



**UNITED STATES AIR FORCE
AFIOH**

**Guide for the Assessment of the
Vapor Intrusion Pathway**

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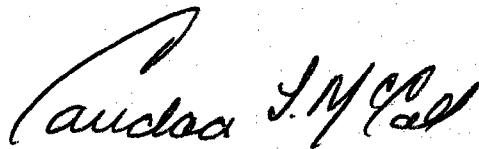
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1 Introduction

This document has been developed by the Health Risk Assessment Branch of the Air Force Institute for Operational Health (AFIOH) as an informational resource for Air Force environmental managers who are interested in evaluating the vapor intrusion pathway (VIP). This pathway has received substantial scrutiny in recent years by the U.S. Environmental Protection Agency (EPA) and state environmental regulatory agencies; the potential health risks from vapor intrusion are being evaluated at numerous sites across the country. Exposures related to this pathway can result from the volatilization and migration of chemicals from contaminated groundwater and subsurface soil that can leak through cracks and holes in buildings located above the contamination. EPA has developed a detailed vapor intrusion guidance (EPA, 2002a) that uses a tiered approach to evaluate the potential risks associated with this pathway. This Air Force-specific document generally follows and supports the modeling and risk assessment approaches recommended by EPA. The primary focus of this document is to provide a discussion of various approaches, problems, and solutions related to assessing and managing the VIP. This guidance covers such areas as sampling and analysis, analytical methods, indoor air quality, risk assessment, remediation, and risk management.

The VIP can be of concern when volatile chemicals are released into the environment, either accidentally through leaks and spills or deliberately through dumping and discharge of waste chemicals. The chemicals of greatest interest for this pathway are volatile organic compounds (VOCs), which include petroleum hydrocarbons (e.g., benzene) and chlorinated solvents (e.g., trichloroethylene [TCE]). 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; however, these chemicals are less volatile and generally less widespread at Air Force bases than are the petroleum hydrocarbons and chlorinated solvents. While EPA's document includes more than 100 chemicals that have sufficient volatility and toxicity to pose a theoretical vapor hazard, at most sites, the problem is typically limited to a handful of chemicals.

This guidance will be most useful for two groups of Air Force environmental managers:

- The Base Bioenvironmental Engineer (BEE) is typically the "first responder" when indoor-air concerns are identified on base. The BEE may be notified of vapor intrusion concerns based on odors, health effects (dizziness, nausea), or other indicators.
- The Civil Engineering (CE) group that oversees restoration activities on the base may also become involved. Their involvement may stem from investigation and cleanup of spills and releases that have occurred across the base and are now part of a formal investigation.

1.1 Background

The Air Force has environmental management responsibilities for hundreds of sites across the country. These sites include active bases, closed bases (through the Base Realignment and Closure [BRAC] program), and remote monitoring stations. Sources of subsurface contamination include fuel storage and refueling areas, leaking tanks and pipelines, floor drains, and industrial areas. In addition, waste chemicals (including VOCs) were often disposed of in on-base landfills, dumped on the ground or into waste pits and evaporation ponds, or used in fire training exercises. If present in sufficient quantity, these chemicals can migrate through the

soil and into the underlying groundwater. Once in the groundwater, these chemicals can move with the groundwater, potentially migrating a substantial distance from the original discharge point. Over time, groundwater plumes can grow to cover several square miles and can pose a substantial investigatory and remedial challenge.

As a result of their chemical properties, VOCs can volatilize out of the groundwater and enter the gaseous phase in the overlying soil. The chemicals in the soil gas can migrate both vertically and laterally through the soil. The rate of migration depends on a number of chemical-specific parameters, such as volatility and mass, as well as geophysical parameters, such as soil type, soil moisture, and total organic carbon (TOC) content. These VOCs can migrate through cracks and holes in the foundation of buildings located above the contamination and into the indoor air of these buildings. As a result, people living or working in buildings above contaminated groundwater or soil may be exposed to hazardous chemicals by inhaling chemicals that have seeped into the indoor air. Similarly, these contaminants can also migrate into ambient (outdoor) air; in such instances, buildings are not present, so the contaminants are rapidly diluted and typically pose little risk.

The resulting indoor-air concentration of chemicals depends on the nature of the building's construction, air turnover rates within the building, activities occurring within the building, and other factors. Buildings constructed using slab-on-grade design or with a basement—both designs have significant direct contact between the concrete foundation and the underlying soil—are considered more vulnerable to soil vapor intrusion than buildings constructed with a crawl space or pier-and-beam construction. In general, buildings with thicker foundations have less vapor intrusion concerns than thin foundation buildings, although this may not hold true if the foundation has extensive cracking.

The VIP is being evaluated with increasing frequency at sites where volatile chemicals have been detected in groundwater. Vapor intrusion concerns have been investigated at active bases (e.g., Altus AFB, Hill AFB) and former bases where buildings are present over contaminated groundwater plumes (e.g., the former Kelly and Lowry AFBs). 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. No longer is it sufficient to compare groundwater concentrations of chemicals to their maximum contaminant levels (MCLs) and make a determination as to the magnitude of the problem. MCLs are drinking-water standards that do not take into account the VIP and thus may not accurately reflect the degree of risk posed by contaminated groundwater. Not only is the VIP considered a standard part of current and future site investigation projects where volatile chemicals are present, but historical investigations are being reevaluated to review the risks posed by this pathway.

1.2 Objectives of This Handbook

This Air Force-specific handbook has been developed to discuss various technical approaches associated with vapor intrusion and to provide perspective for the Air Force project manager (and associated consultants) regarding the development and interpretation of vapor intrusion studies. This guidance is not intended to replace either EPA or state guidance as the primary technical resource for a vapor intrusion project. Rather, by considering project needs and the pros and cons of the various approaches, the Air Force can make a more informed, cost-effective determination of the best way to move the project forward. This guidance should be considered as supplemental

to detailed technical guidance produced by EPA and state regulatory agencies. As a result, there should be minimal conflict among the issues and decision options discussed herein with those provided in agency guidance. This guidance was developed to be relevant for Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) and Resource Conservation and Recovery Act (RCRA) sites, as well as for state-led sites.

Although EPA does not have the formal authority to regulate indoor air, in recent years, they have begun to address vapor intrusion concerns by developing guidance related to subsurface contamination that can impact buildings located above the contamination. EPA's vapor intrusion guidance uses a three-tiered approach to provide a step-wise approach to the assessment of human health risk posed by the soil vapor intrusion pathway. This tiered approach, described in detail in Section 3, moves from a generic screening-level approach (Tier 1) to a conservative fate and transport model (Tier 2) and finally to a site-specific modeling approach (Tier 3). This 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 three-tiered modeling-based guidance. The Colorado Department of Public Health and the Environment's indoor-air guidance (CDPHE, 2004) recommends conducting indoor-air sampling if volatile chemicals are present in the subsurface at levels exceeding threshold concentrations, with no contaminant transport modeling required. Other state agencies also provide opportunities for going directly to indoor-air sampling without conducting extensive soil gas sampling and contaminant transport modeling. Readers of this handbook will need to identify the technical guidance that is applicable to their site.

1.3 Document Organization

This document is organized into nine sections. Following this introduction, Section 2 discusses the initial evaluation of the VIP. Section 3 presents EPA's vapor intrusion guidance. Section 4 discusses sampling and analysis for vapor intrusion, and Section 5 addresses the health risk assessment at vapor intrusion sites. Risk management is discussed in Section 6, and risk communication is addressed in Section 7. Section 8 presents the summary and recommendations, and Section 9 identifies additional technical resources. The appendix replicates a table of chemicals that may be found at hazardous waste sites. A bibliography and a list of acronyms are also provided at the conclusion of the document.

2 Initial Evaluation of the Vapor Intrusion Pathway

The volatilization of chemicals from subsurface soil and groundwater into the indoor air of buildings located above the contamination presents an important exposure pathway that should be considered as part of any risk assessment for a site. A variety of approaches and options should be considered in the development of a vapor intrusion project. This section highlights and summarizes the basic approaches for conducting a vapor intrusion project.

At sites where buildings are present above an area of contamination, the first step is to determine if you have—or may have—a vapor intrusion problem in your building. Several indicators that this pathway may be complete include the following:

- Noticeable odors, particularly in the basement, which could indicate the existence of a vapor intrusion problem
- The presence of chemicals in subsurface soil and groundwater that have sufficient volatility and toxicity to be candidates for vapor intrusion
- Soil gas measurements (particularly sub-slab soil gas data) which could indicate the presence of gas-phase chemicals
- A wet basement or signs of water seeping into the basement in an area with groundwater contamination
- 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 provide conclusive evidence that vapor intrusion is occurring. However, if one or more of these indicators are present, there is the possibility that vapor intrusion is occurring and should be investigated.

EPA and most state agencies recommend using two criteria to evaluate whether to include a chemical in a vapor intrusion study. These criteria are volatility and toxicity. EPA defines a chemical as volatile if its Henry's Law constant is 1×10^{-5} atm-m³/mol or greater. EPA has identified more than 100 chemicals that meet this definition of volatility, including standard VOCs such as benzene and TCE, but also including pesticides such as chlordane and DDE, as well as several PAHs. Secondly, EPA has identified a group of chemicals whose vapor concentration of the pure component poses an incremental cancer risk greater than 1 in 1 million (1E-06) or a non-cancer hazard index greater than 1; this list also runs to well over 100 chemicals. 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 analysis. Table 1 of EPA's 2002 vapor intrusion guidance lists the chemicals that EPA has determined meet these criteria; the EPA list is reproduced in the Appendix of this handbook.

The EPA list provides a reasonable, if conservative, starting point for a vapor intrusion study; however, most users will find that there are only a few chemicals on this list that will be the risk-drivers. If any of the chemicals on the list in the Appendix are detected within 100 feet—horizontally or vertically—of an existing building, EPA recommends that a vapor intrusion study be conducted. Different states provide shorter lists of chemicals of concern, focused primarily on the most volatile of the group. For example, Minnesota (MPCA, 2005) includes 57 chemicals on

their list of chemicals of concern for vapor intrusion, while Colorado (CDPHE, 2004) includes 22 chemicals on their list. These lists may be expanded based on site-specific conditions and depend on the chemicals found, their locations, and their concentrations.

2.1 Conceptual Site Model

An important step in assessing the VIP is to develop an understanding of the site setting and the ways by which people could be exposed to site-related chemicals. This is commonly done by the development of a conceptual site model (CSM), typically shown as a diagram that illustrates the connections between chemical sources and potential receptors. The CSM provides a three-dimensional view of site conditions, showing the contaminant sources, the movement of these contaminants in the environment, and potential receptors and exposure pathways. The CSM links the source of contamination, such as a leaking tank, with potential environmental transport pathways which may ultimately lead to exposure of a receptor. The CSM is useful for identifying which exposure pathways are complete, potentially complete, or incomplete, thus allowing the risk assessor or site manager to focus on those pathways or issues with the greatest significance. The VIP is often only one of many exposure pathways that are present at a site, and the CSM may need to describe these other pathways as well. The CSM should be discussed in the text of the document and should be supported by data, maps, and other supporting information.

