinguish background contamination from site related VI."

Therefore, the preferred approach for determining indoor air background concentrations is the use of literature values. A discussion of the issues associated with site-specific indoor air background sampling also is presented, although it is not the recommended approach.

Literature Values

Literature values present the most feasible way to represent typical background concentrations of VOCs and, therefore, are the recommended approach. This is one of several lines of evidence proposed by several states and the EPA (EPA, 2002) for assessing the impact of background contaminant sources. Specifically, it is recommended that literature values be used to represent the indoor air component of background contamination in addition to measured concurrent site-specific outdoor air values.

Literature values for background concentrations of VOCs in indoor air have been reported in local, regional, national and international studies. Appendix F of the NJDEP VI Guidance presents a summary of available literature studies through June 2002 that were conducted primarily in urban areas throughout the United States and focused on background levels of VOCs in homes and other structures (NJDEP, 2005a). Fifty-two VOCs were included in the summary. The guidance suggests that comparison with literature values is most practical for commonly occurring and frequently studied VOCs (i.e., benzene, carbon tetrachloride, chloroform, p-dichlorobenzene, ethylbenzene, styrene, tetrachloroethylene [PCE], 1,1,1-trichloroethane, trichloroethylene [TCE], toluene, and xylene).

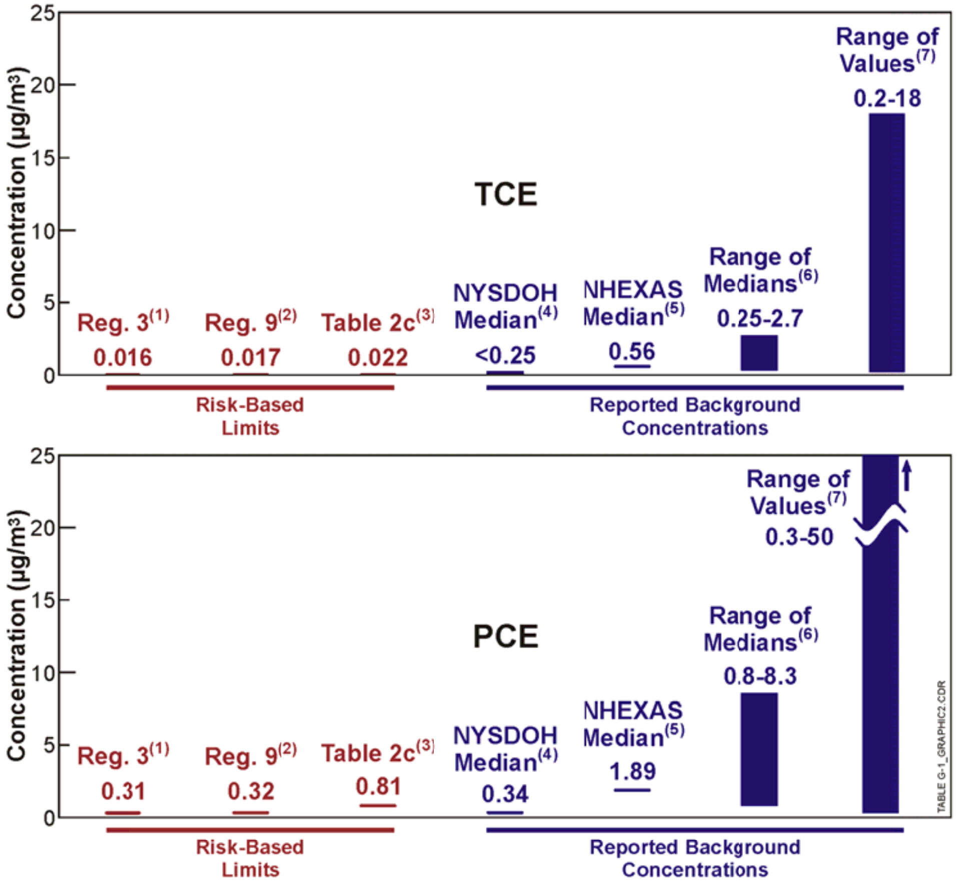
In addition, Table F-1 in the EPA Draft VI Guidance (EPA, 2002) provides a summary of background concentrations derived from eight literature sources. The EPA is continuously expanding the VI database of published or otherwise documented "background" indoor air data in order to identify studies with data sets of known and acceptable quality for the VI database (RTI, 2003). A list of the studies most commonly referred to for literature values, including several recent studies, is presented in Exhibit G-2.

The results of these studies highlight the difficulties of distinguishing background indoor air from VI sources, particularly for those chemicals with risk-based action levels that are one or two orders of magnitude below the median background indoor air concentration indicated by these studies. A comparison of measured background indoor air levels with regional risk-based limits for TCE and PCE is shown in Figure G-1.

When selecting appropriate literature values, one should use the data from the literature judiciously because it can be highly variable and difficult to evaluate for the purposes of representing site-specific background concentrations. The sampling and analytical methods employed may be inconsistent between studies, and the detection limits are not always adequate for measuring background concentrations at the levels required for risk analysis. For example, studies will vary between urban and rural areas, and between buildings with heating, ventilation, and air conditioning (HVAC) systems and those with passive ventilation. When selecting appropriate literature values for use in a background assessment, the following characteristics of each study or database should be considered for relevance to the site and documented:

- Outdoor or indoor air
- Urban or rural communities
- Building characteristics
- Year(s) samples were collected
- Sampling conditions
- Seasonal differences
- Sample size (number of homes evaluated)
- Consistency and type of sampling protocol
- Sample population

Figure G-1: Comparison of Literature Values Representing Background Indoor Air to Risk-Based Limits for TCE and PCE (µg/m3)



(1) **EPA Region 3 RBC**
EPA Region 3 Risk-based Concentration (RBC) Table, updated October 26, 2005.

(2) **EPA Region 9 PRG**
EPA Region 9 Preliminary Remediation Goals (PRG) Table, updated December 28, 2004.

(3) **EPA Table 2c Generic Screening Level**
EPA Draft Subsurface Vapor Intrusion Guidance (EPA, 2002). Table 2c: Generic Screening Levels – target indoor air concentration to satisfy target risk level of 1E-06 and hazard index (HI) of 1.0.

(4) **Median Value in Indoor Air NYSDOH Indoor Air Survey**
Median concentration for 400 indoor air samples from study of VOCs in indoor air of fuel oil heated homes, conducted in New York between 1997 and 2003 by New York State Department of Health (NYSDOH, revised November 14, 2005).

(5) **Median Value in Indoor Air NHEXAS Study**
Median concentrations for 402 indoor air samples from National Human Exposure Assessment Survey (NHEXAS): Distributions and Associations of Lead, Arsenic, and Volatile Organic Compounds in EPA Region 5 (Clayton et. al.,1999).

(6) **Range of Median Values in Indoor Air NJDEP VI Guidance**
Range of median concentrations in background indoor air samples from ten studies summarized in Table F-1, NJDEP VI Guidance Document (2005a).

(7) **Range of Values in Indoor Air BASE Study**
Range of quantifiable concentrations in indoor air measured from 56 U.S. buildings from Building Assessment Survey and Evaluation study (BASE), initiated in 1994 (Girman et. al., 1999).

Finally, it is very important to establish the basis for selecting values from a particular study during the DQO planning process so there is a mutual understanding how they will be applied to site data. Some states have specified background concentrations for chemicals with available data. For example, the Massachusetts Department of Environmental Protection (MADEP) developed indoor air background concentrations for chemicals commonly seen at disposal sites and uses these concentrations in developing its Massachusetts Contingency Plan (MCP) standards (MassDEP, 2006). New York State Department of Health guidance (NYSDOH) recommends that the Massachusetts values be used when available (NYSDOH), 2005). The Connecticut Department of Environmental Protection (CDEP, 2003) also has specified background air concentrations and these are added to risk-based target air concentrations to obtain the target air concentration that is used for comparison to indoor air concentrations.

Collecting Site-Specific Indoor Air Background Samples

Background indoor air sampling is not recommended for most sites due to challenges in obtaining a representative sample. Site-specific background indoor air samples cannot be collected from a building that may be impacted from subsurface VI. Therefore, sampling must occur from "control" buildings (i.e., buildings constructed of similar materials, having similar layouts, and in an area with similar outdoor air background conditions). These "control" buildings must be located in an area where VOCs are not detected in the subsurface (i.e., soil, groundwater, or soil gas). However, even in similar buildings having similar outdoor conditions, the activities, products used, and occupancy patterns within the building can lead to high variability in background indoor air concentrations. Factors such as cigarette smoking, use of paints or solvents, fireplace use, vehicles in a garage, or keeping windows open or closed can affect background indoor air concentrations, making it difficult to collect a sufficient number of samples to overcome this variability and uncertainty. For this reason, the use of literature values based on large numbers of samples can be expected to provide a more acceptable estimate of indoor air background concentrations than site-specific sampling.

Although not recommended for most situations, there may be specific cases where sampling background indoor air is determined to be appropriate, such as a large area of tract housing on a base where many similar houses are present both within and outside the potentially affected areas and where a large number of homes are potentially affected. However, if indoor air background samples are collected, it is important that the sample size is large enough to account for potential variability in individual buildings.

The following issues also should be considered before deciding to collect background indoor air samples from "control" buildings:

1. A sufficient number of samples must be collected to statistically address the variability associated with different activities, product use and occupancy patterns.

2. Background samples should be collected concurrently with indoor air samples and it may be difficult to mobilize a statistically viable background sampling program concurrently with the VI sampling event. Samples collected on a different day or season introduce more variability.

3. Mobilizing a VI investigation in any community requires significant communication, outreach, and logistics. Expanding the sampling program to include buildings outside of the investigation area (i.e., area not impacted by VI) adds a new component of community outreach and logistics.

4. The time necessary to collect a statistically-viable background data set from "control" buildings and reach consensus with regulatory agencies may exceed time-critical schedules for deciding whether or not to install a mitigation system.

For these reasons, background sampling of indoor air from "control" buildings is not considered a feasible approach for most sites.

Outdoor Background Samples

Outdoor air sampling is recommended because it provides background concentrations outside of the building being investigated at the time of the indoor air-sampling event. Furthermore, outdoor air sampling represents site-specific background concentrations, which can vary significantly over short distances. In most cases, outdoor air sampling should be performed concurrently with the indoor air sampling event (and if appropriate, concurrently with near-slab or sub-slab soil gas sampling event) using the same sampling protocols, and the samples should be analyzed for the same target VOCs identified in soil, soil gas, or groundwater.

When collecting site-specific background outdoor air samples to support a VI investigation, there are three components of the investigation that are integral to the assessment of background:

- Identification of target VOCs.
- A site visit and building evaluation performed in advance of the indoor air sampling event to identify and minimize the impact of background indoor air sources and determine locations for indoor and outdoor air sampling. Exhibit G-3 provides a sample building evaluation form that can be used in collecting this information.
- Site-specific outdoor air samples collected concurrently with indoor air VI samples.

Using only outdoor air concentrations to represent background underestimates the true background contribution because it does not include potential contributions from indoor air sources and human activity patterns. For this reason, the use of both outdoor air background concentrations and indoor air values from literature sources should be considered during the DQO planning process for the site.

Identifying Target VOCs

Identification of target VOCs is key to limiting the scope and complexity of the VI investigation and associated background assessment. Target VOCs (i.e., chemicals detected in groundwater, soil, or soil gas that are consequently candidates for VI) should be identified prior to VI sampling. In most cases, a well-developed conceptual site model (CSM) and the investigations leading up to Tier III (i.e., indoor air sampling) should provide sufficient groundwater, soil, and/or soil gas data that can be used to identify target VOCs. Generally, indoor air VI samples, outdoor air samples, and concurrently-collected soil gas samples should be analyzed only for these target VOCs and potential degradation products. However, some states, such as New Jersey (NJDEP, 2005a), may seek analysis of the full list of parameters (based on methodology) during the initial round of indoor air sampling, then allow a reduced list in future sampling events.

Using Sub-Slab Samples to Confirm the Presence of Target VOCs

When sampled concurrently with indoor air, near-slab or sub-slab soil gas sampling can be effective in differentiating sources of indoor air contamination from VOCs associated with VI originating in groundwater, soil, or soil gas. While not used directly to quantify background contributions, the near-slab or sub-slab data can be compared with indoor air data to confirm the presence of target VOCs. It should be noted that sub-slab sampling may not be well received by the building owners, particularly in residences, and may not be practical if permission cannot be easily obtained. Additional challenges may be associated with sub-slab sampling of industrial buildings. Factors to consider when deciding if sub-slab sampling is appropriate for an industrial building include thickness of slabs (as industrial slabs may be substantially thicker than residential buildings), potential for utility lines beneath the slab, and interruption of or interference from industrial operations.

Site Visit and Building Evaluation

The site visit and building evaluation is a necessary component of the multi-faceted approach for assessing background. Prior to collecting indoor air samples (or near-slab or sub-slab samples), at least one site visit and building evaluation should be performed to determine potential sources of contamination. The site visit should include a pre-sampling interview with building occupants. Exhibit G-3 contains a sample building evaluation form and a list of instructions for occupants of buildings, which should be followed at least 24 hours prior to, as well as during, the sampling event. Information collected on the building evaluation form will be used to document surrounding conditions at the time of sampling in order to provide a better understanding of potential vapor entry, air circulation, and background sources of contaminants. The level of detail collected during the building survey should be tailored to the needs of the specific site. Also, several regulatory agencies (e.g., NJDEP [2005a] and DTSC [2005]) provide building evaluation forms and occupant instructions, which they may wamt to be used at a particular site. Therefore, the regulatory agency should be consulted prior to the site visit.

- The site visit and building evaluation provide information used throughout the VI investigation. Building characteristics (e.g., building and foundation type, number of floors, heating and ventilation systems) provide information used in evaluating the VI pathway. Building characteristics are important parameters when using the EPA Vapor Intrusion Spreadsheet Model to estimate indoor air concentrations from subsurface data (EQM, 2004). The walkthrough also allows the investigator to identify potential points of VI into the structure and preferential pathways. It is also the time to select possible indoor air sample locations. Information can be gathered from observations and the interview that can identify potential background sources of contaminants unrelated to VI. In addition, it may be appropriate to use tracer smoke tests or other methods to confirm pressure relationships and air flow patterns, especially between floor levels and between suspected contaminant sources and other areas. For some sites, particularly industrial facilities, it may be advisable to involve a mechanical engineer in the site visit and building walkthrough to provide a better understanding of the ventilation systems and potential pathways for VI. Information on evaluating building air flow patterns is contained in Appendix I.

Specific to background, the building evaluation helps to identify human activities, consumer products, building materials, and furnishings that may contribute to VOCs in indoor air. At this time, any outside contaminant sources that may exist near the building also should be identified and sites for collecting the outdoor air samples should be selected. During the site visit, potential sources of VOCs in the building should be identified by visual observation and by using a photo-ionization detector (PID), or similar air-monitoring device (NJDEP, 2005b). PIDs now have the capability of providing parts per billion by volume (ppbv) detection and are appropriate for performing a walkthrough and identifying potential background sources. However, PIDs are not appropriate for measuring background concentrations of individual VOCs.

If possible, chemicals found during the building evaluation should be removed from the building prior to collecting indoor air samples. If source materials are removed from the building, it is recommended that sampling be delayed for a minimum of 24 hours. Ideally, the building would be ventilated during this time to facilitate removal of the potential source material(s) from indoor air.

Voluntary participation and an individual's right to privacy are very important when conducting indoor and outdoor air sampling. It should be recognized that some occupants may not be able to follow all of the pre-sampling instructions and these situations and resulting sampling conditions should be noted. Ultimately, communication and coordination with building occupants, owners, and regulatory agencies are critical components to a successful evaluation and should be considered during the DQO planning process.

Sampling Approach and Methodology

Outdoor air samples should be collected that are representative of outdoor air contributions to indoor air. Background outdoor air samples should be collected during the same sampling event and timeframe (generally a 24-hour period for residential, or an 8-hour period for occupational) as indoor air VI samples. If a building is sampled more than once to measure temporal or seasonal variability, outdoor air background samples should be collected during each event. It should be noted that outdoor air sampling is recommended for essentially all sites where indoor air is being sampled; however, collection of outdoor air samples may not be necessary at all sites where near-slab or sub-slab soil gas are being sampled. The need for outdoor air sampling to support near-slab or sub-slab soil gas sampling should be determined based on site-specific conditions.

Recognizing that outdoor air can be highly variable over time and space, a site-specific sampling strategy should be developed for each site. Factors to consider in determining the locations and numbers of outdoor air samples include the following:

Because air concentrations have the potential for high variability over time and space, several outdoor air samples should be collected and used to obtain a representative background outdoor air concentration for a particular building or group of buildings (e.g., calculating an average). Outdoor air samples should be collected from locations that are generally upwind from the building or group of buildings being sampled (e.g., based on prevailing wind direction and weather forecasts); however, it is recognized that wind directions can vary widely over a short period of time and the wind direction cannot always be accurately predicted.

The sampling device should be placed in a secure location at least 5 ft off the ground (to approximate breathing zone and to avoid the influence of contaminants being released from soils). The device also should be placed away from wind breaks such as trees or bushes where air circulation might be restricted.

Outdoor air sampling locations should be selected to avoid the influence of indoor air being emitted from the building itself. This is particularly important for industrial facilities. To avoid this, the outdoor air sampling device should not be placed near or downwind from known building exhausts. If several buildings located in close proximity to each other are being sampled concurrently, it may be appropriate to use the same set of outdoor air samples to represent outdoor air at all of these buildings.

Again, the sampling strategy should be developed to best fit the site and obtain the most representative samples given the inherent variability of outdoor air.

Background outdoor air samples should be collected using the same procedures and analyzed using the same methods as the indoor air VI samples. Indoor and outdoor air sample analyses should focus on the target VOCs that were identified in groundwater, soil, or soil gas. Samples should be analyzed using a method that can achieve minimum detection limits comparable to risk-based action levels applicable to the site. The EPA has developed a series of analytical methods for measuring VOCs in air, known as the EPA Compendium of Methods for the Determination of Toxic Organic Compounds in Ambient Air (also commonly referred to as the TO-methods). The EPA's TO-methods for analyses are specific to the sampling method and are frequently recommended for air sampling associated with the VI pathway (see Appendix D of this document). Background outdoor air sampling should be conducted with the same quality assurance/quality control (QA/QC), as investigative air sampling (i.e., the air sampling performed at buildings where VI is suspected). As noted in Appendix D, a comprehensive review of the QA/QC requirements for VI sampling can be found in Appendix I of the NJDEP VI Guidance (2005a).

Assessing the Contribution of Background Sources to Indoor Air

Another method for incorporating consideration of background levels is to compare the background concentrations (both indoor air and outdoor air) to the Measured IA concentration and present these as lines of evidence to demonstrate what portion of the VOC concentration is attributable to VI.

Evaluating Background Indoor Air Data (BKG IA)

When selecting an appropriate literature study(s) to represent background concentrations in indoor air, investigators should consider the criteria discussed elsewhere in this appendix. As a starting point, investigators should propose to use the central tendency (i.e., median) value to represent BKG IA. Many studies provide the central tendency background concentration and some state guidelines (e.g., Connecticut) use the central tendency BKG IA value to adjust (or replace) target air concentrations (CDEP, 2003).

There may be cases where the selected BKG IA value for a target VOC exceeds the VOC's risk-based screening limit for indoor air. These cases should be discussed during the DQO process. If the BKG IA value exceeds the risk-based target VOC value, then the BKG IA value should replace the risk-based value as the target VOC concentration, as it is not possible to clean up below background levels.

If measured IA concentrations are above the risk-based target concentration but below the selected BKG IA concentration for the target constituent, this can be used as one line of evidence that the observed concentrations are attributable to background contamination rather than VI, and therefore, should not require mitigation.

If measured IA concentrations are above the risk-based target concentration and also above selected BKG IA concentration for the target constituent, then the background concentration can be compared to the measured concentration to determine what portion is contributed by background, and a discussion of whether the risk would exceed the target after background is accounted for can be presented. If the concentration with background removed would not exceed the target level, then this can be used as evidence that mitigation should not be required.

Evaluating Background Outdoor Air Data (BKG OA)

A minimum of one site-specific BKG OA sample should be collected concurrently with the indoor air samples at each building or group of buildings; however, it is preferred that several BKG OA samples are collected and averaged. If multiple indoor air sampling events are required (as is usually the case in order to account for seasonal variation), then outdoor air samples should be collected at the same time and in the same area as each of the indoor air sampling events.

Other issues to consider when evaluating BKG OA values include the following:

- In the event that multiple outdoor air samples are collected to represent a group of buildings and the BKG OA is the only value allowed to represent background, investigators should propose to use the maximum value because the BKG OA is likely to underestimate the total concentration of background sources contributing to indoor air concentrations (Zhu et al., 2005; Girman et al., 1999). If used in conjunction with BKG IA, then investigators should propose to use the median value.

- If the BKG OA concentration exceeds the risk-based limit for a target VOC, then the BKG OA value should supersede the risk-based limit for the target VOC.

- If the BKG OA concentration exceeds the measured IA concentration, which may occur in some urban environments, then this VOC should not be addressed as a VI target VOC. In these cases, the agency may request additional BKG OA samples to assess the validity of the outdoor air results.