The following factors should be identified in a CSM:

- **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. These sources will interact with each other over time.
- **Transport Pathways:** 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. The last pathway is most active directly adjacent to buildings, where there is a negative pressure differential between the building and the surrounding soil that tends to pull soil gas upwards towards the building.
- **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 (single-family homes, townhouses, and trailers), industrial and commercial workplaces, office buildings, and educational and recreational settings (schools, gyms).
- **Exposure Pathways:** The only pathway of interest for the VIP is the inhalation of vapors emanating from the subsurface. Other possible exposure pathways that may be considered during other investigations at the site may include ingestion, dermal contact, and inhalation of particulate material.

The above-listed factors represent the most common and likely pathways and scenarios expected to occur at Air Force bases.

2.2 Vapor Intrusion Assessment Options

There are two basic approaches to evaluating whether vapor intrusion is happening at a site or building. These approaches, while distinctly different, are complimentary and can be used in conjunction with each other. The first approach uses a contaminant transport model to estimate vapor intrusion rates, while the second approach relies on direct measurement of indoor air quality. The EPA and most 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.

This section describes the two approaches and compares the pros and cons of each approach. Figure 2.1 outlines the basic approach to vapor intrusion assessment and highlights some of the factors that should be considered.

Contaminant fate-and-transport modeling is usually the first approach used for evaluating the potential impacts of vapor intrusion. This modeling approach has been the subject of many EPA and state guidance documents and is discussed in detail in Section 3. The modeling uses analytical data collected from soil, groundwater, or soil gas from the contaminated area in the vicinity of or beneath a building. This data is typically input into the Johnson and Ettinger (J&E) (1991) vapor intrusion model, which has been adopted by EPA and most state health agencies as the preferred fate-and-transport model. This model combines the analytical data with a variety of soil and building parameters in an algorithm that predicts the indoor-air concentration of volatile chemicals.

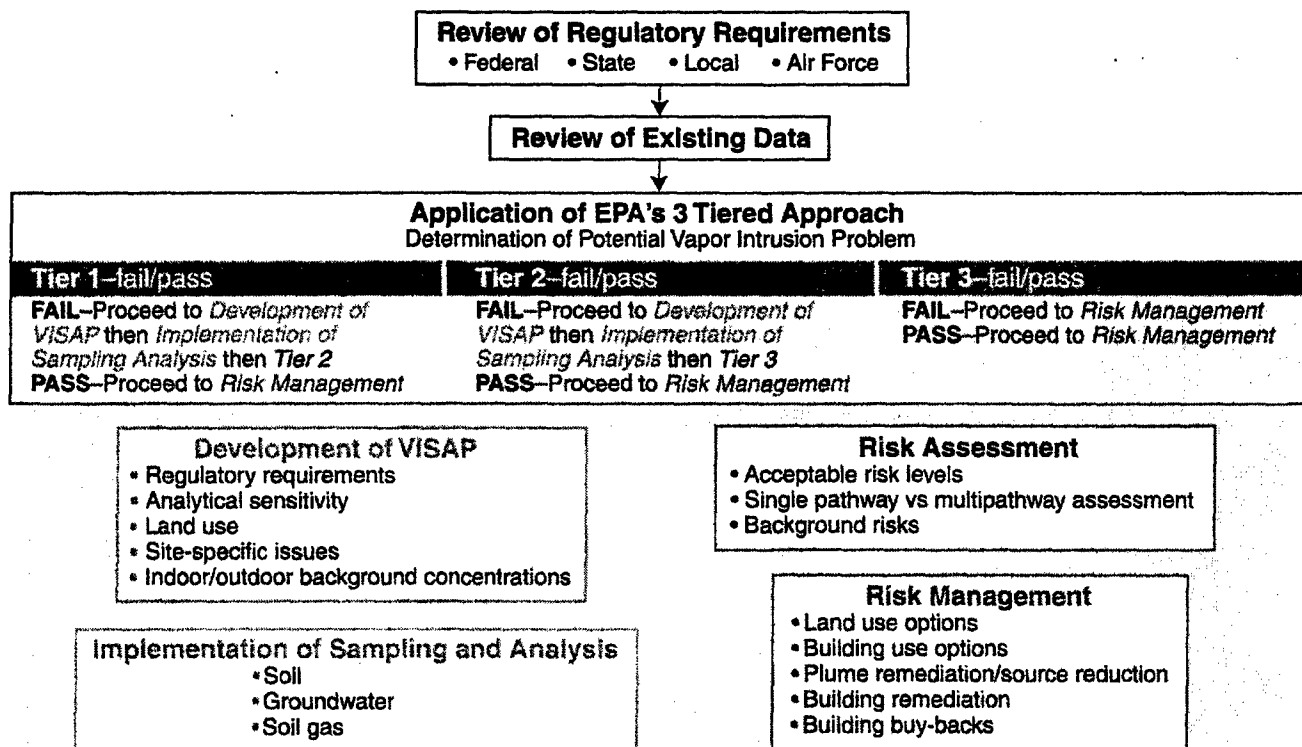


Figure 2.1. Steps in Vapor Intrusion Assessment

(VISAP = Vapor Intrusion Sampling and Analysis Plan)

Some of the potential “pros and cons” associated with contaminant transport modeling are listed in Table 2-1:

Table 2.1. Issues associated with contaminant transport modeling

In support of modeling	Against support of modeling
Can use existing data in many cases	Available data may be old and not representative of current site conditions
Can be used as a desktop tool for screening sites	Screening is often highly conservative and may lead to inaccurate conclusions
Can incorporate a wide variety of site-specific parameters	The model is complex and has many areas of uncertainty
Can be performed without disrupting building occupants	May be difficult to account for range of changing variables over different seasons
Can use different types of analytical data (e.g., groundwater, soil, and soil gas)	Default assumptions used in model may not accurately reflect site conditions
Can be used for future land use and building analysis	Future land use and building assumptions may be very different than modeled
Some models can account for attenuation over time	Attenuation can be difficult to predict, particularly for chlorinated solvents

The second approach involves the direct measurement of indoor air quality by taking air samples within the building (e.g., house, workplace). Although taking indoor-air measurements must be carefully conducted to control for many different variables, this method is increasingly being recommended by state health agencies. For example, the Massachusetts Department of Environmental Protection (MADEP) “generally recommends direct measurement as preferable overall for evaluating conditions in existing buildings associated with current groundwater concentrations” (MADEP, 2002). However, for most environmental projects, the modeling assessment is done prior to collecting indoor-air samples.

Some of the potential “pros and cons” associated with indoor-air sampling are listed in Table 2-2:

Table 2.2. Issues Associated with Indoor Air Sampling

In support of indoor air sampling	Against indoor air sampling
Provides an actual measured concentration – a “snapshot in time”	Impact from background chemicals may be substantial and must be accounted for (for indoor and outdoor background impacts)
Might provide confirmation that the vapor intrusion pathway is complete	A number of environmental parameters (e.g., temperature, soil moisture) may affect vapor intrusion and indoor air
Might be used to validate fate and transport modeling	Samples at different times of year are often required to account for effects of

In support of indoor air sampling	Against indoor air sampling
	seasonality on vapor intrusion
Can be used to develop empirical, site-specific attenuation factors	Sampling may be disruptive to building occupants
Can bypass concern over impact of unknown parameters in soil or buildings	Sampling does not account for attenuation of contaminants (unless long term monitoring is undertaken)
Can provide data suitable for either qualitative screening level assessment or a quantitative risk assessment	Sampling cannot be used to predict vapor intrusion impacts to buildings to be built in the future

2.3 Review of Existing Data

Many bases have sites that have been subject to environmental investigations for a number of years. As a result, a large amount of data may be available. Most commonly, these data would have been collected during some form of preliminary site inspection (PSI), a remedial investigation (RI), or various monitoring activities. These data will often be limited to soil and groundwater sample results, which when used alone may or may not be adequate to address all vapor intrusion concerns. It should be noted that EPA and state agencies are increasingly favoring the use of soil gas data over groundwater or soil data. However, available historical data can be useful for identifying what chemicals are present at a site; if volatile chemicals are not found, this may be sufficient to rule out the VIP. While these data may not have been collected specifically to support vapor intrusion studies, they may still be relevant and prove helpful for understanding the site setting.

The existing data should be compiled and reviewed prior to collection of any additional data. Older data may have a number of characteristics that limit their usefulness, such as the representativeness of the current nature and extent of contamination. Some questions should be considered when reviewing historical data:

- Were analyses conducted for all known or suspected chemicals?
- Were the detection limits sufficiently low for vapor intrusion concerns?
- Has the contamination spread beyond the original study boundaries?
- Were analyses conducted for degradation products?
- Has the land use changed or have additional buildings been constructed on the site?

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 size and volume of building, depth of construction, thickness of floor, air turnover rates, and activities of the occupants. These factors may all figure into the vapor intrusion risk assessment. The second situation is where vapor intrusion models are used to predict what may happen to hypothetical future buildings. In this case, a hypothetical building can be placed anywhere over the plume and vapor modeling will estimate what types of indoor-air concentrations may result. This approach allows the risk assessor to evaluate a range of construction options (thickness of floor, ventilation issues) that may affect building design.

EPA has developed guidance regarding the evaluation of data usability in risk assessment (EPA, 1990). This guidance is specifically designed to provide a clear and consistent process for determining that the data generated 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 that has been collected at a site. It describes what factors to consider when reviewing data and to identify the minimally acceptable performance objectives for a dataset. Five basic data quality issues that may affect the risk assessment are discussed: data sources, detection limits, use of qualified data, background samples, and consistency in data collection. A review of this guidance can help the project manager ensure that the data collected is sufficient to meet the project needs.

The draft AFRPA vapor intrusion document, developed specifically for closed Air Force bases, outlines an approach for conducting site screening using existing data. It presents a tiered approach that screens out sites in a progressive manner based on the quality and abundance of data. Additional data collection is recommended for a limited number of sites that fail the screening process. It may be useful to consult this guidance to review an Air Force-developed approach for screening historical data.

2.4 Data Quality Objectives

The development of site-specific Data Quality Objectives (DQOs) is a critical step that should be completed before any additional sampling and analysis is done. EPA defines DQOs as "quantitative and qualitative statements... that describe what data are needed to support decision making." 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 by the stakeholders associated with the projects, which may include the Air Force, EPA, the state health department, local homeowners, and other potentially affected groups.

EPA has developed a seven-step process for developing DQOs:

1. State the problem
2. Identify the decision to be made
3. Identify the inputs to the decision
4. Define the study boundaries
5. Develop decision rules
6. Specify the acceptable limits on decision error
7. Optimize the sampling design

All vapor intrusion projects should have site-specific DQOs to help the project team understand what data will be collected and how they will be used. Examples of issues that need to be considered when developing DQOs include the type(s) of decisions to be made, the number of samples needed to support these decisions, and the necessary detection limits (analytical sensitivity) for the chemicals of concern. 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 guidance document (EPA, 1994).