Other Factors to Consider When Assessing Background

Most agencies rely on several lines of evidence to assess the potential background sources of indoor air contamination. The use of literature values to represent BKG IA and site-specific measurements to represent BKG OA provides the basic framework for quantifying the contribution of background to indoor air concentrations. However, additional information may be requested to support the determination of concentrations attributable to VI and the need for mitigation. A well-documented site visit and building evaluation may provide additional lines of evidence. Other approaches that have been used to differentiate background from VI are introduced below:

- **Near-Slab or Sub-Slab Data:** Collecting soil gas from near or below a structure’s slab can be used to differentiate chemicals originating in groundwater, soil, or soil gas from those associated with background sources. If chemicals are found in indoor air but not in the near-slab or sub-slab samples, it is likely that they originate from sources unrelated to VI. NJDEP suggests that a concentration gradient between sub-slab and indoor air samples (i.e., greater than 20× higher in the sub-slab) strongly suggests the VI pathway is complete for the constituent (NJDEP, 2005a). The EPA also is considering revisions to the VI Guidance (2002) that would include a comparison of sub-slab and indoor air data to determine whether or not the VI pathway for a selected VOC is complete (Dawson, 2005). An important consideration for sub-slab sampling is the willingness of the building owner to allow this type of sampling.

- **Marker Chemicals or Tracers:** At some sites with sufficiently large datasets, it may be possible to use marker chemicals or tracers (e.g., 1,1-dichlroethylene [1,1-DCE], radon) to help filter out data that are not likely associated with VI. Tracers are VOCs that are detectable in VI samples, but rare in "background" indoor air. 1,1-DCE is one such constituent and was used to distinguish background sources from VI sources at the Colorado Redfield site (Kurtz and Folkes, 2002). Tracers also can be used to estimate a site-specific sub-slab to indoor air attenuation factor (i.e., $C_{indoor}/C_{sub\text{-}slab}$), which can be used to compare with attenuation factors of target VOCs. In this case, one should work with measured tracer indoor air concentrations that are greater than 10× the reasonably expected background concentrations or analytical detection limits (API, 2005).
- **Chemical Ratios:** Results from multiple indoor air samples can be compared to the relative concentrations of related chemicals. For example, benzene, ethylbenzene, toluene, and xylenes (BTEX) are common chemicals associated with gasoline. When compared with each other, indoor air samples should show a similar concentration relationship between the chemicals. If benzene and toluene show a 1:1 concentration ratio in the basement but 2nd floor samples have 3× as much toluene as benzene, the toluene is likely related to an indoor air background source (e.g., nail polish).

Summary

In summary, direct measurements of indoor air are complicated by the presence of background sources of VOCs from both indoor air and outdoor air. For this reason, direct measurements of indoor air are generally not recommended until a site reaches Tier III of a VI investigation. In the event indoor air sampling is required, two lines of evidence that are consistently recognized by state and EPA guidelines to account for background are 1) the use of literature values for BKG IA, and 2) site-specific outdoor air samples (BKG OA). This document discusses the use of both literature values and site-specific outdoor air measurements to represent contribution from background sources for comparison to the measured indoor air concentration.

In presenting this approach, the document also addresses some of the issues associated with assessing background, recognizing that these will vary between sites based on site conditions, agency requirements and guidelines, logistics (e.g., access issues), and time and budget constraints.

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Exhibit G-1

Common Household Sources of Background Indoor Air Contamination	
Acetone	rubber cement, cleaning fluids, nail polish remover
Benzene	automobile exhausts, gasoline, cigarette smoke, scatter rugs, carpet glue
Bromomethane	soil or space fumigant
2 Butanone (MEK)	printing inks, fragrance/flavoring agent in candy and perfume, cigarette smoke
Chlorobenzene	plastic foam insulation, paint-related products
Chloroethane	Refrigerant
Chloroform	generated from chlorinated water (showers)
Cyclohexane	paint thinner, paint and varnish remover
1,4-Dichlorobenzene	moth balls, general insecticide in farming, air deodorant, toilet disinfectant
Dichlorodifluoromethane	refrigerant (CFCs), cleaning solvent
1,1-Dichloroethane	plastic products (food and other packaging material), flame retardant fabrics
1,3-Dichloropropene	Fungicides
Ethylbenzene	paint thinners, insecticides, wood office furniture, gasoline
Formaldehyde	building materials (particle board), furniture, insulation, cigarette smoke
n-Heptane	nail polishes, wood office furniture, petroleum products
n-Hexane	gasoline, rubber cement, typing correction fluid, aerosols in perfumes
Methylene chloride	hairspray, paint stripper, rug cleaners, insecticides, furniture polish
Methyl isobutyl ketone	paints, varnishes, dry cleaning preparations, naturally found in oranges, grapes and vinegar
Methyl-*tert*-butyl ether	gasoline (oxygenating agent)
Naphthalene	wood burning, mothballs, cigarette smoke
Styrene	cigarette smoke, automobile exhaust, fiberglass, rubber and epoxy adhesives, occurs naturally in various fruits, vegetables, nuts, and meats
1,1,2,2-Tetrachloroethane	solvent, paint and rust removers, varnishes, lacquers
Tetrachloroethene (PCE)	dry cleaning, metal degreasing, adhesives and glues, insecticide, rug cleaner
Toluene	gasoline, automobile exhaust, polishes, nail polish, paint thinner, cigarette smoke
1,1,1-Trichloroethane	spot cleaners, glues, insecticides, drain cleaners, shoe polish
Trichloroethene (TCE)	scented candles, automotive cleaning and degreasing products
Xylenes, total	water sealer, gasoline, automobile exhaust, markers, floor polish, cigarette smoke
Sources: NJDEP (2005a), except ATSDR (2005) for naphthalene.	

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Exhibit G-3
Building Evaluation Form

Address: ____ Date:__________________________

Occupant Name: ____________________________________ Phone:__________________________

Owner's Name: ___________________________________ Phone:_________________________

Owner's Address: ____

Point of Contact: ________________________________ Phone:_________________________

Contact Information: ____

Conducted By:_______________________________________ Company:________________________

A. GENERAL BUILDING INFORMATION

Provides information on building construction that will be used to identify possible points of VI (including preferential pathways) and documents the rationale for selecting sample locations.
(* Denotes information used in the EPA Spreadsheet Model.)

Building Type/Use:
☐ Residential
☐ Office
☐ Commercial
☐ Industrial
☐ Government
☐ School
☐ Warehouse
☐ Other: ______________________

Number of Occupants: Adults____ Infants____ Children 1-6____ Children 6-15____

*Area of Building Footprint: _____________________ Number of Floors: _____________________

*Ceiling Height: ______________________ Building Age: _____________________

General Description of Building Construction Materials: __________________________________

____

*Foundation Type: ☐ Basement ☐ Crawl Space ☐ Slab

Foundation Materials: ☐ Poured Concrete ☐ Cinder Blocks ☐ Earthen
☐ Wood Pilings ☐ Other, specify________________________________

Foundation Wall Material:

☐ Poured Concrete ☐ Cinder Blocks ☐ Earthen
☐ Wood ☐ Stone

Draw in the Floor Plan:

If there is a basement, please answer questions in Section B.

If there is not a basement, skip to Section C.

B. BASEMENT INFORMATION

Provides information regarding VI and the potential for groundwater intrusion into basement, as well as documents human activity patterns (e.g., sleeping in the basement) that should be used to determine where samples should be collected.

(* Denotes information used in the EPA Spreadsheet Model.)

*Depth of basement or crawl space: __________________

Is the basement finished? ☐ Yes ☐ No

Does anyone live in the basement as a primary residence or use the basement daily? ☐ Yes
☐ No

The basement is generally: ☐ Wet ☐ Dry ☐ Damp

Is there a sump in the basement? ☐ Yes ☐ No

If yes, please describe the size, the construction, where it is located and whether or not there is a sump pump and how it is activated.

____

____

____

Does the basement have cracks? ☐ Yes ☐ No

If yes, what is the PID/FID/CGI reading? ________________________________

Does the basement have a drainage point in floor? ☐ Yes ☐ No

If yes, what is the PID/FID/CGI reading? ________________________________

Does the basement have pipes or utility conduits through floor or outside walls? ☐ Yes ☐ No

If yes, what is the PID/FID/CGI reading? ________________________________

Is the basement sealed with waterproof paint or epoxy coating? ☐ Yes ☐ No

Does the basement have flooring over the foundation? ☐ Yes ☐ No

If yes, what type? ☐ Tile ☐ Carpet ☐ Wood
☐ Pergo ☐ Other, specify ________________________

Are there odors in the basement? ☐ Yes ☐ No

If yes, describe: ____

C. FIRST FLOOR INFORMATION

Provides information on building construction and human activity patterns to be used to determine where samples should be collected.

What are the walls constructed of? ☐ Cinder Block ☐ Sheet Rock ☐ Paneling
☐ Other, specify ____________________________

Is there flooring in the first floor? ☐ Yes ☐ No

If yes, what type? ☐ Tile ☐ Carpet ☐ Wood
☐ Pergo ☐ Other, specify

Are there pipes or utility conduits through the outside walls or floor? ☐ Yes ☐ No

If yes, what is the PID/FID/CGI reading? __

Are there odors on the first floor? ☐ Yes ☐ No If yes, describe _

D. SECOND FLOOR INFORMATION (if applicable)

Provides information on building construction and human activity patterns to be used to determine where samples should be collected.

What are the walls constructed of? ☐ Cinder Block ☐ Sheet Rock ☐ Paneling

☐ Other, specify ____

Is there flooring in the second floor? ☐ Yes ☐ No

If yes, what type? ☐ Tile ☐ Carpet ☐ Wood

☐ Pergo ☐ Other, specify

____

Are there pipes or utility conduits through the outside walls or floor? ☐ Yes ☐ No

If yes, what is the PID/FID/CGI reading? ____

Are there odors on the second floor? ☐ Yes ☐ No

If yes, describe ____

E. HEATING AND VENTILATION SYSTEMS

Provides information on the type of heating and ventilation system used in the structure to help identify potential indoor and outdoor contaminant sources, as well as provides information to assist with data interpretation.

What type of heating system(s) are used in the building? (Check all that apply)

☐ Heat Pump/Furnace
☐ Steam Radiation
☐ Wood Stove
☐ Other, specify:
☐ Hot Air Radiation
☐ Unvented Kerosene Heater
☐ Electric Baseboard

____

What type of fuel(s) are used in the building? (Check all that apply)

☐ Natural Gas
☐ Fuel Oil
☐ Coal
☐ Other, specify
☐ Electric
☐ Wood
☐ Solar

____

What type of mechanical ventilation systems are present and/or currently operating in the building? (Check all that apply)

☐ Mechanical Fans
☐ Individual Air Conditioning Units
☐ Bathroom Ventilation Fan
☐ Other, specify
☐ Open Windows
☐ Kitchen Range Hood
☐ Air-to-Air Heat Exchanger

____

F. POTENTIAL SOURCES OF INDOOR CHEMICALS:

Helps identify typical sources of indoor air contamination that may be found in the building (including attached garages), and documents whether the item was removed from the building prior to the sampling event.

Which of these items are present in the building? (Check all that apply)

Potential VOC Source	Location of Source	Removed at least 24 hours prior to sampling (Yes/No/NA)
Paints		
Gas-powered equipment		
Gasoline storage cans		
Cleaning solvents (thinner)		
Air fresheners		
Oven cleaners		
Carpet / Upholstery cleaners		
Hairspray		
Nail polish / Polish remover		
Bathroom cleaner		
Appliance cleaner		
Furniture / Floor polish		
Mothballs		
Fuel tank		
Woodstove		
Fireplace		
Perfume / Colognes		
Hobby supplies (e.g., solvents, paints, lacquers, glues, photographic darkroom chemicals)		
Scented trees, wreaths, potpourri, etc.		