3 EPA's Vapor Intrusion Guidance

As described in Section 1, this document supports the basic approach to vapor intrusion assessment as outlined by EPA in their *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils* (EPA, 2002a). This guidance can be used for both CERCLA and RCRA Sites. The EPA guidance is flexible and allows for inclusion of site-specific data into a vapor intrusion assessment. A number of state agencies have also developed or are developing their own vapor intrusion guidance. The Interstate Technology and Regulatory Council (ITRC) is also in the process of developing vapor intrusion guidance.

While there are variations in the approaches recommended by the different agencies, many of the underlying strategies are similar in style and method to that recommended by EPA. In the Introduction to their document, EPA points out that their "guidance" document is just that, rather than a regulation or an enforceable requirement. Other technically sound approaches are also acceptable, as are modifications to the approaches recommended within EPA's document. This document recommends that Air Force project managers base their vapor intrusion study on the technical guidance document(s) most appropriate to their site (and discussed with the regulatory authorities), supplemented by the material presented in this document.

EPA's guidance has been designed "to provide a tool to help the user conduct a screening evaluation as to whether or not the vapor intrusion exposure pathway is complete and, if so, whether it poses an unacceptable risk to human health" (EPA, 2002a). Importantly, the guidance does not provide recommendations on how to manage or eliminate the risk that may be present; these decisions are left to the project manager to work out with local regulatory personnel. EPA's guidance has been developed for residential settings, and the assumptions will need to be adjusted for other settings (e.g., industrial). The guidance was designed primarily for RCRA Corrective Action, CERCLA (Superfund), and Brownfields sites; most Air Force sites will fit under one of these three headings.

One important and noteworthy recommendation from EPA's 2002 vapor intrusion document is that the guidance should not be used for the evaluation of vapor intrusion associated with Subtitle 1 Underground Storage Tank (UST) sites. This exemption is based on the awareness that petroleum hydrocarbons released from USTs are susceptible to natural attenuation and biodegradation; EPA's vapor intrusion assumptions are too conservative for compounds that degrade. As a result, vapor intrusion risk assessments of petroleum hydrocarbon sites will often overestimate the long-term exposure concentration, in turn overestimating the potential risk to the receptors that may be affected. (For further discussion of this subject, please see Section 5.5.1.)

3.1 Summary of EPA's Approach

EPA's 2002 guidance document was developed as a three-tiered approach for screening and evaluating vapor intrusion sites. This approach has been designed to provide a conservative and standardized approach for assessing potential vapor intrusion risk. The guidance uses "simple and generally conservative screening approaches and gradually progresses towards a more complex assessment involving increasingly greater use of site-specific data" (EPA, 2002a). The EPA guidance includes a series of questions and answers designed to explain the tiered screening process to the risk assessor. These questions, presented in a series of flowcharts, can be found in

EPA's 2002 document. This Air Force document does make reference to EPA's question-based approach to vapor intrusion. A summary flowchart showing the most important facets of EPA's approach is presented in Figure 3-1.

It is important to note that EPA's approach allows for collecting indoor air quality data at any step in the process. The results of indoor-air sampling can be used to make risk management decisions and may obviate the need to follow each step in the tiered process. This approach may prove useful at sites where there are obvious concerns, such as sites where there are high chemical concentrations in shallow groundwater or where sensitive sub-populations (e.g., day care centers) are present. Several states (NY, CO) require that indoor air samples be collected early in the vapor intrusion assessment process. This indoor data is then compared directly with health-based standards to evaluate the potential risks present. However, most state and federal agencies start with a modeling-based approach and only move to indoor air sampling when the modeling results suggest it is necessary.

3.2 Tier 1: Primary Screening Step

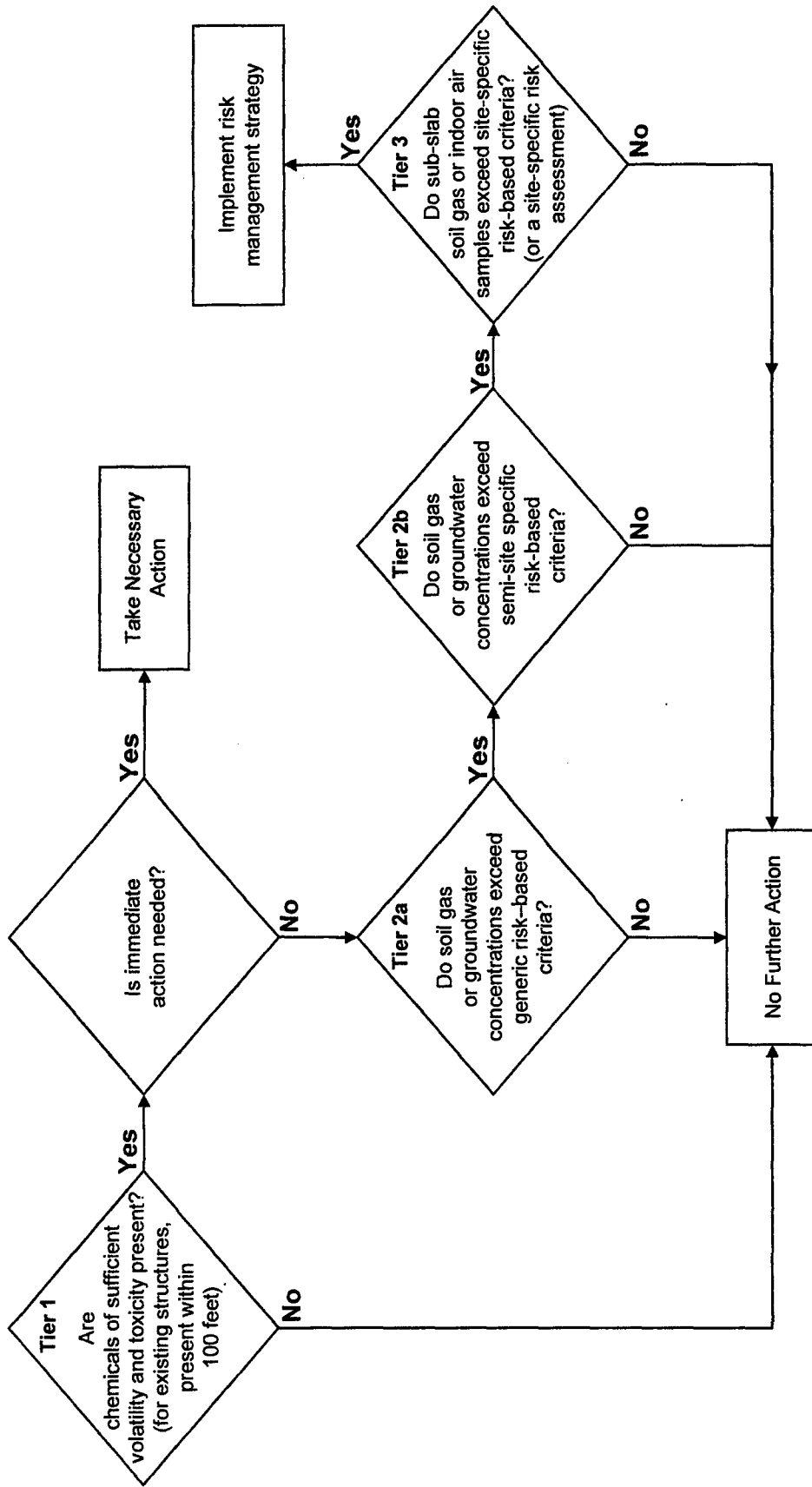
This tier requires a review of the available data and the site history to determine if there are any volatile chemicals present (or suspected of being present) at the site, and if there are, whether those chemicals are considered to be toxic. The first tier is deliberately simplistic and will only screen out those sites with little or no potential risk from vapor intrusion. If volatile and toxic chemicals are known or suspected to be present in the subsurface near (within 100 feet of) currently occupied buildings or areas that could be developed in the future, then the site fails the Tier 1 screen and moves to the next tier in the evaluation process. Alternatively, if volatile and toxic chemicals are not present, the site can be screened out and no further action is necessary. The list of chemicals that EPA considers to have sufficient toxicity and volatility to be included in a vapor intrusion study are presented in the Appendix.

It is not essential to start with Tier 1 and follow each step of the tiered process. For sites that are grossly contaminated or where there are reasons to believe that the VIP is complete, it may be appropriate to move directly to a later tier in the process.

3.3 Tier 2: Secondary Screening Step

This tier involves the comparison of analytical data collected at a site with generic risk-based concentrations for soil gas and groundwater for residential exposure settings. These risk-based concentrations were developed for cancer risks ranging from 1E-04 to 1E-06 and for non-cancer risks corresponding to a hazard quotient (HQ) of 1. Because they were developed using generic residential exposure assumptions (e.g., 350 days/year, 30-year exposure), these concentrations are very conservative for most Air Force settings. They can be modified to more closely reflect the exposure setting of interest, whether it is occupational or military residential. The measured soil gas, groundwater, or indoor-air concentrations are compared to the risk-based concentrations provided in the Tier 2 look-up tables. The Tier 2 screening concentrations were developed using the J&E contaminant transport model combined with conservative default assumptions. If the measured contaminant concentrations are less than the screening values, the site "passes" the screen and no further evaluation needs to be done. If any of the contaminant concentrations exceed their screening value, the site "fails" the screen and proceeds to the next tier in the process.

The Tier 2 secondary screen actually provides two different sets of risk-based concentrations. The first set of screening values is used for a generic screen, while the second set is used for a semi-site-specific screen. The generic criteria are quite conservative and do not allow for incorporation of any site- or building-specific data. The semi-site-specific screen assumes that several site-specific parameters (e.g., soil type, depth to contamination) and building characteristics (e.g., basement or slab-on-grade foundations) will be available. The semi-site-specific screening values are used if the contaminant concentration for a site fails the generic screening step.



Indoor air samples may be taken at any step in the process. This would effectively move the evaluation to the Tier 3 stage.

Figure 3-1. Major Elements of EPA's Tier 1 and Tier 2 Approach

The Tier 2 evaluation requires the user to define the acceptable risk level for the project; the generic screening criteria have been prepared for cancer risks of 1E-04, 1E-05, and 1E-06 or an HQ of 1 for non-cancer risk. These screening criteria have been developed assuming a residential exposure setting; they will be quite conservative if used to evaluate other exposure scenarios. EPA recommends adjusting these criteria to reflect non-residential exposures by modifying parameters such as the exposure duration, air turnover rate, and other relevant parameters.

Tier 2 introduces the concept of an attenuation factor ("alpha") to the vapor intrusion process: alpha represents the differential between the chemical concentration in indoor air and that in soil gas. The attenuation factor, which can range from 0.1 to 0.001, is affected by a variety of issues, including depth to contamination, type of building foundation, and building ventilation rate. Although the attenuation factor will vary from building to building, EPA has developed generic values for several standardized settings. Selecting the appropriate attenuation factor for the Tier 2 assessment—based on available site data (supplemented by literature values as needed)—is an important step; the process for doing this is described in EPA's document. If the risks from the secondary screening are acceptable, the site can be screened out and no further action is necessary. If the screening risks are unacceptable, the site should be evaluated under a Tier 3 assessment.

The approaches and assumptions used to calculate the Tier 2 screening criteria for soil gas and groundwater are reasonable upper-bound values that are intended to be conservative. If contaminated groundwater is the only source of contaminant vapors, then either the soil gas or the soil gas criteria can be used for comparison. EPA recommends that groundwater samples be taken from the top of the water table. If the contaminant source is soil, then only the soil gas criteria can be used for comparison with site data.

For the Tier 2 soil gas criteria, EPA assumed that soil gas 5 feet or less below the building foundation would intrude into indoor-air spaces with an attenuation factor of 0.1—the indoor-air concentration of a chemical would be 10 percent of the sub-slab soil gas concentration. For deep soil gas (below 5 feet), an attenuation factor of 0.01 was used. For groundwater, an attenuation factor of 0.001 was used. These attenuation factors were developed using data from sites where paired indoor air, soil gas, and groundwater samples were available. However, there are certain conditions where this generic attenuation factor may not be accurate. These conditions include the following:

- Very shallow vapor sources (less than 5 feet)
- Residual non-aqueous phase liquid at any depth
- Mobile landfill gas plumes
- Crawl spaces, unfloored basements, or basements with numerous cracks in the floor or foundation
- Very permeable soil between the vapor sources and the building or the presence of horizontal preferential pathways
- Shallow groundwater sources (less than 15 feet below the building)
- Vertical preferential pathways, such as cracked soil, macropores, or karst
- Buildings with a very low air exchange rate (e.g., <0.25/hr)
- Buildings with a high sustained indoor/outdoor pressure differential

The semi-site-specific screening step of Tier 2 includes considering the soil type present at the site, as well as the depth to the contaminant source. The criteria developed for this screening step incorporate this information through the estimation of a building-specific attenuation factor that reflects both the underlying soil type and the depth to the source. The Soil Classification System (SCS) was used to select a set of soil types based on the amount of sand, silt, and clay particles. The four soil types considered by EPA—in order of decreasing grain size—are sand, loamy sand, sandy loam, and loam. Clay was not included because homogenous and unfractured clay deposits occur only rarely. The distance from foundation to contaminant source considered by EPA ranged from 5 feet to 100 feet. This information was then put into the J&E model and a series of attenuation factors were calculated. EPA has calculated semi-site-specific risk-based soil gas and groundwater concentrations for cancer risks levels of 1E-04, 1E-05, and 1E-06 and for a non-cancer HQ of 1. EPA estimates that the semi-site-specific screening values are less conservative than the generic criteria by 2 to 50 times, depending on the soil type and the depth to the source. These screening criteria have been developed assuming a residential exposure setting and will be quite conservative if used for evaluating occupational exposures. EPA recommends adjusting these criteria to reflect to non-residential exposures by modifying parameters such as the exposure duration, air turnover rate, and other relevant parameters.

The Tier 2 criteria can be applied towards either current or future site conditions; they can be used to evaluate vapor intrusion at existing buildings and can also be used to assess the hazards for hypothetical future buildings. In either case, generic and non-site-specific assumptions are made regarding the building foundation, crack space, and ventilation/turnover rates. The conservative assumptions used for these parameters are not intended to be altered for the Tier 2 evaluation. If the Tier 2 criteria (either the generic or the semi-site-specific) are not exceeded, the VIP is considered to be incomplete. If the criteria are exceeded, the project should progress to the Tier 3 evaluation.

EPA recommends that if there is a contaminant source in the unsaturated zone, soil gas data should be used to evaluate the potential vapor intrusion risks in the vicinity of this source. Using bulk soil data to evaluate VIP is not recommended. The presence of preferential pathways—naturally occurring or anthropogenic pathways (soil cracks, pipelines) that are expected to have a high intrinsic gas permeability—should also be considered.

3.4 Tier 3: Site-Specific Screening

This tier is the “site-specific” step of EPA’s vapor intrusion assessment protocol. The first step recommended by EPA in the Tier 3 evaluation is to update the CSM for a site and to identify what additional information may need to be collected to support this evaluation. Activities considered as part of a Tier 3 assessment include the direct measurement of sub-slab soil gas concentrations, indoor-air and background measurements, a home survey for possible sources, and site-specific mathematical modeling. The modeling is intended to be complementary to the actual air concentrations taken during the recommended sampling and will help identify which site parameters have the greatest impact on vapor intrusion at the site or for a particular building.

The Tier 3 volatilization model is the J&E model, which is used to calculate a building-specific attenuation factor and to predict the indoor-air concentration of chemicals of concern. This environmental fate and transport model has been adopted by EPA as their primary volatilization model. EPA (2004) has developed a set of spreadsheets (for both a “screening” and

an "advanced" model) that are pre-programmed with the 1991 J&E algorithm. These spreadsheets include a large number of input parameters (>20); some are generic and some are site-specific. Up to three different soil strata can be included in the advanced model, which is significant because the soil type, grain size, and moisture content can be important determinants regarding transport rates. Tier 3 may be conducted in a phased fashion. For example, if the site-specific transport modeling predicts that indoor-air risks are acceptable, it may not be necessary to collect any additional soil gas or indoor-air data. Conversely, at some sites, it may be more appropriate to skip the modeling and instead take direct measurements of indoor air (e.g., at sites where the Tier 2 assessment indicated a substantial exceedance of the acceptable risk level or where the contaminated groundwater beneath the building is very shallow and the attenuation potential is very small). The determination of how best to proceed with the Tier 3 assessment should be made in consultation with the regulatory authorities and may involve communication with and input from the affected public.

Tier 3 involves collecting a more comprehensive dataset than that used for the Tier 2 evaluation. Soil gas samples may need to be collected from locations immediately adjacent to impacted buildings or from beneath the building foundation (sub-slab). For Tier 3, a more site-specific set of geochemical parameters are incorporated into the J&E contaminant transport model, which is used to predict the indoor air concentration. Additionally, an indoor-air sampling program may be developed and implemented at certain buildings. A Tier 3 assessment is typically used for current or developed sites because much of the site-specific information that is collected is related to building properties or indoor air quality.

At the Tier 3 stage, a refined J&E model may be developed, but quite often, additional modeling results alone may not be adequate to rule out the VIP; sub-slab soil gas and indoor-air samples may be required. The modeling is considered to be useful for determining which factors (e.g., building characteristics, soil moisture content, indoor air exchange rates) have the greatest effect on the predicted results. As many site-specific values for the model parameters should be included as possible. This may require the collection of some additional data that were not collected during previous investigations.

3.5 J&E Modeling Issues

The J&E model has become the standard fate-and-transport model for evaluating subsurface vapor intrusion. The model incorporates both diffusion and advection to estimate the transfer from soil gas into indoor air. Diffusion is the means by which a chemical moves from high concentration to low concentration as a result of the concentration gradient. Diffusion is the primary vapor transport mechanism within vadose zone soil. Advection is the means by which vapor moves due to differences in pressure. Once subsurface vapors are near a building, advection may move the vapors inside due to the pressure differential between the indoor air and the subsurface.

The J&E model includes the following assumptions, which are conservative and may not apply to all sites:

- Steady-state conditions exist.
- An infinite source of contamination is present.
- Subsurface geology is homogeneous.

- Air mixing in the building is uniform.
- Preferential pathways do not exist.
- Contamination is homogeneously distributed within the subsurface.
- Cracks in the building foundation and walls are the primary entry source for vapors.
- Ventilation rates and pressure differences remain constant over time.

These assumptions suggest that the J&E model may not provide accurate results at many buildings, since all of these assumptions will seldom be met. However, the model can serve as a useful tool to assess the likelihood that vapor intrusion will pose an indoor air risk. Because of the conservative nature of the modeling, it may be necessary to collect indoor-air samples if the model predicts high risk. The measured indoor-air concentration of chemicals can then be compared to the predicted concentration and appropriate risk management decisions made.

As noted above, using the J&E model to predict the indoor-air concentration of chemicals is controversial. Schiller (2003) identified three endpoints that the J&E model tends to overpredict:

- The vapor concentration at the source if the source is in the capillary zone and the groundwater level fluctuates
- The vapor concentration in the soil gas adjacent to buildings that are located some distance from the source
- The rate of vapor transport from soil gas into buildings when the default input parameters are used in the J&E model

Schiller (2003) also cites field studies where the measured indoor-air concentration was a thousand-fold lower than the model predicted. It was noted that when site-specific building characteristics and air exchange rates were incorporated into the model, the overprediction was "only" a hundred-fold. Schiller (2003) noted that of the J&E model without proper calibration may result in numerous sites being identified with high risk levels that cannot be confirmed through indoor-air sampling.

4 Sampling and Analysis for Vapor Intrusion

A variety of media may be sampled and analyzed during the course of a vapor intrusion project. Soil gas, groundwater, and indoor air may all be sampled, depending on the phase of the project and the concerns and regulatory requirements at the site. To sample and analyze these various media, it is necessary to develop DQOs, determine the needed detection 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-use issues, sampling should be done in the immediate vicinity of the building(s) in question. EPA (2002a) recommends sampling around any buildings located within 100 feet of documented subsurface 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 to 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 the groundwater and the 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.

Historically, soil and groundwater samples collected as part of the site inspection (SI) or RI study have not been intended to support a vapor intrusion analysis. However, these samples can be useful in performing the initial screen of the VIP. A review of the chemical data, the location of the samples, and the results of the screening will indicate whether sufficient sampling was performed during the SI or RI or whether additional samples are needed to evaluate the VIP. These additional samples may include more soil and groundwater samples or may include soil gas, sub-slab soil gas, or indoor air. The soil gas or indoor air data provides more precise information regarding the migration of volatile chemicals through the subsurface and through the building foundation than can be derived from soil or groundwater data.

4.1 Sampling

Sample numbers and locations depend on several factors, including the nature of the contamination, the size and construction of the building in question, and the underlying geology at the site. These factors need to be considered in the development of DQOs for the project and for the sampling plan and associated Quality Assurance Project Plan (QAPP).

4.1.1 Soil

The sampling of bulk soil is not a preferred approach for vapor intrusion studies. Accurately measuring the concentration 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. The modeling and partitioning equations that are 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 associated with all of the other modeling parameters. However, as discussed by the 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 very difficult to collect soil gas. If default values are used for the J&E model under such soil conditions, however, the contaminant transport rates are likely to be overestimated.

4.1.2 Groundwater

Contaminated groundwater is often the primary media contributing to vapor intrusion at many sites. Because groundwater can be mobile, chemicals can migrate much greater distances than they would if they were located exclusively in soil. Chemicals in groundwater can be in the dissolved phase or 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). Non-aqueous phase liquid occurs when the chemical concentration exceeds the solubility that can dissolve in water. Hence, LNAPL forms on top of the water table (often referred to as "floaters"), while DNAPL ("sinkers") forms at the bottom of the water table. LNAPL is usually present as a discrete layer of consistent thickness; 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. Both groups of non-aqueous phase liquids can be very hard to find and measure accurately. Sampling the groundwater at the appropriate depth is necessary to determine whether LNAPL or DNAPL are present. For LNAPL, the upper layer of the aquifer should be sampled, while for DNAPL, the bottommost layer should be sampled.