Potential VOC Source	**Location of Source**	**Removed at least 24 hours prior to sampling (Yes/No/NA)**
Polish / Wax		
Insecticide / Pesticide		
Kerosene		
Other		

G. BUILDING USE:

Provides miscellaneous information about human activities and building construction that may assist in the data interpretation and identification of indoor and outdoor contaminant sources.

Is there standing water in the building (historic or current)? ☐ Yes ☐ No

Is there water damage in the building (historic or current)? ☐ Yes ☐ No

Is there fire damage to the building? ☐ Yes ☐ No If yes, date__________________

Is there a septic system? ☐ Yes ☐ No If yes, date of system_________________________

Do one or more smokers occupy this building on a regular basis? ☐ Yes ☐ No

Has anybody smoked in the building in the last 48 hours? ☐ Yes ☐ No

Does the building have an attached garage? ☐ Yes ☐ No

If so, is a car usually parked in the garage? ☐ Yes ☐ No

Do the occupants of the building frequently have their clothes dry-cleaned? ☐ Yes ☐ No

Was recent remodeling or painting done in the building? ☐ Yes ☐ No

Date: ________________ Location: ________________ Activity:

____

Are there any pressed wood products in the building (e.g., hardwood, plywood, wall paneling, particleboard, fiberboard)? ☐ Yes ☐ No

Are there new furniture, upholstery, drapes, or other textiles in the building? ☐ Yes ☐ No

Date: ________________ Location: ________________ Item(s):

____

Has the building been treated with any insecticides/pesticides? ☐ Yes ☐ No

Chemicals used and how often they are applied?____________________________________

____

Do any of the occupants apply pesticides/herbicides in the yard or garden? ☐ Yes ☐ No

If yes, what chemicals are used and how often are they applied?________________________

____

Type of ground cover (e.g., grass, pavement, etc.) outside the building: ________________________

Is there a well on the property? ☐ Yes ☐ No

If yes, what is it used for and where is it screened? ________________________________

Is there any other information about the structural features of this building, the habits of its occupants or potential sources of constituent contaminants to the indoor air that may be of importance in facilitating the evaluation of the indoor air quality of the building?

____

____

____

H. OTHER POTENTIAL SOURCES OF INDOOR OR OUTDOOR AIR CONTAMINATION

Helps identify typical sources of background indoor air contamination that may be found in the building or outside the building, and includes a table to document the results of portable field screening measurements. A portable photo-ionization detector (PID) can be used to identify individual cans of solvents that should be removed prior to the sampling event or to identify VI points and help with on-site decisions regarding sample placement.

Outdoor Sources of Contamination (check all that apply):

☐ Garbage Dumpsters
☐ Loading Dock In Use
☐ Airport Flight Path
☐ Heavy Motor Traffic
☐ Construction Activities
☐ Railyard / Railcar Traffic
☐ Nearby Industries, specify _______________________________________
☐ UST/AST (gasoline / heating fuel / other, specify ______________________)

Is there a known spill or release outside or inside the building? ☐ Yes ☐ No

If yes, was it:

☐ Oil
☐ Kerosene
☐ Used Vehicle Oil
☐ Pesticide / Insecticide
☐ Natural Gas
☐ Heating Oil
☐ Solvents
☐ Other, describe_________________________

Describe any additional information about the release (amount, when it occurred, action taken to clean up, etc):

____

____

____

I. BUILDING SCREENING RESULTS (PID/FID/CGI)

Location	FID (ppm)	PID (ppm)	CGI (%)
Basement			
First Floor			
Second Floor			
Other			

PID – photo-ionization detector; FID – flame ionization detector; CGI – combustible gas indicator.

INSTRUCTIONS FOR OCCUPANTS OF BUILDING PRIOR TO SAMPLING EVENT
(to be followed starting at least 24 hours prior to and during the sampling event)

- Operate furnace and whole house air-conditioner as appropriate for current weather conditions.
- Do not keep doors open.
- Do not use air fresheners or odor eliminators.
- Do not smoke in the house.
- Do not use wood stoves, fireplace or auxiliary heating equipment (e.g., kerosene heater).
- Do not use paints or varnishes.
- Do not use cleaning products (e.g., bathroom cleaners, furniture polish, appliance cleaners, all-purpose cleaners, floor cleaners).
- Do not use cosmetics, including hair spray, nail polish, nail polish remover, perfume, etc.
- Do not partake in indoor hobbies that use solvents.
- Do not apply pesticides.
- Do not store containers of gasoline, oil, petroleum-based or other solvents, within the house or attached garage (except for fuel oil tanks).
- Do not operate or store automobiles in an attached garage.

Appendix H: Evaluating the Building Envelope in Vapor Intrusion Investigations

Summary

The approach for investigating the vapor intrusion (VI) pathway has historically focused on subsurface conditions and not on the building envelope[1]. However, conditions within the building envelope can significantly influence whether or not underlying soil or groundwater contamination could result in VI.

VI investigations generally rely on a combination of groundwater sampling, near slab soil gas sampling, indoor air sampling, and sub-slab sampling. In addition, measurement techniques from the building sciences can enhance the characterization of conditions within the building envelope that affect VI. These measurement techniques can provide a better understanding of the VI conceptual site model (CSM) than can be achieved with just indoor air and subsurface sampling. In addition, these measurement techniques can provide data that are useful for evaluating building mitigation measures. Case studies applying these techniques to buildings overlying groundwater contaminant plumes show they can provide a better understanding of potential VI pathways. A standard operating procedure is emerging for conducting building envelope evaluations in support of VI investigations. The results from the case studies discussed in this paper can be used to refine that standard operating procedure.

Introduction

Indoor VI became recognized as a significant environmental problem nearly a decade ago. Prior to that time, volatilization of chemicals in soil and groundwater had been recognized as a potential exposure pathway, but it generally was accorded lesser importance compared to ingestion or dermal contact pathways. However, the nature and importance of volatilization pathways change when contaminated soils or groundwater are near buildings.

Techniques for investigating the potential VI pathway largely have involved exterior groundwater and soil gas sampling to characterize the potential sources of volatile contaminants in close proximity to occupied buildings. These data are then used as input to fate and transport models that evaluate the potential migration and attenuation of these compounds as they move into the breathing zone within the building. If modeling predicts a potential vapor intrusion risk, then sub-slab and indoor air sampling may be used to further characterize potential exposure pathways. Decisions about whether or not a VI pathway is complete in a building are made largely using these data.

Indoor air sampling has significant limitations in identifying potential VI pathways. Indoor air sampling has the potential for producing a determination that a VI pathway exists where none is present because many subsurface volatile contaminants also are present in the air due to background sources. To address the potential problem of making a false positive VI determination, regulatory guidance documents include recommendations for collection of reference area (or background) air samples and provide checklists for obtaining chemical inventory information and rudimentary data on the building envelope. In addition, sub-slab

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[1] Building envelope represents the enclosed inhabited space of a building.

sampling is used to identify potential sources for VI, to aid in interpreting indoor air sampling results.

Measurement techniques exist that are specifically intended to characterize conditions within the building envelope as related to potential soil vapor pathways. These techniques are drawn from the building sciences and are traditionally used in radon mitigation, energy conservation audits, and indoor air quality investigations. This appendix provides an introduction to these measurement techniques and discusses the application of building science principles to VI investigations. The focus here is on techniques for evaluating larger commercial or industrial buildings, but these techniques are also applicable to smaller residential buildings.

This appendix consists of the following sections:

- **The Building Envelope in Vapor Intrusion Investigations – The Regulatory Standard of Practice:** This section discusses how the building envelope is addressed in current regulatory guidance. In general, the current regulatory approach to investigating VI gives limited consideration to the building envelope.
- **A Revised View of the Building Envelope in Vapor Intrusion:** This section presents a detailed view of the physical processes in a building that affect vapor intrusion, based on the building sciences literature. The measurement techniques discussed in this appendix are intended to better characterize these physical processes.
- **Measurement Techniques:** This section describes the specific techniques used in a building envelope investigation. These include measuring indoor and outdoor temperatures, pressure measurements using a micromanometer, observation of air flows and leakage using air current tubes ("smoke tubes"), along with more extensive indoor air quality measurement techniques such as blower door and tracer gas techniques.
- **Case Studies.** Examples of the application of building envelope investigation techniques to VI sites are discussed in this section.

The Building Envelope in Vapor Intrusion Investigations – The Regulatory Standard of Practice

The following section briefly summarizes how the approach to VI investigation as described in regulatory agency guidance documents addresses the building envelope. In general, there is the recognition that building characteristics could affect the potential VI pathway; for example, if a building is slightly overpressurized, this could prevent the entry of soil gas, or higher outside air exchange rates could dilute volatiles that enter a building. However, the available regulatory guidance provides only limited guidance for how to evaluate the building envelope as part of a VI investigation.

Default Vapor Intrusion Conceptual Model

The default CSM for the vapor intrusion pathway dictates the techniques used in a VI investigation (see EPA, 2002 as an example). In this conceptual model, the source of contamination consists of volatile chemicals in soil or groundwater at some distance below the floor of a building. Molecular diffusion moves the volatilized contaminant toward the soil surface until it reaches the zone of influence of the building. Within this zone of influence, convective air movement within the soil column transports the vapors through cracks or other penetrations through the foundation into the inhabited space. This convective sweep effect is induced by a depressurization within the structure caused by a combination of wind effects, stack effects due to building heating, and pressure differences due to mechanical ventilation.

Examples of the causes of depressurization include the following (New Jersey Department of Environmental Protection [NJDEP], 2006):

- Operation of the heating, ventilating, and air conditioning (HVAC) system with inadequate makeup air and unbalanced air supply and exhaust systems
- The use of fireplaces and other combustion sources, which results in venting of exhaust gases to the exterior
- Exhaust fans in bathrooms and kitchens that may not be adequately balanced
- Higher temperatures indoors relative to outdoors during the heating season or as a result of solar radiation on rooftops (known as the "stack effect")
- Pressure exerted on the wall of a building caused by wind movement over the building (Bernoulli's principle).

The combination of these actions and conditions result in a net convective or pressure-driven flow of soil gas from the subsurface through the building foundation to the building interior.

According to the user's guide for the Johnson and Ettinger model (U.S. Environmental Protection Agency [EPA], 2004), the effective range of values of the soil-building pressure difference in residences is 0 to 20 Pascals (Pa). The user's guide cites Loureiro et al. (1990) and Eaton and Scott (1984) as sources for this pressure range. Individual average values for wind effects and stack effects are reported to be approximately 2 Pa (Nazaroff et al., 1985). Typical values for the combined effects of wind pressures and heating are considered to be 4 to 5 Pa (Loureiro et al., 1990)[2]. In the absence of specific data, these statistics also are generally assumed to be applicable to commercial or industrial buildings.

Although pressure-driven transport through penetrations[3] in walls and floors is well recognized as an important VI mechanism, there currently are only limited tools and guidance for investigating building conditions contributing to these transport processes. The default regulatory assumption in VI assessments is that building envelopes are under negative pressure relative to the subsurface. However, this is not uniformly the case, and represents a condition that should be evaluated on a site-specific basis.

Existing Regulatory Guidance for Building Envelope Evaluation

The recently published Interstate Technology and Regulatory Council (ITRC) guidance document summarizes the available guidance for evaluating the building envelope and air-handling system in a building (ITRC, 2007). This guidance includes a checklist identifying broad categories of building-related information (see Appendix B in the ITRC guidance), and a toolbox of building diagnostic tools (see Appendix D in the ITRC guidance). The building diagnostic tools described in the ITRC guidance include pre-sampling surveys and use of tracer

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[2] These represent very small pressure differences: 20 Pa corresponds to approximately 0.08 inch water gauge.

[3] Penetrations comprise foundation cracks occurring through settling, seams between floors and walls, poorly-sealed drains or sumps, or holes for utility conduits or pipes.

gases to evaluate air exchange rates and differential pressure measurements. New York State's soil vapor intrusion guidance (New York State Department of Health [NYSDOH], 2006) encourages the use of air current tubes for evaluating the direction of air flows within a building.

These guidance documents identify some of the tools for building diagnostics, but provide very little guidance for collecting and interpreting building diagnostic data. In addition, building diagnostic information is not viewed as a critical part of VI decision making, which is driven largely by the results from sub-slab and indoor air sampling.

Use of these building diagnostic tools has been a critical part of traditional indoor air quality practice. Greater incorporation of these tools could provide significant value to VI investigation and decision making.

A Revised View of the Building Envelope in Vapor Intrusion

The following subsections describe the physical processes related to the building envelope that affect VI. The measurement techniques discussed in the following section are intended to create a better understanding these physical processes, and to help make more informed decisions regarding the identification and mitigation of VI pathways.

Pressure Differences

The small indoor-outdoor pressure differences that cause the driving force arise from the stack effect, wind pressure, and operation of the HVAC system. These three causes are discussed in the following subsections.

Stack Effect

One cause of pressure differences across the building envelope is indoor-outdoor temperature differences (or the stack effect). Under heating conditions, air will flow into the building at lower floors and out of the building at higher floors. During the cooling season, the direction of the pressure differences and airflows may reverse. The stack effect from indoor-outdoor cooling may be offset by heat generated by building occupants and from operation of equipment, such as computers, in a building. The magnitude of the pressure differences depends on the building height, the indoor-outdoor temperature difference, and resistance to vertical airflow within the building caused by interior walls and floors. In addition, the stack effect may differ in various parts of the building, depending on the heat load on the building exterior (Persily, 1994).

Wind Pressure

Higher pressure differences occur on the windward size of buildings. Wind pressure tends to pressurize a building positively on the façade it is hitting, and as the wind goes around the corner of the building it speeds up considerably, creating negative pressure on the downwind portion of the building walls and roof. These outdoor pressure differences can promote leakage of air into or out of the building envelope[4]. The magnitude of the wind-induced pressure difference varies with wind speed, direction, and surface roughness (i.e., height of obstructions surrounding the building) (Persily, 1994).

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[4] The leakage area through the walls of a building includes poorly fitting or poorly insulated doors and windows.

HVAC System Operation

HVAC systems supply, return, and exhaust air from spaces in a building. For spaces in the building, relative pressurization will be determined by the amount of supply air (which includes outside air), return air, and exhaust air, as well as the construction of interior walls. Fire and smoke rated walls are designed to provide a seal between spaces to prevent the movement of fire and smoke in the event of a fire. These walls also restrict the movement of air from the HVAC system between spaces. It is possible to create a negative pressure in one area while positively pressurizing adjacent areas. In some instances, for example, biohazard laboratories or isolation rooms, there is a requirement that the rooms be under negative pressure relative to other spaces to prevent the movement of contaminants.

Relative pressurization may also change in spaces as the operation of the HVAC system changes. Variable air volume terminals used to control temperature in many commercial buildings vary the amount of supply air, which may cause changes in the relative pressurization of the spaces. Constant volume air handling systems, which control temperature by varying the temperature of the supply air, provide a more consistent relative pressurization in the building and spaces. In addition, outside air is provided through the HVAC system to makeup for exhaust air and, ideally, to positively pressurize the building relative to the outside (i.e., more outside air is provided to the building than is exhausted from the building). Note this design approach differs from the regulatory conceptual model, which assumes that buildings generally are under negative pressure and therefore susceptible to VI. The amount of outside air may change over time as well, depending on the operation and maintenance of the HVAC system.

The relative pressure of the building and spaces within it, and the amount of airflow through cracks, also depends on the tightness of the building envelope. Envelope leakage occurs at many locations over the building envelope, with most of the leaks at interfaces between envelope components such as window-wall and floor-wall intersections. The distribution of these leaks over the envelope depends on the envelope design, construction quality and deterioration in building materials over time (Persily, 1994).

However, building HVAC and envelope systems are dynamic and relative pressures throughout the buildings are expected to change. Any investigation protocol must take into account the dynamic nature of these systems and measure pressures under a variety of expected operating conditions.

Airflow Within a Building

Airflow within buildings is an important means of pollutant movement and can transport contaminants to spaces within buildings that are far from the pollutant sources. Airflow rates within buildings depend on the number and location of internal leaks, the pressure differences across these leaks, and the relationships between airflow rate and pressure difference for these leaks. The pressure differences created by the stack effect and ventilation system (described previously) will affect the airflow within buildings. In particular, imbalances in the ventilation system can result in air flow and pollutant transport throughout different zones of a building, producing indoor pollutant concentrations in locations away from sources (Persily, 1994). Air flows within large buildings can be complex and difficult to characterize. However, one author argues that air flows can be understood better through characterizing the pressure field within a building (Lstiburek et al., 2002a; 2002b). Again, pressure differences can be expected to change over time as the operation of the HVAC system changes to maintain temperatures throughout the building.

Vertical Airflow Paths

Vertical airflow within a building occurs through air paths such as elevator shafts, stairs, plumbing, and electrical chases (Persily, 1994) and joints between floors and walls (Lstiburek et al., 2002). Vertical airflow through these paths can be caused by pressure from the stack effect as well as imbalances created by operation of the HVAC system.

Measurement Techniques

This section describes some instrumentation and measurement techniques for better understanding conditions within a building that could create indoor vapor intrusion.

Air Temperature

Air temperatures are measured to better understand indoor-outdoor differences, and relative differences at various locations within a building. Temperature measurements should be made in numerous locations (outdoors – at ground level and on the roof; indoors; on all floors of a building and at multiple locations on each floor), and at different times of the day at those locations. Data to be recorded along with the measured temperature include the location and time of measurements. Digital temperature data loggers can provide a more refined understanding of temperature trends over time within different areas of a building. Understanding outdoor/indoor temperature differences and the temperatures on different floors of a building can provide an indication of the presence of a stack effect, which is a potential driver for VI.

Air temperatures can be measured using digital electronic thermometers. These hand-held, battery-powered devices employ a thermocouple, thermistor, or resistance temperature detector (RTD). A variety of probes are available that differ in response time and measurement range.

When measuring outdoor air temperatures, a probe with an appropriate range (i.e. within the range of typical indoor and outdoor ambient temperatures) should be used. Also, outdoor air temperature measurements should not be made in direct sunlight, where the probe can be affected by solar radiation. Indoor measurements can be influenced by nearby windows (Persily, 1994), so temperature measurements should be made near the center of rooms whenever possible.

Pressure Measurements

Measuring pressure differences across walls and floors can significantly improve understanding of the VI conceptual model. This involves creating a pressure map using a digital micromanometer. The purpose of this map is to identify pressure differences between indoor air and outdoor spaces, pressure differences between different indoor spaces, and pressure differences across floor/wall intrusions. If sub-slab probes are present, pressure differences should be measured from the probes as well. The results from such mapping would be used to identify indoor spaces with significant depressurization relative to outdoors, the subsurface, or other indoor spaces.

To measure the pressure differences across interior or exterior walls, the two sides of a micromanometer are connected to pressure taps on either side of the wall. These pressure taps can be the ends of tubes run underneath doorways, through windows, or through other openings. The tubes must not be compressed. Pressure differences across walls, doors, or windows can be small (as little as 1 to 5 Pa), and can be affected by gusts of wind. Measurements should be recorded under conditions of little wind, unless the objective is to observe wind effects on pressure differences.

Data to be recorded along with the pressure measurements include the locations where the pressure taps have been placed, whether or not the air handling system is operating and whether or not the measurement is relative to outdoors, another indoor space, a different floor, or the subsurface. Observing pressure measurements over time can provide an indication of the dynamic nature of pressures within the building; for example, pressure measurements should be made at a location of a period of several minutes. Also, in some cases, there may be seasonal differences in building pressures depending on climatic conditions and HVAC operation. A building envelope survey may require more than one site visit, conducted at different times of the year, to address possible seasonal variability.

Air Infiltration

Differential pressure measurements (described previously) can provide indirect information about the pathways of air infiltration into a building. More direct indications can be obtained through the use of air current tubes (or smoke tubes) and tracer gases. Tracer gases are a more specialized investigation technique, and are discussed under “Other Techniques.”

Air Current Tubes

Air current tubes are used to study airflow patterns within buildings and in rooms. They are also used for finding leaks in ducts and interior spaces. Air current tubes contain fuming sulfuric acid, which reacts with water vapor to produce an easily visible smoke. Air current tube kits come with a rubber bulb for use in emitted small jets of smoke into a penetration or conduit. The direction of airflow through the penetration can then be easily observed (Persily, 1994).

Outdoor Air Exchange Rate

Outdoor air exchange rate describes how much fresh air is being delivered to an indoor space. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) 62-2004 standard specifies minimum ventilation rates acceptable to building occupants and is intended to maintain indoor comfort and minimize the potential for adverse health effects (ASHRAE, 2004). Understanding how much outside air is being delivered may be useful in modeling indoor air concentrations potentially from VI[5]. This information also could be useful in designing mitigation measures, particularly those involving overpressurization, dilution (delivering additional outside air to an indoor space), or better balancing the building HVAC system.

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[5] Outdoor air intake essentially dilutes concentrations of VOCs entering a building through vapor intrusion. Site-specific estimates of outside air intake along with site-specific pressure measurements can be used to refine vapor intrusion modeling performed using the Johnson and Ettinger model.

Techniques for estimating the outside air exchange rate include thermal balancing (measuring temperatures in supply and return ducts, and in outside air intakes) and measuring the decay rate of tracer gases (Persily, 1994). Digital data loggers that measure temperatures are used to calculate the percent of total air exchange rate that is outdoor (fresh) air. Data loggers should be placed at the outside air intake (outdoor air temperature), at the inlet to the supply duct of the room being evaluated (mixed outdoor and recirculated air temperature) and in the return duct (return air temperature) (McDermott, 2001). The total air flow being delivered to an indoor space can be obtained from reviewing drawings of the building air-handling system, or from direct measurement of the face velocity across the air supply duct or ducts. The outdoor air exchange rate can be calculated from the percent of total air exchange rate that is outdoor air and the total air exchange rate.