4.1.3 Soil Gas

Soil gas has become the preferred media for evaluating the VIP. Using soil gas data instead of soil or groundwater data avoids some of the problems that are hard to predict accurately using contaminant fate-and-transport models. These hard-to-model processes include the volatilization of chemicals from groundwater, transport across the capillary fringe, and bioattenuation. In addition, 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).

Soil gas can be collected in one of three ways: **actively, passively, or by surface-flux chambers.** **Active soil-gas collection** is probably the most commonly used method. Active methods involve the 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., ug/L), which can be input directly into contaminant transport models.

Passive soil gas collection is essentially just 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 measure 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 uses. Passive soil-gas results are useful only to make an initial qualitative determination as to whether VOCs are moving through the soil.

The third option for measuring chemical present in soil gas is the **flux chamber**. This is essentially 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. The flux chamber 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: the static chamber and the dynamic chamber. The static chamber does not use "sweep" gas to maintain a steady-state concentration in the chamber. The dynamic flux chamber, by contrast, has a "gas in, gas out" that allows the chamber to reach a steady-state condition with regard to the chemical flux from the subsurface. The static chamber is more sensitive than the dynamic chamber 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 in a quantitative risk assessment. The use and interpretation of flux chamber results should be determined in the development of the DQOs.

In addition, flux chambers cannot be placed at the slab/wall connection, the crack that 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.

4.1.4 Sub-Slab Sampling

Some consider sub-slab sampling to be the quickest way to get an accurate assessment on vapor intrusion conditions. The buildings selected for sub-slab sampling should be chosen with full consideration of both the CSM and the project DQOs. One approach recommended by some regulatory agencies is to collect several sub-slab samples 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 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. DTSC and MADEP 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. It may be difficult to get agreement from the building owner/occupant to allow this kind of activity.

A limitation of sub-slab sampling is that it gives no information on what is happening in the vadose zone between the groundwater and the slab. The results of sub-slab sampling cannot be used in the J&E model, which requires a minimum distance of 5 feet of soil. Sub-slab sampling is used for the direct measurement of soil vapor immediately below the slab. EPA (2002) has recommended an attenuation factor associated with a slab of 0.1; based on updated information, DTSC (2005) recommends a value of 0.01. DTSC also recommends that at least two sub-slab samples be taken, 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.

Several factors should be considered regarding sub-slab sampling:

- Sensitivity of detection limits (should meet risk-based requirements)
- Seasonal and/or temporal variability
- Spatial variability (soil types, building design, plume location)
- Degradation products resulting from either aerobic or anaerobic metabolism

The results of the sub-slab samples are coupled with an attenuation factor appropriate for the building of interest and compared with the risk-based criteria developed by EPA. If the site concentrations are below the risk-based criteria, it may be concluded that the pathway is incomplete and no further study is needed. If the site concentration exceeds the criteria, indoor-air samples will need to be collected to further evaluate the risks associated with the VIP.

4.1.5 Indoor-Air Sampling

Indoor-air sampling may be conducted in response to occupant complaints regarding odor; this sampling would evaluate whether chemicals present in the subsurface can be detected in the indoor air and evaluate the results of contaminant transport modeling. Meeting these different objectives may require different detection limits, and the project manager needs to take this possibility into account when developing project DQOs.

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 exposure should be collected. The sampling canisters and flow regulators should be adjusted to collect an integrated air sample over the exposure duration of interest.

EPA and a number of states recommend that indoor-air samples be collected at least twice to account for seasonably variability in building parameters and subsurface volatilization. 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 will create a pressure differential that pulls gases up from the subsurface.

The number and location of sampling points will vary from building to building. In general, several samples should be taken from the basement and from high-trafficked areas. The DTSC (2005) recommends that 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, the DTSC (2005) recommends taking at least one sample from each discrete office.

There are several different techniques that can be used to monitor indoor air quality. 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, the required detection limits, the duration of the monitoring, and the project goals. The selection of the proper sampling techniques is dependent in large part on how the data will be used and what detection limits are needed. The pros and cons of the different monitoring techniques are discussed below.

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 the indoor air. This information can be critical for determining whether the source of an indoor air contaminant is coming from vapor intrusion or is associated with chemical use or storage within the house. A copy of EPA's occupied dwelling questionnaire from their 2002 vapor intrusion guidance is included as Appendix B of this document.

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 detection 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 collect an adequate amount of contaminant to meet sensitive detection limit requirements. Sampling time can vary from minutes to weeks or even months, depending on the required detection limits. 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 is trapped, thus yielding lower detection limits. Advantages of time-integrated monitoring include achievement of low detection 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 several 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 analysis system for real-time monitoring can use various detectors, including gas chromatography (GC), GC/mass spectrometry (GC/MS), and infrared spectroscopy (IR), as well as other techniques.

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. 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 detection 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 detection 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. They are typically non-selective sampling methods; they measure classes of chemicals rather than individual chemicals. The most commonly used direct-measurement detectors are flame ionization detectors (FIDs) and photo ionization detectors (PIDs). The FIDs and PIDs 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. The 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 contamination may result from either indoor or outdoor sources and may be an important component of the chemicals measured during indoor-air sampling. Outdoor sources may include gas stations, industrial facilities, and roadways (along with widespread regional sources such as power plants or refineries). Indoor sources may include storage of petroleum hydrocarbons (gasoline for lawnmowers, etc.), paints and varnishes, solvents and strippers, offgassing of textiles, carpeting, and drycleaning, glues and hobby materials, household cleaners, and fumes from smoking or fireplaces.

Because chemical use and storage varies among different households and buildings, the contribution of background contaminants should be accounted for at each building where the indoor air is sampled. Ideally background sampling would be conducted at all potentially impacted buildings; however this may not always be practicable. At bases or sites with a large number of buildings, this may require making generalized assumptions for buildings with similar use profiles. For example, the contribution from outdoor air contaminants to background levels may be very similar from building to building.

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 leach 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. Several regulatory agencies, including the EPA, Cal-EPA, and MADEP, have prepared a questionnaire that includes detailed questions regarding possible sources of background chemicals in indoor air. A copy of EPA's questionnaire from their 2002 vapor intrusion guidance is attached as Appendix B.

For additional information regarding indoor-air sampling, the 2002 publication *Indoor Air Sampling and Analysis Guide*, WSC Policy #02-430 (MADEP, 2002) is extremely detailed. This document is available online by selecting the "indoor air" document at the Massachusetts publications website <http://www.mass.gov/dep/ors/orspubs.htm>.

4.1.6 Building Design Issues

The Air Force has a wide variety of building styles that can be affected in different ways by vapor intrusion. Examples of various Air Force buildings include residential housing, barracks (group housing), industrial buildings, airplane hangers, warehouses, 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 rate at which vapor can migrate 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 may not accurately model vapor intrusion into buildings with a crawl space. Caution should be used when using the J&E model to evaluate vapor intrusion at 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 the 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 Air Force 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.

4.2 Analytical Methods

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.

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 1999;
- Compendium of Methods for the Determination of Inorganic Compounds in Ambient Air, EPA/625IR-96-010a, June 1999

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

The two methods of greatest importance for measuring VOCs in indoor air (as well as in soil gas) are EPA's toxic organic TO14 (and TO-14A) and TO15 methods. In general, these methods have the sensitivity needed to provide data with detection 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 and condensed 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. The TO-15 Supplemental method can achieve detection limits in the low 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” (SIM), which focuses on specific compounds rather than a suite of compounds.

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. Detection limits for these techniques range from 0.01 to 1.0 ppbv, depending on the chemical.

Because there is some degree of flexibility built into EPA's *Compendia* procedures, it is important to select a laboratory that has experience with the methods and techniques needed for the project. Standard operating procedures (SOPs) and calibration procedures may rely on various options included in the analytical protocols that require the expertise of experienced personnel.

5 Health Risk Assessment at Vapor Intrusion Sites

The results of a vapor intrusion project, whether modeled or measured, are presented as the indoor-air concentration of the chemical of interest. The indoor-air concentrations are presented as either $\mu\text{g}/\text{m}^3$ or as ppbv. These concentrations can be compared with the screening criteria or can be used for a site-specific risk assessment. This section of the guidance document discusses how the results of a vapor intrusion study can be included in a risk assessment.

Health-based 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 remediation 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). The Air Force Center for Environmental Excellence's (AFCEE's) *Guidance for Contract Deliverables, Appendix D: Risk Assessment Methods, Version 2.1* should also be reviewed prior to conducting a risk assessment.

A risk assessment consists of four distinct phases:

- **Hazard identification** includes site investigation, collection of data, and identification of chemicals of concern.
- **Exposure assessment** includes identification of potentially exposed receptors and exposure pathways, as well as exposure duration, frequency, and exposure point concentration.
- **Toxicity assessment** identifies the toxicity criteria for the chemicals of concern.
- **Risk characterization** combines the results of the 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.

For the past several decades, risk assessments have focused primarily on exposure to soil or groundwater as the primary exposure pathways. Soil exposure routes include ingestion, dermal contact, and inhalation of dust. Groundwater exposure routes include ingestion, dermal contact, and inhalation of VOCs while showering. Inhalation of vapors from the subsurface was not considered or evaluated in most risk assessments. As a result, some sites with a complete VIP may have been missed. EPA and state health agencies are now requiring that this pathway be evaluated in a routine and consistent way, and in some cases, they have reopened closed sites to evaluate this pathway.

5.1 Hazard Identification

The hazard identification phase of a risk assessment encompasses two primary elements: site characterization and identification of chemicals of concern. Older sites may not have been well characterized for the VIP; available data should be carefully reviewed in light of the project DQOs to determine how well the site has been characterized and if additional sampling is needed. For vapor intrusion projects, the chemicals of concern will typically be those chemicals that meet the criteria for toxicity and volatility (see list in Appendix). The chemicals of concern for other pathways may include these chemicals or may be part of a different group.

5.2 Exposure Assessment

5.2.1 General Exposure Factors

The exposure assessment typically includes the CSM (described in Section 2.1) and evaluates the pathways and routes by which people may be exposed to site chemicals. Although this document focuses on vapor intrusion and inhalation exposure, there may be a number of other exposure pathways by which a receptor may be exposed to site-related contamination. An important aspect of the CSM is to distinguish between complete and incomplete exposure pathways. Complete pathways are typically evaluated in the risk assessment, while the incomplete pathways are not. Pathways that are currently incomplete may be complete for future scenarios (assuming future site development). The exposure assessment also identifies the 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, or visitors.

An important component of the exposure assessment is the 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—commonly assumed to be 30 years for residents and 25 years for workers (these assumptions will vary for military personnel, as discussed in Section 2.2). EPCs are calculated for all chemicals of concern identified in the hazard assessment step. The EPC should be an upper bound—but not worst-case—concentration of 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 percent upper confidence limit (UCL) on the mean concentration (95 UCL). However, in the case of vapor intrusion, there are often a limited number of soil gas or groundwater samples in the vicinity of the building of interest. For sub-slab soil gas and indoor air, there may only be a few samples available. As a result, the maximum detected concentration may be used as the EPC. 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 project manager 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 non-depleting (where the concentration of the contaminant source remains unchanging).

5.2.2 Air Force-Specific Exposure Factors

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 the 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. This handbook recommends that the Air Force-specific residential exposure duration values be used when conducting a vapor intrusion risk assessment for residential scenarios at

active duty bases. This will provide a more realistic risk estimate than can be achieved using EPA's default values. Similarly, the generic screening values for soil gas and groundwater developed by EPA (as discussed in Section 3 of this report) can be adjusted to account for the shorter exposure duration at Air Force bases.

5.3 Toxicity Assessment

The toxicity assessment identifies the toxicity values for carcinogenic and non-carcinogenic endpoints for all chemicals of concern. For most states, the preferred toxicity criteria are the validated criteria developed by EPA. In December 2003, EPA published a memo listing the preferred sources for human health toxicity values for use in Superfund risk assessments (OSWER Directive 9285.7-53). The recommended hierarchy of toxicity criteria is as follows:

1. **EPA's Integrated Risk Information Service (IRIS) Database.** These toxicity values normally represent the official EPA scientific position regarding the toxicity of the chemicals based on the data available at the time of the 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 the most current, the basis for which is transparent and publicly available, and which have been peer-reviewed.

In California, the Cal-EPA has developed their own values for a number of chemicals that should be used in preference to EPA values for risk assessments conducted within that state. The information for 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. The Cal-EPA toxicity values are considered to meet the standards for "other toxicity values" in EPA's hierarchy. This is of particular importance for TCE, as discussed in the preceding paragraph.

One of the more important toxicology issues currently impacting vapor intrusion risk assessments is the controversy surrounding the toxicity criteria for TCE. EPA withdrew the 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 indicated that it was ten- to forty-fold more carcinogenic than previously thought. This finding greatly increased concern over TCE vapor intrusion since TCE is a common soil and groundwater contaminant at Air Force bases because of its widespread use as a solvent and degreaser. EPA's draft risk assessment for TCE was found to have a number of controversial analyses and conclusions, and it was challenged by industry and the Department of Defense (DoD). As a result, the draft risk assessment and toxicity value for TCE have not been finalized, and EPA has withdrawn their support for widespread implementation of the 2001 TCE toxicity estimates (Inside EPA, 2003). The EPA, the DoD, and other federal agencies, working together through an interagency agreement, have requested that the National Academy of Sciences (NAS) review EPA's draft risk assessment and the scientific data for TCE and provide a recommendation regarding the cancer potency of TCE. The NAS review and EPA's subsequent revisions to their TCE risk assessment are not expected to be completed for several

years. As a result, EPA does not currently have a validated toxicity value for TCE. Following EPA's 2003 memo (OSWER Directive 9285.7-53), the AFIOH suggests that the TCE toxicity value developed by the Cal-EPA be used for TCE vapor intrusion risk assessments since it has been validated and peer-reviewed and is based on human inhalation studies.

5.4 Risk Characterization

The risk characterization step combines the analytical data, exposure information, and toxicity criteria in a series of calculations that results in numerical risk estimates for each chemical. Toxicity values for carcinogens are presented as "cancer slope factors", sometimes called "unit risk factors" for inhalation carcinogens. 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. EPA's acceptable risk range spans two orders of magnitude, from 1E-04 (1 in 10,000) to 1E-06 (1 in 1 million). These cancer risks estimates are classified as "excess lifetime cancer risks" and are solely associated with exposure to site-related chemicals. They are separate and distinct from "background" cancer risks (essentially the lifetime cancer risk from all causes), which are around 1 in 3 (0.3 percent) for the U.S. population. Cancer risks for carcinogenic chemicals are typically added together for a cumulative risk estimate. Similarly, cancer risks for different pathways (e.g., vapor intrusion or soil ingestion) may also be added together to yield the total cancer risk associated with exposure to site chemicals.

Toxicity criteria for noncarcinogenic effects 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, inflammation, or various organ effects. Non-cancer risks for individual chemicals are presented as an HQ, which is essentially a ratio of the acceptable exposure level with the exposure level calculated for the site. The HQs for different chemicals are typically added together, resulting in a cumulative hazard index (HI). Similarly, the HIs for different pathways may also be summed for a total HI associated with exposure to site chemicals. The acceptable HQ or HI is typically 1—the site-related exposure should not exceed the level considered acceptable by EPA. If an HI exceeds 1, EPA recommends that the HQs for different chemicals be examined and separated by target organ effects.

As previously noted, what is referred to as the CERCLA acceptable excess cancer risk range covers from 1E-04 to 1E-06. Project managers are given discretion to make site-specific decisions about what level of risk is acceptable. Typically, EPA's preference is to manage risks towards the lower end of the risk range at residential sites, while commercial and industrial settings may be managed towards the upper end of the risk range. Individual states often set their own acceptable risk level rather than using the CERCLA risk range. For example, Colorado uses 1E-06 as their acceptable risk level, while California accepts 1E-05 as their acceptable risk level. It is the Air Force preference to use the CERCLA risk range, but this may need to be negotiated with regulatory agencies on a site-by-site basis. At CERCLA sites, it is the Air Force position that the entire risk range be considered. EPA's 1991 memo "Role of the Baseline Risk Assessment in Superfund Remedy Selection Decisions" discusses risk-based decision making at Superfund sites.

An important component of the risk characterization step is the identification of the primary uncertainties present in the risk assessment. Accounting for the primary uncertainties is important

for the risk manager, to support defensible decision making. All four primary components of risk assessment can have major uncertainties associated with them, as discussed below.

The effectiveness of the hazard identification phase 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. The selection of an EPC for the risk assessment should take into account these uncertainties. It may be useful to calculate two sets of risk, one based on the maximum detected concentration and one based on a more representative concentration, such as the 95 UCL.

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 Air Force personnel. For example, the standard assumption that a person will spend 30 years in the same house is likely to be a substantial overestimate for most Air Force personnel. Available information regarding military exposure profiles should be reviewed to determine the most appropriate assumptions to use.

The toxicity assessment has a number of inherent uncertainties associated with it. For many chemicals, toxicity criteria are derived from animal studies and extrapolated to humans. The testing protocols for animal studies may be very different than the exposure scenarios for humans. Many scientists have questioned the relevance of high-dose animal studies to the typical low-dose human-exposure scenarios. Typically, EPA uses the lowest dose that causes an effect as the basis for the development of toxicity criteria. A number of uncertainty factors are also included in the toxicity criteria for both carcinogens and noncarcinogens. In general, the 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.

5.5 Additional Risk-Related Issues

5.5.1 Petroleum Hydrocarbons

As noted previously, EPA recommends that their 2002 guidance not be used for the evaluation of vapor intrusion associated with Subtitle 1 UST sites because petroleum hydrocarbons released from USTs are susceptible to natural attenuation and biodegradation; EPA’s vapor intrusion assumptions are too conservative for compounds that degrade. As a result, vapor intrusion risk assessments of petroleum hydrocarbon sites will often overestimate the long-term exposure concentration, in turn overestimating the potential risk to the receptors that may be present.

However, not all states concur with this position. California EPA requires that petroleum hydrocarbons at sites in California be evaluated for the possibility of vapor intrusion (DTSC, 2005). The California guidance acknowledges that while biodegradation may occur at many sites, there are locations where conditions will not support biodegradation. Their guidance recommends that two geochemical indicators of aerobic biodegradation—oxygen consumption and the generation of carbon dioxide—be measured in the soil gas to evaluate bioattenuation. 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.

5.5.2 Regulation of Industrial Sites

There has been ongoing discussion as to whether EPA or the Occupational Safety and Health Administration (OSHA) has jurisdiction over regulating vapor intrusion concerns at industrial sites. An agreement between the two agencies back in 1990 gave OSHA the authority to manage indoor air quality in the workplace (Schiller, 2003). However, this was before vapor intrusion became a serious concern, and OSHA focused primarily on exposure to volatile chemicals that were actively used in the workplace. Since vapor intrusion is a result of subsurface contamination, which EPA does regulate, it has been unclear which agency has regulatory authority. The acceptable OSHA Permissible Exposure Limits (PELs) are the maximum concentration of a chemical in the air that a worker may be exposed to without respiratory protection. The PELs were developed to protect healthy workers and do not consider other populations, such as children or sick people. The OSHA PELs were developed to protect against direct and voluntary job-related chemical exposure, not from indirect and involuntary contamination-related chemical exposure. OSHA PELs are typically two to three orders of magnitude higher than EPA's more restrictive risk-based values.

Although there has been a great deal of debate on this issue recently, it is not clear that there has been a formal resolution of responsibilities. In general, for individuals who work in a job that uses industrial chemicals and are notified of potential exposure via OSHA-mandated hazard communication information, their exposure is most likely regulated by OSHA. For these individuals, workplace exposure to chemicals will greatly predominate over vapor intrusion exposure. However, for individuals who do not work with chemicals (e.g., an office worker) and do not have OSHA hazard communication information in their workplace, vapor intrusion from subsurface contamination might be their primary exposure pathway. In this instance, EPA would be the regulating agency.

Appendix F of the California vapor intrusion guidance (DTSC, 2005) contains a discussion of the use of OSHA PELs in California. The DTSC states that they do not consider OSHA standards to be an applicable or relevant and appropriate requirement (ARAR) for cleanup under CERCLA regulations.

6 Risk Management at Vapor Intrusion Sites

The risk management phase of a vapor intrusion project 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 the 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 remediate the 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.

Based on the results of the risk assessment, the vapor intrusion risks may be substantial enough that they must be managed. Risk management is not 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 reduce 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 of the report 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. Although they are different concepts, many people use these terms interchangeably. Remediation 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. Examples of mitigation include the 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.

6.1 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 exposure limit (LEL). These scenarios may pose an immediate—or near-term—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. 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. The 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.

6.2 Risk Management for Chronic Risks

A risk management strategy should be developed if the risk assessment indicates the 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.

The Massachusetts Indoor Air guidance document (2002) listed several remediation and mitigation options for reducing risk from vapor intrusion. The mitigation options are listed below:

- **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 the 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, the building 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 the 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. The 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 the 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.

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 the 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 the 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 the 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. Oxygen and nutrients may be supplied to speed the rate of degradation.

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 the soil gas. Soil removal and soil vapor extraction may have the most substantial short-term effects either by eliminating the source of the 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 typically takes 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 the long-term risks can be reduced.

There are alternate risk management strategies that rely on land-use and building-use controls more than remediation or mitigation. For example, the Air Force can choose to not use a particular building if the vapor intrusion risks to the occupants are too high. Similarly, they can choose not to develop property that is located over a groundwater or soil gas plume, thus avoiding indoor air problems from vapor intrusion.