Other Techniques

Depending on the characteristics of the building and VI problem being addressed, there are some more advanced techniques that can be used in evaluating the building envelope. Although there are likely to be fewer opportunities for using these techniques, they may provide valuable data under specific circumstances.

Blower Door

One such technique is an air tightness measurement using a "blower door." This device is capable of pressurizing or depressurizing a building and measuring the resultant air flow and pressure. The name comes from the fact that, in the common use of the technology, there is a fan (i.e., blower) mounted in a door (Sherman, 1998). Blower doors are used to estimate infiltration for both indoor air quality and energy consumption estimates. Measurement of the effective leakage area of a building envelope can be weather dependent; use of a blower door to pressurize an indoor space to a known and consistent pressure allows for making determinations of leakage areas that are reproducible and comparable between buildings.

Tracer Gases

Sulfur hexafluoride is commonly used as a tracer gas for measuring air infiltration, contaminant migration, and outside air intake rate (Persily, 1994; Sherman, 1998; Reardon et al., 2002). Sulfur hexafluoride has desirable properties for a tracer gas by being inert, not absorbed on building materials and furnishings, easily and inexpensively measured at part-per-billion concentrations air, nontoxic, and nonflammable. However, a potential drawback to the use of sulfur hexafluoride is that it is an ozone depleting chemical. Other compounds that have been used successfully as tracer gases include carbon dioxide and Freon-134a (1,1,1,2-tetrafluoroethane). Freon-134a has the advantage over sulfur hexafluoride of a reduced ozone depletion potential.

For monitoring air infiltration and contaminant migration in a space, a known quantity of a tracer gas is released from a source location (such as a basement in contact with subsurface soil). Gas samples are then collected over time at different locations in the building using gas-tight syringes. Using tracer gases for evaluating contaminant migration pathways is a subsequent step after using techniques such as air current tube testing and pressure mapping; data from these initial techniques are needed to assist in interpretation of tracer gas testing results. In those cases where they may be needed, a standard operating procedure for tracer studies is available from the

American Society for Testing and Materials (ASTM, 1993). Methods for data interpretation of tracer gas testing data for simple and complex buildings are covered in Sherman (1998).

Evaluation of Building Envelope Survey Data

The approach for using building envelope survey data to evaluate potential VI pathways is drawn from practices used to diagnose indoor air quality problems (EPA/NIOSH, 1991). Observations made during an initial walkthrough of a building can be used to develop hypotheses regarding pressure conditions that may promote or retard potential VI pathways. For example, hard-to-open doors, or the sensation of air movement indoors may provide an indication of pressure differences; these can be investigated further to identify the magnitude and possible causes. Observations of floors may show penetrations, such as cracks, seams or drains, which can be tested further for air flows. Some examples of how building envelope measurement data can be evaluated are described below:

- **Indoor-outdoor temperature differences (stack effect):** The indoor-outdoor pressure difference resulting from a temperature difference can be evaluated using the Shaw-Tamura infiltration model. In this model, pressure difference is a function of the indoor-outdoor pressure difference and the building height. Further description of this model is presented in CEC, 2006.

- **Pressure measurements:** There are no regulatory criteria for indoor pressure measurements. However, for a building envelope survey, pressure measurements can be interpreted using EPA guidance for radon mitigation (EPA, 1993). Sub-slab depressurization systems for radon mitigation are designed to achieve a 6 to 9 Pa pressure difference between the subsurface and indoors. This represents the pressure difference needed to prevent soil gas intrusion into a structure where indoor pressures are governed by heating and the operation of appliances or fans. A matrix outlining the levels used to interpret pressure measurements is presented in Table H-1. The need for further investigation of the potential VI pathway can be assessed based on the magnitude and direction of the pressure measurements (i.e. positive relative to outdoors, or negative relative to outdoors).

- **Air current tube measurements:** The results from air current tubes will provide an indication of the direction of air flow through a penetration in the floor or wall. To make full use of air current tube data, it is important to document the location of the test as well as the test result.

- **Measurements of outdoor air exchange:** The outside air exchange rate can be calculated from the percent of total air exchange rate that is outdoor air and the total air exchange rate. The percent of total air exchange rate that is outdoor air is calculated from the temperature differences in the supply and return ducts, and in the outside air intakes; an example of this calculation is shown in McDermott, 2001. The outdoor air exchange rate can then be compared with the recommendations presented in ASHRAE, 2004.

Case Studies

Evaluation of the building envelope has been conducted at two buildings at the Naval Amphibious Base, Little Creek, in Virginia. These two case studies describe surveys conducted by a multidisciplinary team including a VI specialist (an industrial hygienist) and a mechanical engineer with experience with HVAC systems. These case studies show how some of the measurement techniques discussed previously can be used to gain a better understanding of the conceptual model and to make decisions regarding management of the VI pathway.

Building 3602, School of Music

Building 3602 is a rectangular 24,000-square-foot (sq ft) building (approximately 465 feet by 50 to 60 feet) with three stories, constructed in the early 1950s. The building has a small basement (approximately 60 by 60 feet), formerly used as a mechanical room and currently used for storage, located in the central part of the building.

Groundwater sampling detected concentrations of trichloroethylene (TCE), possibly released from a nearby plating shop, in groundwater near the building. Elevated concentrations of TCE, including dense nonaqueous phase liquid (DNAPL), were detected in deep groundwater, approximately 20 feet below grade. Concentrations of TCE and its degradation products (cis-1,2-dichloroethylene and vinyl chloride) were low or not detected in shallow groundwater. The water table under the building was estimated to be from 5 to 7 feet below grade.

Concerns had been raised about the potential for VI into Building 3602, because concentrations of chlorinated VOCs in groundwater were higher than screening levels developed using agency methods (i.e. assumptions in the EPA's draft 2002 VI guidance). In 2005, in response to these concerns, groundwater grab samples were collected from the surface of the water table at locations around the building. Also, a survey of the building was conducted to identify connections between the soil and building envelope and evaluate potential depressurization from operation of the HVAC system.

The survey involved a limited review of the available plans for the building, a walk-through of the building to visually inspect the basement and first floor for potential intrusion points and to evaluate ventilation characteristics in the inhabited areas, and a limited review of the MSDSs maintained for the building.

Observations from the survey were that the building was built approximately 3 feet above grade, on fill, with only a small number of openings penetrating through the slab. These principally were rain leaders from the roof to subsurface storm drains located inside interior partition walls, helping to isolate them from the occupied spaces. The primary potential route for VI was a sump located in a subgrade mechanical room that may have intercepted groundwater. A grab sample of water ponded in the sump did not detect any VOCs. Testing with air current tubes indicated that the building appeared to be positively pressurized relative to the basement mechanical room.

The results from the building survey showed there were only limited potential for VI from VOCs in groundwater underlying Building 3602. The groundwater grab samples showed only very low concentrations of VOCs in shallow groundwater near the building[6]. These were lower than site-specific risk-based concentrations calculated using the Johnson and Ettinger model,

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[6] Concentrations deep within an aquifer are viewed as less likely to pose a risk for vapor intrusion, because these must migrate to the top of the water table through liquid diffusion in order to become available for volatilization into the overlying vadose zone (Rivett, 1995).

using the dimensions for Building 3602. The occupied portion of the building largely appeared to be positively pressurized relative to the mechanical room or subsurface, reducing the potential for a driving force for VI. In addition, a previously-conducted pilot treatability study in groundwater had resulted in the dechlorination of TCE (the principal constituent of interest) to the less toxic cis-1,2-dichloroethylene, reducing potential inhalation risks should a VI pathway be present.

The groundwater sampling and building evaluation provided multiple lines of evidence that groundwater contaminants underlying this building were not associated with a potential VI pathway. The building survey provided qualitative information that a VI pathway was not present in Building 3602. In this case, the modeling was performed using the conservative default assumption that the building was under negative pressurize. Based on the results from these activities, further evaluation of a potential VI pathway (i.e., indoor air or sub-slab sampling) was deemed not to be necessary.

Building 3165 (Public Works Building)

Building 3165 is a one-story building approximately 40,000 sq ft in floor area, consisting of five wings used for offices and shops. The building has undergone several renovations, including updating floor plans, office finishes, and HVAC system. A survey of this building was conducted in 2006. According to as-built construction drawings, the foundation slab in Building 3165 is approximately 5 inches thick and constructed of concrete. In general, there were few penetrations through the floor slab; however, carpet and vinyl composite tile covering the concrete floor in office spaces did not allow observation of cracks and penetrations in those areas.

In the office areas, there were packaged rooftop air handling units with outside air intakes and a split-system air handling unit that recirculates inside air in a manner similar to residential central-air conditioning systems (i.e., with no outside air intakes). The split-system air handling unit appeared to have been installed to improve distribution of airflow throughout the building. The split-system and rooftop air handling units were controlled by wall-mounted thermostats located throughout the building and appeared to operate simultaneously. The units typically operated in a manner such that the fans ran when cooling or heating was necessary, but there was no air flow if there was no cooling or heating demand. The main lavatory exhaust fans were controlled by occupancy sensors and were activated only when a person entered the room.

Testing of building pressurization was performed using air current tubes and a digital micromanometer. During regular operation, the office area pressurization varied depending on whether exhaust fans and rooftop units are operating. When the rooftop units are not running, and the lavatory exhaust fans are on, the office area was negatively pressurized. However, if the exhaust fans were off, the building was neutrally or positively pressurized relative to the outside. Testing of penetrations into the floor (principally floor drains) showed that the interior space generally was positively pressurized relative to those penetrations. Testing results indicated that most of the building was either neutrally pressurized or slightly positively pressurized relative to outdoors. The one difference was a locker room that contained a roof-mounted exhaust fan, which operated continuously. There was only limited supply air provided to this area, and pressure measurements showed that the locker room was significantly depressurized (between -15 and -20 Pa) relative to the outdoors.

VOCs were detected in shallow groundwater samples collected near the building. Along with the groundwater samples, soil samples were collected to estimate soil texture properties. The groundwater analytical data, soil properties, and data collected during the building survey were used to evaluate potential VI pathways using the Johnson and Ettinger model. Two scenarios were used to calculate these risk estimates:

- **Typical conditions**: Building dimensions and conditions for a typical building wing were used to calculate estimated risk from VI for most of the building. Typical conditions are based on the assumption that the building is only slightly negatively pressurized (- 1 Pa) relative to the underlying soil. The exposure factors were based on standard default worker exposure assumptions (250 days/year exposure frequency, 25 years exposure duration).
- **Negative pressure conditions:** Building dimensions and conditions for the locker room were used to calculate estimated risk from VI for areas under negative pressure. This scenario reflected the significant depressurization observed in the locker room (-20 Pa). For purposes of calculating risk, the exposure factors were based on the assumption that a worker is present in the locker room for 2 hours/day (out of 8 hours/day). Therefore, the exposure frequency was assumed to be 25 percent of the standard default, or 62.5 days/year.