7 Risk Communication

An important and often overlooked component of a vapor intrusion project is the development of a risk communication plan. Vapor intrusion projects can be invasive to building occupants because they can involve such activities as indoor air sampling, sub-slab drilling, installation of depressurization devices, and removal of nearby sources of possible contamination. This situation can dismay and cause stress to building occupants, who may be very concerned about their health or property values. This section discusses some of the important risk communication issues that need to be considered as part of a vapor intrusion project.

Risk communication is the process of building, maintaining, and repairing relationships with stakeholders on issues that affect them. 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 an Air Force vapor intrusion project, the most common stakeholders include the Air Force, EPA and local regulatory authority, the occupants of the building(s), local or adjacent—even offsite—residents or workers, and environmental advocacy groups. All of these groups or individuals have an interest in the possible consequences of a contaminated site with vapor intrusion concerns. Some stakeholders may have very different views on an issue than others. For example, one group may feel that the level of risk does not justify an expensive remediation program, while a different group may feel that any risk is too great and the site should be cleaned up. Other issues may include differences of opinion in such areas as health, environmental justice, safety, economic, political, social, or historic issues.

7.1 Importance of Risk Communication

The most common concerns of stakeholders at vapor intrusion sites relate to possible health impacts, real estate valuation, concern over groundwater contamination, plume migration, and the noise and impacts of remediation and mitigation of vapor intrusion.

There are several important goals associated with effective risk communication:

- Increase the knowledge and understanding of the situation by all parties
- Establish, maintain, and—in some cases—repair trust and credibility among the stakeholders
- Achieve agreement or consensus on issues and solutions (Note: This can be difficult)

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 will typically result in public outrage and, quite often, rejection of the solution. An example of this could be an Air Force project manager at a public meeting telling local residents that TCE had been detected in groundwater below their houses but that the Air Force had investigated the situation and determined that vapor intrusion was not a concern at this site and that no further investigation or remediation would be performed. If the stakeholders were not involved, or at least informed, of the steps leading up to this conclusion, they will almost certainly reject the conclusions of the Air Force. Such a scenario may in turn lead to protracted arguments and discussion about what was done at the site, what the results mean, and what the path forward should be. It is much better to have multiple opportunities for stakeholder to provide input throughout the project than to wait until the assessment is completed.

There are multiple benefits that can be achieved by having a risk communication program:

- Being proactive on issues rather than reactive, which can result in a shorter schedule and reduced expense
- Improved relationships with stakeholders, which can result in less hostility and less adverse press
- Better risk management decisions because of buy-in by various parties
- Improved public perception
- Better legal standing

7.2 Key Considerations

Most Air Force project managers will have little training in risk communication and public relations. If the problem is small (small plume, minimal number of buildings impacted, no off-site impacts), risk communication needs can be modest. However, if the problem is large (e.g., thousands of off-base homes above a solvent plume at the former Kelly AFB), a more substantial risk communication plan is needed, including training for the involved individuals. Risk communication training is available to Air Force personnel through the Civil Engineer Corps Officer School (CECOS) for the Interservice Environmental Education Review Board (ISEERB). The CECOS training schedule can be found at <https://www.cecosp.navy.mil>.

Getting stakeholder involvement and participation can be a challenging process. At most Air Force bases, the project manager often has to brief audiences on environmental projects. However, given the nature of vapor intrusion and the potentially invasive nature of the sampling, informing the public is obviously required.

The ISEERB course presents a short list of key risk communication points to consider, particularly in contentious situations where there are low levels of trust among the parties, coupled with substantial concern regarding the risks associated with the project. Some of the key points are provided below:

Responding to Difficult Questions from the Audience

- Allow the questioner to vent their frustration—do not interrupt or challenge them
- Try to determine the underlying concern—often the questioner masks their true concern (inadvertently) with a secondary concern
- Empathize with them—but do not act sympathetic or say “I know how you feel”
- Clearly state your facts and conclusions
- Identify follow-up actions to take to show them you are taking their concerns seriously

Responding to Hostile Questions from the Audience

- Don't take the hostility personally—they are upset at the situation and are venting their frustration out at you, the public face for the Air Force
- Remember that it is “not about you”—after all, you did not create the problem
- Let the questioner vent their frustration
- Observe the non-verbal body actions—this can give clues to underlying issues

Be an Active Listener

- Hear (feel) the emotions behind the words
- Note the phrases they use, especially those they repeat
- Note the voice changes and words they emphasize
- At the appropriate time, paraphrase what they said to ensure that you understand their concern

The ISEERB course also recommends a number of things the presenter (representing the Air Force) needs to do to maintain credibility with the audience:

Traps to Avoid

- Using humor (occasional bits okay, but be careful)
- Using jargon—do not get too technical or slangy; remember, your audience does not have the familiarity with the subject material that you do
- Taking it personally—they are not upset with you personally
- Too much hedging—don't hem and haw
- Making guarantees—in a word, don't
- Describing worst-case scenarios
- Using risk comparisons—this makes them feel like you are trivializing their concerns
- Saying “I don't know” too much—while it is good to admit what you do and do not know, you can do damage to your situation if you appear too ignorant

Non-Verbal Cues and Body Language

- Maintain eye contact when you speak
- Mirror the spacing of your questioner—stay in their comfort zone
- Use an open body position—do not be clenched up or too casual
- Lean in slightly towards the questioner
- Relax—visible nervousness hurts your credibility
- Avoid barriers between yourself and your audience
- Dress appropriately for the setting and your audience

7.3 Final Remarks

It is important to remember that the concerns and frustrations of the audience result from the fact that something has happened to them or their property over which they have little or no control. They are nervous about what could happen to their health from the intruding vapors, as well as concerned about how this might affect their real estate valuation. Although the risks from vapor intrusion at a site may be found to be minimal or even non-existent, people will still be concerned over the involuntary nature of the situation. They have been told that they may be exposed to toxic chemicals seeping into their house through no fault of their own. They are nervous, they are upset, and they may be looking to vent their frustration and anger on the Air Force representative. It is important to have effective risk communication skills to avoid making a difficult situation worse.

Depending on the project circumstances, it may be necessary to get the AF public affairs office involved, particularly when the media is involved. The project manager is encouraged to consult both the public affairs office and risk communication experts at AFIOH for help in message development and distribution.

8 Summary and Recommendations

A recent paper published by the legal firm Goodwin and Procter (2004) contained a set of “strategic considerations for responsible parties” regarding vapor intrusion sites. These considerations echo the information presented in this guidance document and are summarized here for Air Force managers to remember when addressing vapor intrusion sites.

- Undertake appropriate planning to address the VIP in the remedial investigation.
- Collect sufficient site-specific data to be able to avoid using EPA-derived default values to the extent possible.
- Determine whether the migration of volatilized contaminants from the subsurface to indoor air is occurring, not just whether contaminants of concern are present in indoor air.
- Even if a site has an approved remedy in place, be prepared to respond to requests for reassessments.
- If vapor intrusion is identified as an issue at your site, consider all your remedial options.
- Before you begin, establish a plan for communicating sampling results.

EPA is currently updating their 2002 vapor intrusion guidance. The 2002 guidance has been criticized by some groups as being excessively conservative. The May 24, 2005 issue of the Risk Policy Report provided a status report on the changes that EPA is proposing to make to address these concerns. The proposed changes include the following:

- Lowering the attenuation factor, which would lower the estimate of how much soil gas can seep inside a building
- Increasing the number of variables that regulators must consider in assessing the likelihood of vapors entering a structure (These variables include the type of building foundation, chemical-specific attenuation factors, and different layers of soil under the building)
- Increasing the number of technologies available to assess VIPs
- Allowing regulators to consider a site’s future use when assessing the vapor’s potential risk

EPA has indicated that these changes will make a vapor intrusion assessment more accurate than the current methods. It will also make the screening process more effective, as more sites will be screened out before advancing to a Tier 3 analysis phase.

9 Additional Technical Resources

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

As previously noted in this document, new guidance for the VIP continues to be prepared by EPA and state health agencies. 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 environmental consultants have compiled lists of different websites that contain information on the assessment of the VIP. (Note: the listing of a company does not mean endorsement by the Air Force. The listed companies are provided solely as a technical resource.)

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>.

Geosyntec Consultants, another organization with experience in vapor intrusion projects, also maintains a list of vapor intrusion documents. This list can be found at http://www.geosyntec.com/vi_links.asp.

Haley and Aldrich maintain a vapor intrusion webpage that lists vapor intrusion documents. This list can be found at <http://www.haleyaldrich.com/vilinks.html>.

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.

In addition, the Interstate Technology and Regulatory Council (ITRC) is preparing a vapor intrusion guidance document. The status of this document can be reviewed on the ITRC homepage at <http://www.itrcweb.org/homepage.asp>.

In addition to these resources, the Health Risk Assessment Branch (RSRE) of the Air Force Institute for Operational Health (AFIOH) can provide support for Air Force vapor intrusion projects. More information regarding RSRE capabilities can be found at http://www.brooks.af.mil/afioh/Environmental%20Programs/about_rsre.htm.

Appendix A

Table A-1 lists chemicals that may be found at hazardous waste sites and indicates whether, in the judgment of EPA, these chemicals are sufficiently volatile (Henry's Law Constant $> 10^{-5}$ atm m³/mol) to result in potentially significant vapor intrusion and sufficiently toxic—an incremental lifetime cancer risk greater than 10^{-6} or a non-cancer hazard index greater than 1 (in some cases both)—to result in potentially unacceptable indoor air inhalation risks. The approach used to develop Table A-1 is documented in Appendix D of U.S. Environmental Protection Agency (2002). *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils*: EPA/540/1-89/002.

Table A-1. Question 1 Summary Sheet

CAS No.	Chemical	Is Chemical Sufficiently:		Check Here if Known or Reasonably Suspected To Be Present ³
		Toxic? ¹	Volatile? ²	
83329	Acenaphthene	YES	YES	
75070	Acetaldehyde	YES	YES	
67641	Acetone	YES	YES	
75058	Acetonitrile	YES	YES	
98862	Acetophenone	YES	YES	
107028	Acrolein	YES	YES	
107131	Acrylonitrile	YES	YES	
309002	Aldrin	YES	YES	
319846	alpha-HCH (alpha-BHC)	YES	YES	
62533	Aniline	YES	NO	NA
120127	Anthracene	NO	YES	NA
56553	Benz(a)anthracene	YES	NO	NA
100527	Benzaldehyde	YES	YES	
71432	Benzene	YES	YES	
50328	Benzo(a)pyrene	YES	NO	NA
205992	Benzo(b)fluoranthene	YES	YES	
207089	Benzo(k)fluoranthene	NO	NO	NA
65850	Benzoic acid	NO	NO	NA
100516	Benzyl alcohol	YES	NO	NA
100447	Benzylchloride	YES	YES	
91587	beta-Chloronaphthalene	YES	YES	
319857	beta-HCH (beta-BHC)	YES	NO	NA
92524	Biphenyl	YES	YES	
111444	Bis(2-chloroethyl)ether	YES	YES	
108601	Bis(2-chloroisopropyl)ether	YES	YES	
117817	Bis(2-ethylhexyl)phthalate	NO	NO	NA
542881	Bis(chloromethyl)ether	YES	YES	
75274	Bromodichloromethane	YES	YES	
75252	Bromoform	YES	YES	
106990	1,3-Butadiene	YES	YES	
71363	Butanol	YES	NO	NA
85687	Butyl benzyl phthalate	NO	NO	NA

CAS No.	Chemical	Is Chemical Sufficiently:		Check Here if Known or Reasonably Suspected To Be Present ³
		Toxic? ¹	Volatile? ²	
86748	Carbazole	YES	NO	NA
75150	Carbon disulfide	YES	YES	
56235	Carbon tetrachloride	YES	YES	
57749	Chlordane	YES	YES	
126998	2-Chloro-1,3-butadiene (chloroprene)	YES	YES	
108907	Chlorobenzene	YES	YES	
109693	1-Chlorobutane	YES	YES	
124481	Chlorodibromomethane	YES	YES	
75456	Chlorodifluoromethane	YES	YES	
75003	Chloroethane (ethyl chloride)	YES	YES	
67663	Chloroform	YES	YES	
95578	2-Chlorophenol	YES	YES	
75296	2-Chloropropane	YES	YES	
218019	Chrysene	YES	YES	
156592	cis-1,2-Dichloroethylene	YES	YES	
123739	Crotonaldehyde (2-butenal)	YES	YES	
98828	Cumene	YES	YES	
72548	DDD	YES	NO	NA
72559	DDE	YES	YES	
50293	DDT	YES	NO	NA
53703	Dibenz(a,h)anthracene	YES	NO	NA
132649	Dibenzofuran	YES	YES	
96128	1,2-Dibromo-3-chloropropane	YES	YES	
106934	1,2-Dibromoethane (ethylene dibromide)	YES	YES	
541731	1,3-Dichlorobenzene	YES	YES	
95501	1,2-Dichlorobenzene	YES	YES	
106467	1,4-Dichlorobenzene	YES	YES	
91941	3,3-Dichlorobenzidine	YES	NO	NA
75718	Dichlorodifluoromethane	YES	YES	
75343	1,1-Dichloroethane	YES	YES	
107062	1,2-Dichloroethane	YES	YES	
75354	1,1-Dichloroethylene	YES	YES	
120832	2,4-Dichlorophenol	YES	NO	NA
78875	1,2-Dichloropropane	YES	YES	
542756	1,3-Dichloropropene	YES	YES	
60571	Dieldrin	YES	YES	
84662	Diethylphthalate	YES	NO	NA
105679	2,4-Dimethylphenol	YES	NO	NA
131113	Dimethylphthalate	NA	NO	NA
84742	Di-n-butyl phthalate	NO	NO	NA
534521	4,6-Dinitro-2-methylphenol (4,6-dinitro-o-cresol)	YES	NO	NA
51285	2,4-Dinitrophenol	YES	NO	NA
121142	2,4-Dinitrotoluene	YES	NO	NA
606202	2,6-Dinitrotoluene	YES	NO	NA
117840	Di-n-octyl phthalate	NO	YES	NA
115297	Endosulfan	YES	YES	

CAS No.	Chemical	Is Chemical Sufficiently:		Check Here if Known or Reasonably Suspected To Be Present ³
		Toxic? ¹	Volatile? ²	
72208	Endrin	YES	NO	NA
106898	Epichlorohydrin	YES	YES	
60297	Ethyl ether	YES	YES	
141786	Ethylacetate	YES	YES	
100414	Ethylbenzene	YES	YES	
75218	Ethylene oxide	YES	YES	
97632	Ethylmethacrylate	YES	YES	
206440	Fluoranthene	NO	YES	NA
86737	Fluorene	YES	YES	
110009	Furan	YES	YES	
58899	gamma-HCH (Lindane)	YES	YES	
76448	Heptachlor	YES	YES	
1024573	Heptachlor epoxide	YES	NO	NA
87683	Hexachloro-1,3-butadiene	YES	YES	
118741	Hexachlorobenzene	YES	YES	
77474	Hexachlorocyclopentadiene	YES	YES	
67721	Hexachloroethane	YES	YES	
110543	Hexane	YES	YES	
74908	Hydrogen cyanide	YES	YES	
193395	Indeno(1,2,3-cd)pyrene	NO	NO	NA
78831	Isobutanol	YES	YES	
78591	Isophorone	YES	NO	NA
7439976	Mercury (elemental)	YES	YES	
126987	Methacrylonitrile	YES	YES	
72435	Methoxychlor	YES	YES	
79209	Methyl acetate	YES	YES	
96333	Methyl acrylate	YES	YES	
74839	Methyl bromide	YES	YES	
74873	Methyl chloride (chloromethane)	YES	YES	
108872	Methylcyclohexane	YES	YES	
74953	Methylene bromide	YES	YES	
75092	Methylene chloride	YES	YES	
78933	Methylethylketone (2-butanone)	YES	YES	
108101	Methylisobutylketone	YES	YES	
80626	Methylmethacrylate	YES	YES	
91576	2-Methylnaphthalene	YES	YES	
108394	3-Methylphenol (m-cresol)	YES	NO	NA
95487	2-Methylphenol (o-cresol)	YES	NO	NA
106455	4-Methylphenol (p-cresol)	YES	NO	NA
99081	m-Nitrotoluene	YES	NO	NA
1634044	MTBE	YES	YES	
108383	m-Xylene	YES	YES	
91203	Naphthalene	YES	YES	
104518	n-Butylbenzene	YES	YES	
98953	Nitrobenzene	YES	YES	
100027	4-Nitrophenol	YES	NO	NA

CAS No.	Chemical	Is Chemical Sufficiently:		Check Here if Known or Reasonably Suspected To Be Present ³
		Toxic? ¹	Volatile? ²	
79469	2-Nitropropane	YES	YES	
924163	N-Nitroso-di-n-butylamine	YES	YES	
621647	N-Nitrosodi-n-propylamine	YES	NO	NA
86306	N-Nitrosodiphenylamine	YES	NO	NA
103651	n-Propylbenzene	YES	YES	
88722	o-Nitrotoluene	YES	YES	
95476	o-Xylene	YES	YES	
106478	p-Chloroaniline	YES	NO	NA
87865	Pentachlorophenol	YES	NO	NA
108952	Phenol	YES	NO	NA
99990	p-Nitrotoluene	YES	NO	NA
106423	p-Xylene	YES	YES	
129000	Pyrene	YES	YES	
110861	Pyridine	YES	NO	NA
135988	sec-Butylbenzene	YES	YES	
100425	Styrene	YES	YES	
98066	tert-Butylbenzene	YES	YES	
630206	1,1,1,2-Tetrachloroethane	YES	YES	
79345	1,1,2,2-Tetrachloroethane	YES	YES	
127184	Tetrachloroethylene	YES	YES	
108883	Toluene	YES	YES	
8001352	Toxaphene	YES	NO	NA
156605	trans-1,2-Dichloroethylene	YES	YES	
76131	1,1,2-Trichloro-1,2,2-trifluoroethane	YES	YES	
120821	1,2,4-Trichlorobenzene	YES	YES	
79005	1,1,2-Trichloroethane	YES	YES	
71556	1,1,1-Trichloroethane	YES	YES	
79016	Trichloroethylene	YES	YES	
75694	Trichlorofluoromethane	YES	YES	
95954	2,4,5-Trichlorophenol	YES	NO	NA
88062	2,4,6-Trichlorophenol	YES	NO	NA
96184	1,2,3-Trichloropropane	YES	YES	
95636	1,2,4-Trimethylbenzene	YES	YES	
108678	1,3,5-Trimethylbenzene	YES	YES	
108054	Vinyl acetate	YES	YES	
75014	Vinyl chloride (chloroethene)	YES	YES	

¹ A chemical is considered sufficiently toxic if the vapor concentration of the pure component (see Appendix D) poses an incremental lifetime cancer risk greater than 10⁻⁶ or a non-cancer hazard index greater than 1.

² A chemical is considered sufficiently volatile if its Henry's Law Constant is 1 x 10⁻⁵ atm-m³/mol or greater (US EPA, 1991).

³ Users should check off compounds that meet the criteria for toxicity and volatility and are known or reasonably suspected to be present.

Source: U.S. Environmental Protection Agency (EPA) (2002) *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils*: EPA/540/1-89/002

Appendix B

Appendix B contains the "Occupied Dwelling Questionnaire" that was originally presented in EPA's *Draft Guidance for Evaluating the Vapor Intrusion to Indoor Air Pathway from Groundwater and Soils (Subsurface Vapor Intrusion Guidance; EPA 2002a)*. 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 (MADEP, 2002) and California (DTSC 2005). It is recommended that a similar questionnaire be used when collecting indoor air samples at Air Force 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				
	Never	Hardly ever	Occasionally	Regularly	Often
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: _____

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Note: This bibliography contains writings cited in this document, as well as other reports and guidance that will be of use to Air Force environmental managers.

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List of Acronyms

AEH	Air exchanges/hour
AFCEE	Air Force Center for Environmental Excellence
AFRPA	Air Force Real Property Agency
BEE	Base Bioenvironmental Engineer
BRAC	Base Realignment and Closure
Cal-EPA	California Environmental Protection Agency
CE	Civil Engineering
CECOS	Civil Engineer Corps Officer School
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
CSM	Conceptual site model
DNAPL	Dense non-aqueous phase liquid
DoD	Department of Defense
DQO	Data quality objective
DTSC	Department of Toxic Substances Control
EPA	U.S. Environmental Protection Agency
EPC	Exposure point concentration
FID	Flame ionization detector
GC	Gas chromatography
GC/MS	Gas chromatography/mass spectrometry
HI	Hazard index
HQ	Hazard quotient
IR	Infrared spectroscopy
IRIS	Integrated risk information system
ISEERB	Interservice Environmental Education Review Board
J&E	Johnson and Ettinger
LEL	Lower exposure limit
LNAPL	Light non-aqueous phase liquid
MADEP	Massachusetts Department of Environmental Protection
MCL	Maximum contaminant level
NAS	National Academy of Science
OSHA	Occupational Safety and Health Administration
PAH	Polycyclic aromatic hydrocarbon
PEL	Permissible exposure limit
PID	Photo ionization detector
ppbv	Parts per billion by volume
PPRTV	Provisional peer reviewed toxicity value

pptv	Parts per trillion by volume
PSI	Preliminary site inspection
QAPP	Quality Assurance Project Plan
RCRA	Resource Conservation and Recovery Act
RfC	Reference concentration
RfD	Reference dose
RI	Remedial investigation
SCS	Soil classification system
SI	Site inspection
SIM	Selective ion mode
SOP	Standard operating procedure
SVOC	Semi-volatile organic compound
TCE	Trichloroethylene
TOC	Total organic carbon
UCL	Upper confidence limit
UST	Underground storage tank
VIP	Vapor intrusion pathway
VOC	Volatile organic compound