The results from the building evaluation, groundwater sampling, and modeling suggest that, even in the event of conditions promoting VI, concentrations of VOCs in groundwater are unlikely to present human health risks from VI inside Building 3165.

The recommendation from these activities was that further evaluation of potential VI pathways is not required.

Conclusions

Historically, the conceptual model for the VI pathway has focused on subsurface conditions, and not on the building envelope. Conditions within the building envelope can significantly influence whether or not underlying soil or groundwater contamination could result in VI.

Measurement techniques drawn from traditional indoor air quality, radon mitigation and energy conservation audits exist that can better characterize conditions within the building envelope, for purposes of identifying potential VI pathways. Examples of the application of these techniques to buildings overlying groundwater contaminant plumes show they can provide a better understanding of potential VI pathways without having to resort to indoor air or sub-slab sampling. A key limitation with any VI investigation techniques is that they provide a snapshot of conditions over time. This is true with environmental sampling (such as indoor air, sub-slab or soil gas sampling), as well as airflow and pressurization measurement techniques. All of these techniques provide an evaluation of conditions at the time of surveying or sampling, whereas building conditions may be dynamic. As with sampling, overcoming this limitation may involve collecting building measurements during multiple surveys at different times of the year, to capture seasonal variability in building conditions.

The experience with these case studies is being used to expand and refine the standard operating procedure for conducting building envelope evaluations in support of VI investigations. As discussed previously, the current regulatory standard of practice for VI investigation relies heavily on sampling and characterization of subsurface conditions. It is possible that better decisions can be obtained regarding VI pathways by incorporating building envelope evaluations into investigation approaches. In addition to geologists, chemists and risk assessors, the VI investigation team would greatly benefit from the involvement of building science practitioners such as mechanical engineers and industrial hygienists.

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Table H-1. Suggested Interpretation of Pressure Level Measurements

Condition	Description	Comments	Possible Outcome
Positively Pressurized	Consistent pressure measurements of > 6 to 9 Pa relative to outdoors.	Based on the pressure difference needed to prevent soil gas intrusion in a structure with combined heating and appliance or fan operation effects (0.025 to 0.035 in water, based on EPA, 1993).	No apparent driver for VI pathway. Further investigation may not be needed
Neutral to Positively Pressurized	Consistent pressure measurements of <2 to 5 Pa relative to outdoors. OR Highly variable pressure measurements typically greater than zero.	Minimum acceptable pressure difference needed to prevent in a structure with either heating effects OR appliance/fan effects (0.01 to 0.02 in water, based on EPA, 1993).	Potential driver for VI pathway unlikely be present. Exterior investigation may be warranted to confirm presence or absence of a strong subsurface vapor source. A VI pathway is not likely to be present, taking into consideration of other lines of evidence (i.e. the results from exterior investigations of potential subsurface sources)
Neutral to Negatively Pressurized	Consistent pressure measurements of -5 to <2 Pa relative to outdoors. OR Highly variable pressure measurements <5 Pa	Range of depressurization that could occur either from heating effects OR appliance/fan effects (0.01 to 0.02 in water, based on EPA, 1993).	Potential transient (intermittent) driver for VI pathway may be present. Further investigation may be warranted to identify a potential source and transport pathways for VI (i.e. groundwater and near slab sampling).
Negatively Pressurized	Consistent pressure measurements of > -6 to -9 Pa relative to outdoors.	Range of depressurization that could occur from heating effects and appliance/fan effects (0.025 to 0.035 in water, based on EPA, 1993).	Potential driver for VI pathway. Further investigation may be warranted. Consideration may need to be given to either exterior or interior sampling.

Note:
1 Pa = 0.004 inches of water
VI – Vapor Intrusion
Adapted from EPA, 1993

Appendix I: Air-Flow Modification Mitigation Measures for Verified Pathways That Pose Calculated Risk

Introduction

This appendix presents an overview of different mitigation techniques available for reducing the indoor air concentration of vapors migrating indoors from subsurface areas. Mitigation measures are interim corrective actions taken to reduce the health risk to building occupants while source control measures are being studied and implemented. Mitigation measures often are discussed in the context of existing buildings; however, there may be instances with former DoD properties (e.g., Base Realignment and Closure [BRAC] sites) or active sites for which new construction plans must consider an existing vapor intrusion (VI) pathway. Mitigation measures are generally the same for new and old construction. However, it is typically easier and less expensive to have the measure included in the design phase of a new building.

It is generally believed that most vapor-phase intrusion occurs via cracks in masonry foundations (as opposed to diffusion through concrete) and through cracks in floorboards and walls where the building has a crawl space. Of particular concern are the small perimeter cracks that generally develop at the intersection of the footing/wall/slab. Other problematic entry points include the space around incoming utility pipes as well as settling or shrinking cracks that can develop over time within the walls or the slab (MADEP, 1995). Therefore, mitigation measures either deal with the prevention of gas entry from cracks and other entrance points, or alternatively remove the contaminants from indoor air once they have entered. Of these two options, prevention of soil gas entry is the most widely used. The most commonly used mitigation techniques are discussed below. Table I-1 presents the advantages and disadvantages of each mitigation technique.

More detailed information regarding the installation of vapor mitigation measures can be found in the EPA's *Options for Developing and Evaluating Mitigation Strategies for Indoor Air Impacts at CERCLA Sites* (EPA, 1993), and the Massachusetts Department of Environmental Protection *Guidelines for the Design, Installation, and Operation of Sub-Slab Depressurization Systems* (MADEP, 1995).

Mitigation Measures that Prevent Vapor Entry

Mitigation measures that prevent vapor entry are the most frequently used and have been extensively field verified as to their effectiveness. The three main methods of preventing vapor entry are installation of a subsurface depressurization (SSD) system, building pressurization/HVAC optimization, and the sealing of soil gas entry routes.

Subsurface Depressurization Systems

The purpose of an SSD system is to create a negative pressure field directly underneath a building in relation to the building ambient pressure. This negative pressure field becomes a "sink" for any gases present beneath the building foundation. Volatile organic compounds (VOCs) caught in this negative pressure field are collected in a pipe and vented to a discharge point above the roof of the building. SSD systems can be constructed for buildings with both slab-on-grade construction and crawl space construction. A description of each of these systems is presented below.

Sub-Slab Depressurization Systems

A sub-slab depressurization system typically consists of the following components:

- A cored hole through the slab, with a sump pit excavated below (typically one hole/sump pit is sufficient for single family residences; more may be required for larger buildings). The amount of subsurface material extracted for the sump is typically from 6 to 10 gallons

- Polyvinyl chloride (PVC) pipe (typically a 4-inch-diameter pipe) extended from the sump pit to the exhaust point above the roof
- A fan, mounted in the pipe run, either in an attic or outside of the building, used to create the negative pressure field beneath the slab
- A manometer, mounted on the vertical PVC pipe run, which gives a continuous indication of fan performance.

A cross-sectional view of a typical sub-slab depressurization system is shown in Figure I-1.

The first sump of a sub-slab system is preferentially placed as close to the center of the slab as possible to extend the pressure field as far as possible using minimal holes/sumps. After the initial sump is created, diagnostic testing is performed by placing an exhaust fan over the sump hole and measuring the pressure differential at perimeter locations. If the negative pressure field extension is measured at the most distant locations, then one sump is adequate and the rest of the system can be installed (i.e., the PVC pipe run and exhaust fan can be placed in the system). If the first sump was not sufficient to achieve the negative pressure differential across the entire slab, then additional holes/sumps will need to be created until the pressure extension is measured at all sub-slab locations.

An alternative design to a sump is to create sub-slab “trenches” that may run the length of the building to channel vapors to one point where they are exhausted by the PVC pipe. If trenching is chosen, care must be taken to avoid hitting underground utility pipes. In this type of system, coring of the slab is not necessary, and all components of the system can be kept exterior to the building.

Crawl Space Depressurization Systems

A crawl space depressurization system is very similar to a sub-slab system. The difference is that perforated pipe and a vapor barrier material are used instead of PVC pipe and a sump. A crawl space system typically consists of the following components:

- Perforated pipe, typically 4-inch-diameter, laid in contact with the soil in the crawl space
- A vapor barrier material, typically made of polyethylene or rubber material, placed over the perforated pipe and sealed to the perimeter foundation walls and interior support beams
- PVC pipe, typically 4-inch-diameter, connected to the perforated pipe underneath the vapor barrier and extended to the exhaust point above the roof
- A fan, mounted in the PVC pipe run, either in the attic or outside of the building, used to create the negative pressure field beneath the vapor barrier; and
- A manometer, mounted on the vertical PVC pipe run, which gives a continuous indication of fan performance

Diagnostic testing cannot be performed in crawl space systems due to the inability to achieve a sufficiently tight seal with the vapor barrier material. However, post-installation air monitoring has shown these systems to operate very effectively (EPA, 1993). A crawl space depressurization system would look similar to the sub-slab system shown in Figure I-1 with the exception that there would not be a sump, and a vapor barrier material would be present in place of the slab.

Considerations for Installing SSD Systems

Important considerations involving the installation of SSD systems are the following:

- Before a SSD system is installed, the depth to groundwater should be determined. In general, the groundwater table should be at least 6 inches below the building slab or crawl space surface for an SSD system to be effective (MADEP, 1995).

- The installation of an SSD system should be conducted under the direct supervision of a competent professional with specific experience in building vapor mitigation. Many firms specialize in installing SSD systems for residential and commercial radon mitigation. The EPA maintains a list of competent firms in its EPA Radon Contractor Efficiency Program, which is a good starting place for locating an installation contractor. Alternatively, the National Environmental Health Association (NEHA), a private organization, maintains the National Radon Proficiency Certification Organization, which certifies radon mitigation contractors. The NEHA list of certified contractors can be found on its website at: http://www.radongas.org.
- Exhaust fans used in SSD systems require maintenance. Fans typically used for residential systems are very stable, requiring maintenance approximately every 10 years. Conversely, the larger fans used for commercial facilities require maintenance one or more times a year, depending on the specific manufacturer's recommendations.
- An advantage of an SSD system is that confirmatory indoor air sampling is often not required to determine system effectiveness because negative pressure extension can be verified during system installation.

  Note: *Radon systems are the same type of system that is required for VOC vapor mitigation. The standards for installing radon mitigation systems are presented in ASTM standard E2121-03, "Standard Practice of Installing Radon Mitigation Systems in Existing Low-Rise Residential Buildings" (ASTM, 2003). Additional information and updates on EPA recommendations for radon standards can be found at the EPA website (www.epa.gov/radon).*

Building Pressurization/HVAC Optimization

This mitigation approach involves positively pressurizing the building interior relative to the sub-slab, which removes the driving force for entry of soil gas into the building. An example of pressurization is a clean room. Pressurization is accomplished through balancing the building heating, ventilating and air-conditioning (HVAC) system; balancing involves careful adjustments of the system that increase the quantity of outside air provided to the building while adjusting fan speeds to increase overall air flow into interior spaces. Typically, only small increases in building pressure (e.g. <0.001 inches of water, or 0.25 Pa) are needed to prevent vapor intrusion (ITRC, 2007; EPA, 1994). Building pressurization is most feasible in new construction or newer buildings, which are more tightly constructed. Building pressurization requires regular monitoring, inspection and maintenance of the HVAC system to remain effective. Design of a building pressurization mitigation measure needs to take into account leakage caused by opening of doors and windows, which might disrupt the over-pressurization created in the interior space. Normally, HVAC systems operate on a cycle, and airflows are reduced or shut down on nights or weekends when a building is unoccupied. The effects of such cycling need to be addressed when using the HVAC system as a mitigation measure. Other factors to be considered include energy costs associated with the heating and cooling of additional outside air, and the controls needed for the HVAC system to maintain the needed pressure differences.

Note: *Modifying the HVAC system to over-pressurize interior spaces may be most effective as part of an overall building energy conservation program, including taking steps to reduce air leakage and infiltration, and by using computer-controlled building management systems to optimize operation of the HVAC system.*

Sealing Soil Gas Entry Routes

To prevent the entrance of soil gas through sealing, a gas-tight physical barrier must be placed in the pathway between the vapor source and the interior space. Numerous sealants, caulks, and membranes are commercially available to seal entry routes. The complexity of the sealing effort is site-specific and depends on the level of mitigation required. Major and minor entry routes for vapors must all be identified and sealed to effectively mitigate VI through sealing alone.

The major vapor entry routes include the following:

- Exposed soil
- Sumps
- Floor drains
- French drains
- Uncapped hollow block walls.

The minor vapor entry routes include the following:

- Slab/wall cracks
- Block wall pore openings.

Important considerations involving the use of sealants for vapor mitigation are the following:

- In most cases, in order to significantly reduce the infiltration of soil gas, sealing must be supplemented with another mitigation technique.
- Foundation and/or soil settling can cause a building's sub-structure to move or shift. These dynamics often cause sealed entry routes to reopen over time and introduce new entry routes. Therefore, periodic inspections of the sealed openings are critical to ensuring the long-term effectiveness of this mitigation technique.
- It is difficult to determine the effectiveness of this mitigation measure because there is no way to test for a pressure differential between the building and the sub-slab area. Therefore, indoor air sampling is typically required.

Mitigation Measures that Remove Contaminants from Indoor Air

Mitigation measures that dilute or remove contaminants from indoor air also may be used. These methods are not typically chosen due to the large increase in energy required to move and condition more air into a building. The two main removal options, dilution ventilation and indoor air cleaning, are discussed below.

Dilution Ventilation Measures that Remove Contaminants

Exposure to contaminants that have entered through the basement/crawl space can be controlled by diluting the indoor air with uncontaminated outside air. This technique works through increasing the building's air exchange rate, which can be controlled through mechanical ventilation systems and infiltration/exfiltration rates. Infiltration/exfiltration is the natural flow of air into and out of a building due to the pressure difference between inside and outside. This flow is influenced by weather conditions and by the tightness of a building. Dilution ventilation techniques are typically only reasonable to consider for single family residences.

Ventilation can be used as a mitigation technique by following one or more of the following approaches:

- Increase ventilation using natural ventilation (i.e., open doors and windows)
- Mechanically induce air movement and air exchange with or without energy recovery.

Use of Dilution Ventilation to Lower Contaminant Levels

Increasing natural ventilation by opening doors and windows has proven effective for reducing radon concentrations in some residences (EPA, 1993). However, it is not recommended due to the obvious problems of security, heating costs, and cooling costs. Also, it will not work if a resident decides to shut windows or doors.

Mechanical Introduction of Air With or Without Energy Recovery

The mechanical introduction of outdoor air can act to dilute indoor constituent concentrations and pressurize the building to reduce the influx of contaminants. Another option for increasing the introduction of outside air is to introduce air through a separate system, such as a window-mounted fan or a ducted outdoor air fan. Use of an energy recovery device to pre-condition the outdoor air will reduce the energy penalty for introduction of additional outdoor air.

Considerations for Using Dilution Ventilation to Remove Air Contaminants

Important considerations to be made before selecting dilution ventilation as a mitigation technique include the following:

- An energy analysis should be made to determine the additional cost associated with the increased introduction of outside air
- Increased filtration may be required to ensure dust, pollen, and other environmental contaminants are removed from the outside air before being introduced into the building
- If dilution ventilation is used in a large commercial facility, a qualified HVAC contractor will be required to ensure that the system is appropriately balanced with additional air flow
- Periodic indoor air sampling may be required to show that the dilution measures are working
- Outdoor air may also be contaminated, which will make dilution ventilation an ineffective approach for diluting indoor air contamination

Indoor Air Cleaning to Remove Contaminants

The removal of gaseous air pollutants requires the use of a sorbent material. This approach has been applied in industrial manufacturing processes, but the effective removal or organic constituents in residential or commercial settings has not been well documented (EPA, 1993).

The most frequently used process for removing gaseous pollutants from indoor air is sorption by solid sorbents such as activated carbon. The effectiveness of this type of system is dependant on the following:

- Air flowrate through the sorbent
- Concentration of the pollutant in the air stream
- Presence of water vapor (humidity)
- Physical and constituent characteristics of both the pollutants and the sorbent

Activated carbon has been used to reduce indoor concentrations of low molecular weight gases and odors to low levels meeting occupational health standards. However, the ability of this type of sorbent to remove high concentrations of pollutants, the useful life of this sorbent, and the ability of this sorbent to adapt to the variations in type and concentration of indoor pollutants is still being studied.

Verification of the Performance of the Chosen Mitigation Measure

The plan for installation of a mitigation measure must include a means for verification of system performance. The performance criteria should be discussed with the appropriate regulatory agencies during the design phase for the mitigation measure. Steps should be taken to have a visual means of verifying system performance that will minimize the amount of air sampling necessary. However, some air sampling is typically required in at least a subset of the areas receiving mitigation measures. Visual ways of verifying system performance that may be used include the following:

- Installation of a manometer: A manometer is typically installed on the exhaust pipe leading to the fan on an SSD system. This manometer provides a real-time indication that the fan is operating, and may be sufficient to prove that the system is working.
- Periodic pressure testing: In some cases, a perimeter sampling hole may be left in place to enable periodic verification of pressure field extension beneath the slab where an SSD system has been installed.
- Visual system inspection: An annual visual inspection of the mitigation system integrity may also provide sufficient verification of system performance. This would include inspection of sealed joints, inspection of pipes for cracks, a fan inspection, etc. A checklist should be devised for the specific system to document that all components subject to failure were inspected and approved, or replaced if necessary.

Cost of Mitigation

Cost of mitigation will vary with the type of mitigation and the size and construction of the building. Sub-slab depressurization systems similar to those used for radon mitigation currently are approximately $2,500 for residential buildings; installation of resistant barriers in new homes is approximately $350 to $500 (National Safety Council, 2002). The cost for mitigation systems in larger commercial buildings is approximately $2 per square foot of area requiring mitigation (Folkes and Arell, 2003). These costs are only for installation and can vary depending on the building being fitted with a mitigation system.

In assessing overall costs of mitigation, indirect costs also should be considered, because these costs can be significant (Folkes and Arell, 2003). These costs may include:

- Performance monitoring. Performance monitoring is usually required to determine if the system is meeting the cleanup criteria. Monitoring costs include labor and supplies for sample collection, constituent analysis, data evaluation, and reporting. Costs for performance monitoring will vary with each site, depending on the decisions made for number and types of samples following installation of the mitigation system and the frequency and time period over which monitoring must continue. General information on costs of sampling devices and constituent analysis is provided in Appendix F; however, these estimates do not include labor for sample collection, data evaluation and reporting.
- Electricity for operation of the mitigation system
- Maintenance costs
- Community relations costs (site visits, public meetings, educational materials, etc.)

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Table I-1. Vapor Intrusion Mitigation Methods

Method	Advantages	Disadvantages
Mitigation Measures That Prevent Vapor Entry		
Sub-Slab Depressurization Systems	Possible to verify negative pressure field extension. Fans for residential applications are very reliable and typically last for 10 years or more without maintenance. Shown to be effective in vapor reduction applications. Indoor air sampling is often not required to prove the effectiveness of the system.	Need to route exhaust pipe through building. Additional energy cost associated with exhaust fan. Commercial fans require frequent maintenance and may be noisy.
Crawl Space Depressurization Systems	Easy to install in crawl spaces with even surfaces. Provides the added advantage of drying the crawl space to limit moisture problems such as mold. Shown to be effective in vapor reduction applications. Fans for residential applications are very stable and typically last for 10 years or more without maintenance. Indoor air sampling is often not required to prove the effectiveness of the system.	Unable to verify negative pressure field extension. Can be difficult to get a good seal of the vapor barrier to the foundation wall if it is irregular in shape. Hard to install if the crawl space has an uneven surface. Additional energy cost associated with exhaust fan. Commercial fans require frequent maintenance and may be noisy. Need to route exhaust pipe through building.
Sealing of Vapor Entry Points	Does not require use of an exhaust fan. Fairly simple to install. Shown to be effective in vapor reduction applications (EPA, 1993). Avoid need for installing pipe runs in building.	Extensive surface preparation may be required. Requires periodic inspections to ensure airtight seals over time. Difficult to seal all entry routes- access to floor/wall joints is difficult and can be labor intensive. Unlikely to be approved as a sole means of vapor reduction- usually used in combination with another method. Indoor air sampling may be required to demonstrate the effectiveness of the remedy.
Mitigation Measures That Remove Contaminants from Indoor Air		
Natural Dilution Ventilation	Can be used in any building with operable windows and doors. Has been shown to be effective for radon reduction (EPA, 1993). Avoid need for installing pipe runs in building.	Additional costs associated with cooling or heating of air inside building. Security concerns associated with open doors and windows. May introduce contaminants from outside. Indoor air sampling may be required to demonstrate the effectiveness of the remedy. May not be feasible year-round due to weather conditions (e.g., cold winter and hot summer temperatures).
Mechanical Introduction of Air With or Without Energy Recovery	Can act to pressurize the building to prevent the influx of vapors. Avoid need for installing pipe runs in building.	Additional energy costs associated with providing and conditioning additional incoming air. May require redesign of existing HVAC system. Noise problems may be associated with fan use. Data not available to show effectiveness in removing vapors. Indoor air sampling may be required to demonstrate the effectiveness of the remedy. If system is inadvertently changed or modified it may no longer be protective of VI pathway.
Indoor Air Cleaning to Remove Contaminants	Avoid need for installing pipe runs in building.	Data not available to show effectiveness in removing vapors. Additional energy costs associated with moving air through a filter. Indoor air sampling may be required to demonstrate the effectiveness of the remedy. Operations and Maintenance costs associated with the installation, removal, and disposal of filters and equipment.

Figure I-1. Cross-Section of a Sub-Slab Depressurization System